Proceedings of the 2006 IEEE International Conference on Robotics and Automation
Orlando, Florida - May 2006

On the use of an active wearable exoskeleton for tremor suppression via biomechanical loading*

E. Rocon, A.F. Ruiz, F. Brunetti, and J.L. Pons
Instituto de Automática Industrial
Consejo Superior de Investigaciones Científicas
Ctra. Campo Real, km 0.2, 28500 Arganda del Rey, Spain
erocon@iai.csic.es

J.M. Belda-Lois, J.J. Sánchez-Lacuesta
Instituto de Biomecánica
Universidad Politécnica de Valencia
Camino de Vera s/n., 46022 Valencia, Spain

Abstract – **Biomechanical loading, in particular, viscous loading of the upper limb has been proposed in the literature as a means for suppressing pathologic tremor. It is expected that an improvement on manipulative function can be obtained by reducing the tremorous motion associated to some neurological disorders. This article presents two non-grounded control strategies to suppress tremor by means of a orthotic (wearable) exoskeleton. These two strategies are based on biomechanical loading and notch filtering of tremor via internal forces. Both controls strategies will be evaluated and validated on the robotic exoskeleton called WOTAS (Wearable Orthosis for Tremor Assessment and Suppression). At the end, results obtained in the pre-clinical trials and conclusions of this study are presented.**

I. INTRODUCTION

Tremor is characterized by involuntary oscillations of a part of the body. The most accepted definition is as follows: “an involuntary, approximately rhythmic, and roughly sinusoidal movement" [1]. Tremor is a disabling consequence of a number of neurological disorders. Although the most common types of tremor were subject to numerous studies, their mechanisms and origins are still unknown. The most common of all involuntary movements, tremor can affect various body parts such as the hands, head, facial structures, tongue, trunk, and legs; most tremors, however, occur in the hands.

Tremor is a disorder that is not life-threatening, but it can be responsible for functional disability and social embarrassment. More than 65% of the population with upper limb tremor present serious difficulties performing daily living activities [1], [2]. In many cases, tremor intensities are very large, causing total disability to the affected person. There is no know cure for a lot of tremor diseases. The overall management is direct toward keeping the patient functioning independently as long as possible while minimizing disability. In addition to medication, rehabilitation programmes and deep brain stimulation, biomechanical loading has appeared as a potential tremor suppression alternative.

Biomechanical loading relies on an external device that either passive or actively acts mechanically in parallel to the upper limb. Significant results have been obtained in reducing hand tremor by applying mass, friction, and viscous resistive forces. The effects of load and force on tremor have received considerable attention by the research community. Amongst others, Adelstein [3], 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 increases. Tremor absorption is often confused with tremor isolation. The approach of tremor absorption, however, is based on tremor reduction devices that act mechanically in parallel to the oscillating limb.

This phenomenon gives rise to the possibility of an orthotic management of tremor. An orthosis is a wearable device (exoskeleton) that acts in parallel to the affected limb. In the case of tremor management, the exoskeleton 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. One of the specific and important common aspects to the field of orthotic rehabilitation is the intrinsic interaction between human and robot. This issue, in its simplest manifestation, implies a mechanical interaction between the robot and the human, most often solved through impedance control approaches [4]. The basic principles and considerations regarding impedance control were addressed by [5], in an excellent work. In his paper, Hogan pointed out the conditions for causality in the treatment of dynamic interaction between manipulator and environment, used the concept of mechanical impedance to address the mechanics of muscular skeletal system, dealt with the implementation of this control approach, and eventually, addressed the selection of appropriate impedance for a given application.

Biomechanical loading for tremor reduction can be approached either by ambulatory robotics based orthotic devices or by non-ambulatory table or wheelchair mounted devices. The former approach is characterized by selective tremor suppression through internal forces at particular joints, while the later relies on global application of external forces that leads to the overall tremor reduction. In Figure 1(a), a tablemounted tremor suppression device is shown (Neater Eater). It is an example of mechanisms implementing the external force concept for reducing tremor. Figure 1(b) shows the internal force concept, a wearable exoskeleton device applies tremor cancelling forces between upper-limb segments (the WOTAS-DRIFTS device [6]).

While wearable tremor suppression exoskeletons are already a matter of research, non-ambulatory systems have

---

0-7803-9505-0/06/$20.00 ©2006 IEEE

lead to commercial products, see, for instance, the so-called Neater Eater [7]. In addition, the MIT damped joystick, [8], the controlled Energy-Dissipation Orthosis, CEDO, [9], or the Modulated Energy Dissipation Arm, MED, (cited in [10]), are implementations of non-ambulatory, wheelchair- mounted tremor suppression prototypes. As far as wearable tremor suppression concepts are concerned, just the well-know wearable tremor-suppression orthosis, [10], has been reported in literature. This is a passive damping loading device, which acts mechanically in parallel to the wrist in flex-extension. It completely constrains both wrist abduction-adduction and prono-supination.


(a) (b)

Fig. 1 Typical examples of (a) non-ambulatory tremor suppression mechanism (Neater Eater) and (b) orthotic device for tremor reduction (WOTAS, Wearable Orthosis for Tremor Assessment and Suppression).

This article presents two novel non-grounded control strategies to suppress tremor by means of a orthotic (wearable) exoskeleton. These two strategies are based on biomechanical loading and notch filtering of the tremor with internal forces. In the next section, we discuss on two alternative control approaches as being considered for tremor suppression. 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 must be proposed. As part of the next section, a sinusoidal model for the tremor is used. Based on this model a two-stage modelling approach is used to detect tremor and voluntary motion. Next, both controls strategies will be evaluated and validated on the robotic exoskeleton called WOTAS (Wearable Orthosis for Tremor Assessment and Suppression). WOTAS will be described in section III. This will be followed by the description of the experiments and results obtained in the preclinical trials. Eventually, the conclusions and future work of this study are given.

II.CONTROL STRATEGIES FOR TREMOR SUPPRESSION

The approach to suppress the pathological tremor within this study is to assist the limb with compensatory technology in order to decrease the amplitude of tremor. Shortly, the control system should works as follow: sensors coupled to limb measure its motion, an error cancelling algorithm performs a real-time discrimination of the undesired component of motion, tremor information is input to the controller in order to generate the desired actuator performance to suppress the tremor. This concept can be implemented through passive and active systems.

In active concepts, a force proportional to the limb velocity is usually exerted at the application point. This force is generated by the system's motors as a result of a control algorithm. In passive concepts, a mechanical damper is used, thus the dissipative force usually results from viscous friction provided by the damper.

One of the main drawbacks of passive systems described in literature is that the dissipative force is also loading the patient's voluntary motion. As a consequence, the user feels a mechanical resistance to the motion. Even though in active systems this could be avoided, filtering out the voluntary motion we can eliminate the resistance to the voluntary motion. 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 in next section. Furthermore, it is proposed two different control approaches based on biomechanical loading for tremor suppression: 1) Tremor reduction through impedance control - implements an impedance control, i.e. the stiffness, damping and mass properties of the upper limb can be modified to study its effects on tremor, 2) Notch filtering at tremor frequency - based on noise reduction techniques and implements an active noise filter at the tremor frequency.

A. Modelling of tremor

In addition to be important to distinguish between desired and undesired motion, the analysis of the tremor signal, both in terms of frequency and amplitude, is relevant to asses the stationary characteristics of tremor, i.e. frequency drift and amplitude variation. This information is important when designing control strategies to counteract tremor.

A number of estimation algorithms have been developed for tremor suppression. As a first approach, we used robust algorithms based on the IEEE-STD-1057 Standard which is is a standard for fitting sine waves to noisy discrete-time observations, [11]. In particular, the weighted-frequency Fourier linear combiner (WFLC) developed by Riviere in the context of actively counteracting physiological tremor in microsurgery. The WFLC is an adaptive algorithm that estimates tremor using a sinusoidal model, estimating its time-varying frequency, amplitude, and phase [11]. The main problem of using the WFLC is that it requires a previous filter stage in order to remove the voluntary motion of the overall movement. This filter stage introduces a time delay that could considerably affect the implementation of the control strategies for tremor suppression.

The ideal solution used was the development of an algorithm capable of estimating voluntary and tremorous motion with a small phase lag. It is well known that the frequency of the voluntary motion of activities of daily living, ADL, occurs at frequencies lower than the tremorous movements, [2]. Based on this statement we have developed a new algorithm comprising two stages for the solution of this problem.

In the first stage, several algorithms were compared and the one selected for the estimation of the voluntary motion was a Benedict-Bordner Filter, [6]. This is a tracking algorithm used in the field of radar that model the dynamics of a system. This algorithm implements both estimation and filtering equations.

The combination of these actions allows the algorithm to filter the tremorous movement from the overall motion at the same time as reducing the phase lag introduced when compared to classical filters. The parameters of the equations were adjusted to track the movements with lower dynamics (voluntary movement). This stage does not consider any movement of high frequency, in particular spasms which are very common in patients that suffer from neurological disorders. Spastic movements are considered as tremorous movements and thus, the control strategies would try to filter out and reduce their amplitude.

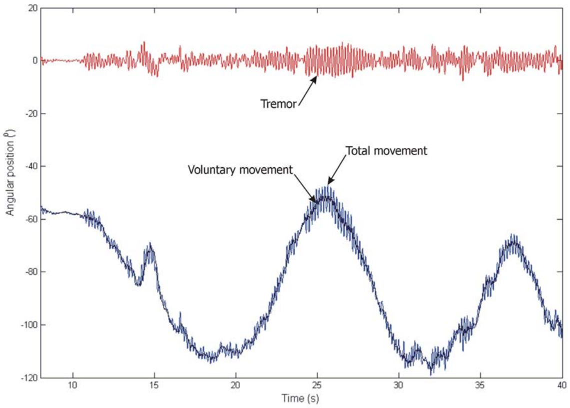

Fig. 2. Modelling of tremor as a sinusoidal non-voluntary motion: Modelling of tremor as a sinusoid: movement performed by the patient (grey), estimation of voluntary movement (black) and estimation of tremor(red).

In the second stage, the estimated voluntary motion is removed from the overall motion and the assumption that the remaining movement is tremor is made. After this, we use the WFLC in order to estimate the tremor. In this stage, the algorithm estimates both the amplitude and the time-varying frequency of the tremorous movement. This algorithm was evaluated with data obtained from 33 patients suffering from different tremor diseases. The estimation error between the estimated and the real voluntary movement in the first stage was 1,04±1,4 degrees. The second stage algorithm has a convergence time always smaller than 2s for all signals evaluated and the Mean Square Error (MSE) between the estimated tremor and the real tremor (obtained off-line by means of manual decomposition based on classical filters techniques), after the convergence, is smaller the 1 degree. The total time required to estimate both movements, after the convergence period, is one sample period (1 ms). The combination of both techniques resulted in a very efficient algorithm with small processing cost for estimating in real time the voluntary and the tremorous components of the overall motion. Figure 2 illustrates the performance of the algorithm when separating voluntary and tremorous movements of a essential tremor patient.

B. *Tremor reduction through impedance control*

The impedance of a system can be defined as a relationship between the reaction force of the system to an imposed external motion and the motion itself. In general, impedance comprises three components, i.e. stiffness, damping and mass. There is evidence, [3], that all three components modify the biomechanical characteristics of tremor at the upper limb, which in general can be described by a second order system.

In this approach, the musculo-skeletal system (each upper-limb articulation contributing to tremor) is modelled as a second order biomechanical system [12]. Our approach consists in changing the biomechanical characteristics of the musculoskeletal system by means of selecting the appropriate modified value damping and inertia of the musculo-skeletal system in order to reduce the amplitude of the tremorous movement, see Figure 3. Unlike other approaches in the literature, the control scheme is conceived so that the effect of the suppression load on voluntary motion is minimized.

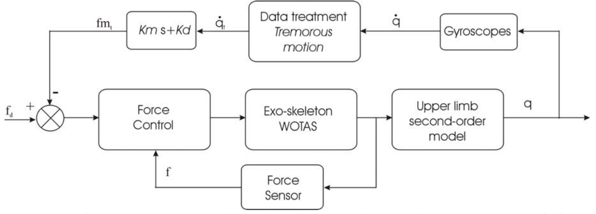

Fig. 3. Control strategy to modify the biomechanical parameters of the upper limb.

The upper loop of the control strategy has the aim of altering the apparent impedance of the upper limb. the coefficients *Km* and *Kd* describe the reference mass and damping characteristics of the upper limb. Based on these coefficients and on a filtered version of the joint motion (so that just tremor is fed back) the actual impedance force, f_{mt}, is computed and fed back. This impedance force should tend to vanish as tremorous motion is suppressed, therefore, as error is obtained between f_{mt} and the desired impedance force f_d which is set o zero.

The big challenge in this approach is to distinguish error from intended motion before error cancelling can occur. This requires the real-time error estimation presented in previous section.

C. *Notch filtering at tremor frequency*

Tremor is usually defined as rhythmic, involuntary muscular contraction characterized by oscillations at central frequency, [1]. Tremor frequency varies according to the particular neurological disorder being considered. In particular, while Essential tremor takes place in the frequency range between 5 and 8 Hz, rest tremor is usually found at a slightly lower frequency range, 3 to 6 Hz.

In addition, for a given type of tremor, its main frequency varies from patient to patient, but tends to be quite stable for a particular subject. This property should be exploited when designing a control strategy to counteract tremor. In particular, repetitive control, can handle periodic (repetitive) signals and disturbances. Repetitive control can be regarded as a subset of learning control since the control action is determined using the stored error values from preceding periods. Even though repetitive approaches can handle periodic signals (tremor), it is not free from some common problems: tight stability conditions, poor response to non-periodic and non-harmonic signals and poor noise characteristics.

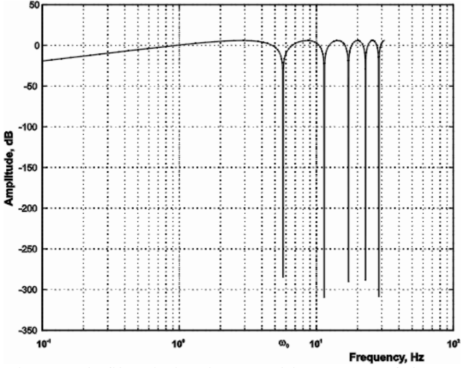

Fig. 4. An active notch filter is implemented by means of the active orthosis. In this scheme the notch filter frequency, ω_0, lies exactly at the tremor frequency.

As reported by Inoue, [13], a stabilizing compensation and smoothing of the control signal over periods can be used to overcome the above mentioned problems. The idea behind this control strategy is that active actuators generates an equal but opposite motion, based on a real time estimation of the involuntary component of motion, actively compensating and effectively subtracting the tremor for the overall motion. In Figure 4, the effect of the repetitive is graphically shown as a function of frequency. It can easily be observed the theoretically infinite attenuation at ω_t (tremor frequency) and its harmonics.

As in the previous control approach, the quality of the tremor suppression control approach is strongly dependent on accurate estimation and tracking of tremor frequency.

III.WOTAS

The active orthosis (exoskeleton) WOTAS was developed under the framework of the European project DRIFTS [14]. The concept of WOTAS is to develop an active upper limb exoskeleton based on robotics technologies capable of applying forces to cancel tremor and retrieve kinematic information from the tremorous upper limb. The overall aim of this project was to develop a powered orthosis to provide means of testing non-grounded tremor reduction strategies in three joints of the upper limb. This robotic orthosis platform is able to monitor, diagnose and control tremor in subjects. This robotic exoskeleton is equipped with kinematics (angular position, velocity and acceleration) and kinetic (interaction force between limb and orthosis) sensors. Moreover, it could also apply dynamic force to the articulations of the upper limb by means of a set of flat DC motors + pancake gears [6].

Innovations of the WOTAS exoskeleton are its portability, it is a no invasive system, and provides direct information from each joint of the upper limb, allowing the estimation of the contribution of each articulation to the overall tremorous motion in the kinematic chain of the upper limb. This platform also allows the implementation of different control strategies to tremor suppression for each joint, in such a way that independent control strategies could be applied to each joint.

The total weight of the final system is roughly 850g. A programme of testing was performed to identify the ease of use characteristic and the range of workspace carried out by a normal user. The system was used in the laboratory to perform a wide variety of manoeuvres in free mode. These preliminary tests have successfully demonstrated the correct operation of the system and the capability of the system to access the workspace, in other words, the system does not affect the normal range of motion of the user. The weight of the orthosis is acceptable and does not cause discomfort to the user.

The WOTAS concept provides a means of testing nongrounded tremor reduction strategies. 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, see Figure 1b).

A. *Control Architecture*

WOTAS' control architecture is mainly composed by 3 components, namely, the exoskeleton structure with its sensors and actuators; a standard PC where the RT control algorithms of the orthosis are executed and a standard desktop PC that works as a host computer and implements the interface with the clinician.

This control architecture aims to interface the control algorithms with the exoskeleton. The WOTAS circuitry and sensors serve two functions: 1) Obtain the position, angular velocity and acceleration signals for control, data collection and evaluation. 2) To generate the power signal to activate the actuator.

WOTAS is able to operate basically in three control modes: 1) *Monitoring mode*. WOTAS operates in free mode (no force is applied to the upper limb) and monitors tremor parameters of the patients, 2) *Passive Control mode*. WOTAS is able to change biomechanical characteristics of upper limb, such as viscosity or inertia, in order to suppress tremor. It virtually modifies the upper limb impedance (section II-B), 3) *Active Control mode*. WOTAS is able to apply forces opposite to the tremorous movement based on a real time estimation of the involuntary component of motion. This leads to an active compensation and effective suppression of tremor (section II-C).

The control of the entire active exoskeleton is being implemented in the MatLab RT suite by Mathworks. This environment provides mathematical libraries that help implement complex control strategies in real time. The interface between the MatLab environment and the active orthosis is based on a standard data acquisition board. In order to provide an interface to all the control strategies a software application was developed in C language. It communicates with the low level controller (either by TPC/IP, wired serial link or BlueTooth) using Dynamic Link Libraries (DLLs) that implements this communication, [15].

IV. EXPERIMENTAL RESULTS

In order to evaluate the performance of the device developed to suppress tremor we have planned an experimental phase involving 4 patients suffering from different tremor diseases. The experiments were realized in cooperation with Hôpital Erasme, in Belgium, and were accompanied by a neurologist. During these trials we have evaluated the performance of the elbow joint of WOTAS device.

A. *Material and Methods*

The trials were realized in four different conditions.With this approach we tried to avoid the Placebo effect of the orthosis.

- *Condition 1*. The users knew the orthosis state (active, monitoring mode), and the moment in which the orthosis was switched on. The task was to keep the arms outstretched.
- *Condition 2*. The users did not know the orthosis state. The orthosis operation mode was selected by the doctor. The task was to keep the arms outstretched.
- *Condition 3*. The users knew the orthosis state, and the moment in which the orthosis was switched on. The task consists on reaching the nose with the finger.
- *Condition 4*. The users did not know the orthosis state. The orthosis mode was selected by the tester. The task was to reach the nose with the finger.

During the trial WOTAS operated in its three different control modes: monitoring, passive and active modes. When operating in the passive mode WOTAS applied viscosity to the movement. The values of viscosity added to the movement were between 0,1 to 0,3 N.m.s/rad.

The data plotted is the output voltage coming from the gyroscopes placed on elbow. This output voltage was sampled at 2000 Hz rate. The data has been filtering using a Kernel Smoothing algorithm and a gaussian window 51 points width. The parameter selected to compare the tremor level is the Power contained in the frequency band from 2 Hz to 6 Hz [2]. It can be defined as follows:

$$\Phi(f) = \frac{FFT(x) \cdot FFT(x)^*}{N} \tag{1}$$

$$P = \sum_{i=f_1}^{f_2} \frac{\Phi(i)}{T} = \frac{1}{Nt_s} \sum_{i=f_1}^{f_2} \Phi(i) \tag{2}$$

where x is the signal in the time domain, N is the length of the signal, t_s is the sampling period and, f_1 and f_2 are the lower and upper limits of the range of interest.

B. *Users*

As said before, four patients participated in these experiments. Table I summarizes the main characteristics of each patient. It was not possible to use the data from one patient since he seems not to tremor during the trials. All patients gave their written consent to the experiments.

TABLE I
PATIENTS INFORMATION

Subject	**Gender**	**Diagnosis**	**Characteristics**
1	Female	Essential tremor	Presents flaccidity in the tissues of the arm. It is more evident over the triceps area.
2	Male	Essential tremor	Presents flaccidity at the arm tissues. His tremor is small. His data has not taken into account, because in the trials there was not evidence of tremor.
3	Female	Sclerosis	Her pathology causes desinhibition problems, therefore her comments should be considered with caution.
4	Female	Essential tremor	Presents a severe tremor in all the joints of the upper arm.

C. *Results*

As said in the previous section, we have calculated the power spectrum between 2 Hz and 6 Hz in order to assess the WOTAS effectiveness. For patient 1, who has an evident tremor at 4 Hz, with the trials being realized in condition 1, the reduction ratio of the tremor power was 28% when applying a viscosity of 0.2 Nms/rad and 30% when the viscosity applied over the tremor movement was 0.3 Nms/rad. When the trial was in condition 2 the reduction ration was 24% for a viscosity of 0.2Mms/rad, and 30% for a viscosity of 0.3 Nms/rad.

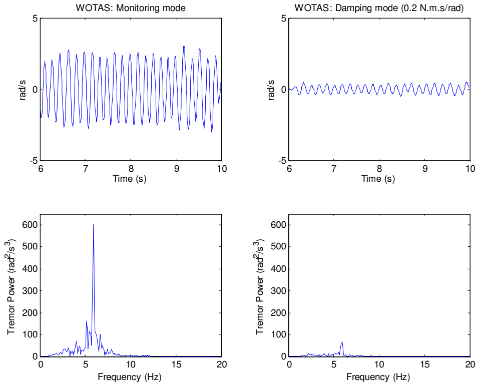

Fig. 5. The graphics illustrated the reduction in the tremor power when WOTAS is applying viscosity to the tremorous movement.

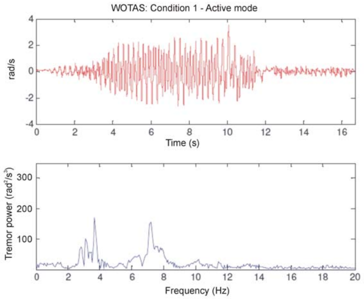

Fig. 6. Amplitude and Fourier Transform of the tremor movement acquired by the gyroscopes during the application of active control strategies to suppress tremor.

Patient 3 presented a very small tremor amplitude during the trials at the elbow level. With WOTAS operating under condition 1 and applying a viscosity of 0.1 Nms/rad there was no reduction in the tremor power. Nevertheless, the reduction in the tremor power was 30,9% under condition 1 and with a viscosity of 0.2 Nms/rad applied over the tremorous motion. As said before, this patient has a very small tremor amplitude. In addition, the support of the arm seemed to be very large for the user. This could explain why there was a fail in tremor suppression for small values of viscosity applied over the tremorous movement. On the other hand, this patient (who has sclerosis) related that she noticed improvement in the task performance only by wearing the orthosis.

Patient 4 presented a very severe tremor at the elbow level. With this patient the efficiency of the orthosis to suppress tremor achieved a 80% reduction in the tremor power with a viscosity of 0.3 Nms/rad applied, see Figure 5. The user reports that she felt an important degree of tremor reduction when the viscous mode was active.

The active control strategy was evaluated just with patient 4. As can be seen in Figure 6 the active strategy failed to suppress tremor. The tremor peak at 4 Hz is present and other peak appears at harmonic frequencies of the tremor peak. Furthermore, the user reported a worsened sensation of tremor in addition to an annoyance sensation when this active mode was running.

V. DISCUSSION AND CONCLUSIONS

This paper presents a robotic orthosis platform able to monitor and control tremor in subjects. This robotic exoskeleton is equipped with kinematics (angular position, velocity and acceleration) and kinetic (interaction force between limb and orthosis) sensors. In addition, it could also apply dynamic force to the articulations of the upper limb by means of a set of flat DC motors + pancake gears.

The system was evaluated with tremor patients. The patients wore WOTAS while operating in free, passive and active modes. The system was able to measure and estimate tremor parameters, Figures 5 and 6. 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 a reduction ratio in the order of 80% in tremor power for patients with severe tremor.

In this paper a completely novel approach to biomechanical management of tremor, noth filtering (active tremor suppression), was introduced. The evaluation of the results for both showed that passive (impedance control) and active tremor suppression control strategies differs deeply in their behaviour for tremor suppression. A priori viscous friction seems a more feasible strategy than active filtering. Further investigations will be realized in order to improve the performance of the active control strategy.

Flaccidity of tissues at the upper arm has been the major problem to attach WOTAS to the arm and can explain partially why the values differ for the mild to the severe cases of tremor. If the fixation is not good the device will not be able to detect small movements. To solve this problem we decided to use a textile substrate to clutch the flaccid tissues and then enhance performance of the fixation supports.

These experiments were the pre-clinical trials of the orthosis, further trials with a large number of patients will be held in a close future and other different aspects of WOTAS operation will be evaluated. The testing bench will help analyze the effect of the biomechanical loading on the voluntary motion and quantify its effects on fatigue. In addition, the carryover of attenuation effects after the impedance is removed must be subject to study. This is in line with the study of the effects of long term strengthening of muscles when subject to the training effect the orthosis is imposing to the patient.

ACKNOWLEDGMENT

The work presented in this paper has been carried out with the financial support from the Commission of the European Union, within Framework 5, specific RTD programme “Quality of Life and Management of Living Resources", Key Action 6.4 “Aging and Disabilities", under contract no. QKL6-CT-2002-00536, “DRIFTS - Dynamically Responsive Intervention for Tremor Suppression".

REFERENCES

[1] R. Elble and W. Koller, *Tremor*. The Johns Hopkins University Press, 1990.

[2] E. Rocon, J. Belda-Lois, J. Sanchez-Lacuesta, and J.L.Pons, “Pathological tremor management: Modelling, compensatory technology and evaluation,” *Technology and Disability*, vol. 16, pp. 3–18, 2004.

[3] B. Adelstein, “Peripheral mechanical loading and the mechanism of abnormal intention tremor,” *Ph.D. dissertation*, MIT, 1981.

[4] W. Harwin, L. Leiber, G. Austwick, and C. Dislis, “Clinical potential and design of programmable mechanical impendances for orthotic applications,” *Robotica*, vol. 16, pp. 523–530, 1998.

[5] N. Hogan, “Impedance control: An approach to manipulation: Part I, II and III,” *Journal of Dynamics Systems*, Measurement and Control, vol. 107, no. 1, pp. 1–23, 1985.

[6] E. Rocon, A. Ruiz, J.L.Pons, J. Belda-Lois, and J. Sánchez-Lacuesta, “Rehabilitation robotics: a wearable exo-skeleton for tremor assessment and suppression.” Proceedings of the IEEE International Conference on Robotics and Automation, 2005, pp. 2283–2288.

[7] J. Michaelis, “Introducing the neater eater,” *Action Res.*, vol. 6, no. 1, pp. 2–3, 1988.

[8] J. Hendriks, “A second-generation joystick for people disable by tremor,” in *Proceedings of the 14th Annual RESNA Conference*, E. NY, Ed. RESNA Press, 1991, pp. 248–51.

[9] M. Rosen, A. Arnold, I. Baiges, M. Aisen, and S. Eglowstein, “Design of a controlled-energy-dissipation orthosis (cedo) for functional suppression of intention tremors,” *J. Of Rehabilitation Research and Development*, vol. 32, no. 1, pp. 1–16, 1995.

[10] J. Kotovsky and M. Rosen, “A wearable tremor-suppression orthosis,” *J. Of Rehabilitation Research and Development*, vol. 35, no. 4, 1998.

[11] C. Riviere, “Adaptive suppression of tremor for improved human-machine control,” *Ph.D. dissertation*, Johns Hopkins University, 1981.

[12] S. Pledgie, K. E. Barner, S. K. Agrawal, and T. Rahman, “Tremor suppression through impedance control,” *IEEE Transactions on Rehabilitation Engineering*, vol. 8, no. 1, pp. 53–59, 2000.

[13] T. Inoue, “Practical repetitive control system design,” in *Proc. of the 29th IEEE Conf. on Decision and Control*, 1990, vol. 3, pp. 1673–1678.

[14] M. Manto, M. Topping, M. Soede, J. Sanchez-Lacuesta, W. Harwin, J. Pons, J. Williams, S. Skararup, and L. Normie, “Dynamically responsive intervention for tremor suppression,” *IEEE Engineering in Medicine and Biology*, vol. 22, no. 3, pp. 120–132, 2003.

[15] J. Moreno, B. Freriks, F. Thorsteinsson, J.Snchez, and J.L.Pons, “Intelligent knee-ankle-foot orthosis: The gait project approach,” *Rehabilitation Sciences in the New Millenium - Challenge for Multidisciplinary Research*, pp. 271–274, 2004.