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On the use of FES to attenuate tremor by modulating joint impedance

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***Abstract*— In this paper, we describe a closed-loop pathological tremor attenuation system using Functional Electrical Stimulation (FES). The proposed strategy, which is based on the modulation of joint impedance using FES, was developed after experimental evidence was obtained on open-loop trials with tremor patients. The method relies firstly on an online tremor estimation algorithm, which also filters the voluntary motion performed by the patient. Based on this information, the impedance of the trembling joint may be increased accordingly by applying the appropriate stimulation parameters on a pair of antagonist muscles that act on the joint, thus attenuating the effects of tremor. An experimental evaluation of the system, which involved 4 healthy subjects and 1 tremor patient, is also presented.**

I. Introduction

Tremor, which may be defined as an involuntary, approximately rhythmic, and roughly sinusoidal movement, is one of the most common movement disorders [1]. It can affect the different body parts, but presents particularly high incidence on the hands. Although it is not a life-threatening pathology, it often decreases significantly the person's quality of life, since patients present reduced ability to perform simple daily tasks, such as drinking a glass of water or opening a door.

An absolutely effective treatment for pathological tremor is not yet available, since current pharmacological and surgical alternatives still present limitations with respect to effectiveness, risks, and costs. A different approach is the use of assistive technologies, such as robotic devices [2], upper limb exoskeletons [3], and the use of Functional Electrical Stimulation (FES) [4]. Nevertheless, the design of active tremor compensation systems presents several challenges. Such a device must be able, for instance, to distinguish between voluntary and pathological motion and also to react to changes in the trembling motion, since tremor often presents highly time-varying dynamics. Furthermore, tremor compensation must be accomplished while minimizing the induced fatigue, pain, and discomfort.

In his pioneer work [4], Prochazka proposed a single-joint tremor compensation system using FES in which a pair of antagonist muscles were stimulated in anti-phase with respect to tremor. The controller was designed in such a way that the closed-loop gain of the system was maximized for the tremor frequency. A simple model of a FES-actuated joint was used, but the possibility to provide long-term tremor suppression using electrical stimulation was demonstrated.

In this work, however, we are not especially interested in controlling joint motion to counteract tremor. Instead, we are mainly interested in increasing the FES-induced joint impedance in order to reduce tremor amplitude and also to provide an extra stability to support the person's intended motion. This additional impedance may be provided using FES to co-contract antagonist muscles, while producing minimum joint displacement.

In preliminary experiments, this alternative has been evaluated on trials involving tremor patients, where the validity of the approach has been confirmed. In these experiments, the stimulation levels that provide suitable impedance for that particular tremor were set manually or in open-loop schemes. An improved closed-loop solution would require the addition of other features, such as estimation of tremor time-varying intensity and a method to compute the appropriate stimulation levels. In a previous paper [5], both problems were addressed.

In this paper, firstly we describe briefly the neuromusculoskeletal principles and preliminary open-loop experiments conducted to validate the approach. Next, the closed-loop tremor attenuation strategy is presented, including both methods of online tremor estimation while filtering voluntary motion and the FES controller that modulates joint impedance. Section IV presents then the experiments designed to evaluate the solution, which were conducted on healthy subjects with no neurological impairment, but under the effects of a FES-induced tremor, and on one tremor patient. A discussion on the potential advantages and drawbacks of the method closes the section, while the final remarks are presented in the last section.

II. Evidence on open-loop experiments

From consolidated knowledge in motor control [6], it is known that humans co-contract their muscles when performing specific tasks. Indeed, although it may be as an inefficient approach in terms of energy consumption, simultaneously contracting antagonist muscles is one of the strategies employed by the CNS in tasks that require more precision and stability, since the joint impedance is increased.

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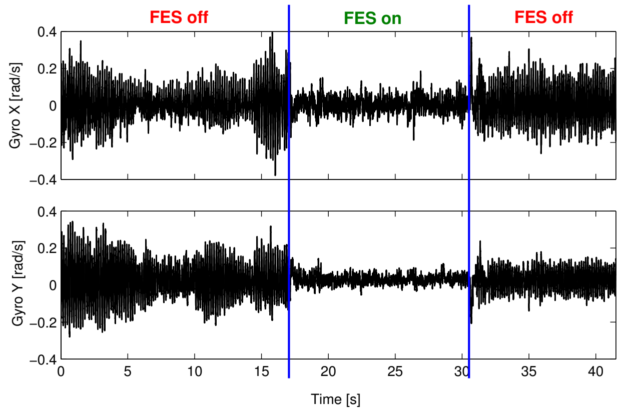

Fig. 1. **Patient 1**. Effect of FES with fixed stimulation parameters on tremor intensity. Motion measured in 2 axis are represented.

In terms of musculoskeletal dynamics, increasing joint impedance without producing any residual joint motion is possible when antagonist muscles deliver the same, but opposing torques to the joint. In this condition, impedance may be modulated by the muscles activation level due to either intrinsic and proprioceptive contributions to muscle active viscoelasticity [7]. Since this property is also valid for muscles activated using FES, it may be inferred that artificially inducing co-contraction is one of the simplest strategies to reduce the effects of pathological tremor.

Simulation studies were conducted to validate the method [8], but in order to provide experimental support for the strategy, experiments were conducted with patients diagnosed with Essential Tremor (ET), a pathology in which tremor amplitude often during voluntary action. In these experiments, which were approved by the local medical research council, a commercially available stimulator (Cefar Physio 4) was used to stimulate muscles related to the pathological motion presented by the patient. Since inter-subject variability is high among patients, before each trial the muscles were carefully chosen and the corresponding stimulation levels were tuned manually.

In Fig. 1, we illustrate one of the results obtained with patient 1, who presentes a mild tremor at the fingers, particularly at the thumb. For that reason, we have chosen to stimulate the muscles concerned with thumb abduction-adduction (*Abductor Pollicis Brevis*, APB, and *Adductor Pollicis*, AP). In the figure we may observe the pathological motion measured using a 2-axis gyrometer in periods with and without the compensatory stimulation. Since the stimulation level was tuned manually, an Electromyography (EMG) system was used to detect those moments when FES was on.

The data illustrated shows that when no FES was applied, tremor was highly variable. However, once the stimulator was turned on and correctly tuned, tremor intensity decreased significantly. After the trial, the subject reported that the extra stability due to the FES-induced co-contraction was a positive effect. Also, no particular remarks on discomfort due to stimulation were made, which may indicate that using less varying stimulation may be more comfortable to the patient with respect to the method presented in [4].

In trials with other patients, other issues related to the method have became evident, such as problems due to incorrect placement of the electrodes and the difficulty to effectively evaluate tremor reduction, considering that tremor itself is highly variable. On the other hand, the validity of the proposed method has been illustrated on several patients.

III. Tremor attenuation strategy

The results described on the previous section indicate that this approach may be applied to portable FES systems designed to provide effective functional benefit to tremor patients. Nevertheless, in order to design such a device, additional capabilities must be integrated to the system.

Since tremor is often highly nonstationary, an essential feature is to detect tremor onset based on measurements from sensors of motion or muscular activity. Additionally, online tremor estimation while filtering the voluntary motion simultaneously performed by the patient is potentially useful, since more advanced compensation systems may be designed. Such algorithm is described in Sec. III-A. The following subsection is devoted to the closed-loop compensation system, in which the tremor state estimation is used to compute the FES parameters that will provide the additional joint impedance in order to reduce tremor amplitude.

A. Online Tremor Tracking

To perform online tremor characterization, but considering that the sensor used for that purpose also measures the intentional motion performed, we first assume that the measured data may be modeled by

$$s(k) = s_t(k) + s_v(k) + \nu_s(k), \qquad (1)$$

where s_t is the tremor component, and s_v is the voluntary motion. s is measured by a motion sensor, which may be an inertial sensor, an optical tracking system, digitizing tablets. ν_s is an additive white Gaussian noise, $\nu_s \sim N(0, \sigma_s^2)$, that represents sensor error.

Different solutions [9], [3] have already been proposed to accomplish the online estimation of both tremor and voluntary motion from the readings of a noisy sensor. Here, we briefly present a method which was originally presented in our previous works [10], [11], where a deeper presentation of this problem may be found.

In our approach, both tremor and voluntary motion are modeled as nonstationary signals. Since tremor may be seen as a quasi-periodic motion, truncated Fourier series have been chosen to represent it, i.e.,

$$s_t(k) = \sum_{n=1}^{N_t} \left[a_n(k) \sin\left(n \sum_{g=1}^{k} \omega(g) \right) + b_n(k) \cos\left(n \sum_{g=1}^{k} \omega(g) \right) \right], \quad (2)$$

where ω is the time-varying fundamental frequency, a_n and b_n are the coefficients and N_t is the number of harmonics, the model order. ν_{st}, an additive white Gaussian noise, $\nu_{s_t} \sim N(0, \sigma_{s_t}^2)$, represents modeling errors. ω, a_n, and b_n are time-varying parameters.

Regarding voluntary motion, although it is a slower movement, it does not present the regular features of the tremor motion. Hence, it was modeled as an Auto-Regressive Moving Average (ARMA) model, with fixed filter parameters tuned to represent the low frequency behavior assumed for voluntary motion, i.e.,

$$s_v(k) - \sum_{n=1}^{N_v} c_n s_v(k-n) = \sum_{n=0}^{N_v-1} d_n \nu_{s_v}(k-n), \quad (3)$$

where ν_{s_v} is a white Gaussian noise, $\nu_{s_v} \sim N(0, \sigma_{s_v}^2)$, and N_v is the model order.

In order to apply the recursive algorithm to simultaneously estimate both motions and the tremor parameters, the referred models must be represented in a stochastic state space form. With respect to tremor representation, the following augmented state vector $\mathbf{x}_t$ is considered:

$$\mathbf{x}_t(k) = \begin{bmatrix} s_t(k) & a_1(k) & \cdots & a_{N_t}(k) & b_1(k) & \cdots & b_{N_t}(k) & \omega(k) \end{bmatrix}^T,$$

where tremor, $\mathbf{x}_{t,1}(k)$, is given by Eq. (2), a static nonlinear model, and the other states, representing the time-varying model parameters, are modeled as random walks. Both tremor and its parameters have been explicitly included in the filter augmented state vector due to the interest in representing individually the uncertainties of each model.

Concerning the ARMA model that describes voluntary motion, in order to reproduce Eq. (3) N_v auxiliary variables α_n were used. The filter states related to voluntary motion, $\mathbf{x}_v$, are

$$\mathbf{x}_v(k) = \begin{bmatrix} \alpha_1(k) & \cdots & \alpha_{N_v}(k) \end{bmatrix}^T,$$

where $\mathbf{x}_v(k)$ is given by

$$\begin{bmatrix} c_1 & 1 & 0 & \cdots & 0 \\ c_2 & 0 & 1 & \cdots & 0 \\ \vdots & \vdots & & \ddots & \vdots \\ c_{N_v-1} & 0 & 0 & \cdots & 1 \\ c_{N_v} & 0 & 0 & \cdots & 0 \end{bmatrix} \mathbf{x}_v(k-1) + \begin{bmatrix} d_0 \\ d_1 \\ \vdots \\ d_{N_v-2} \\ d_{N_v-1} \end{bmatrix} \nu_{s_v}(k). \quad (4)$$

and $\mathbf{x}_{v,1}(k) = s_v(k)$. Using this state space representation, process and measurement noises are not correlated. This is particularly suitable to the current problem, since measurement noise corresponds to sensor noise only.

To obtain the full state vector, we combine the states regarding tremor and voluntary motion:

$$\mathbf{x}(k) = \begin{bmatrix} \mathbf{x}_t(k) \\ \mathbf{x}_v(k) \end{bmatrix}, \quad (5)$$

from which the total number of states is defined by $N_x = 1 + (2N_t + 1) + N_v$. The respective process covariance matrix, $\mathbf{Q}$, is composed by the individual variances.

Finally, the measurement model is simply given by Eqs. (1). Hence, the model presents a linear relation with respect to the state vector, and its variance r is directly related to sensor noise.

The optimal estimator for linear systems with additive Gaussian noise is the KF. Since the obtained system is nonlinear, a modification of the Kalman filter for such class of problems has been used, the EKF. In the EKF, the Kalman equations are applied to the first-order linearization of the nonlinear system around the current state estimate [12]. All the parameters and initial estimates used to configure the proposed recursive algorithm are available in [11].

Once the tremor model parameters are estimated for every time-instant, tremor power or intensity may be computed directly from the coefficients of truncated Fourier series:

$$P_t(k) = \frac{1}{4} \sum_{n=1}^{N_t} \|b_n - i a_n\|^2, \quad (6)$$

B. Closed-loop tremor compensation

Here we describe an uncomplicated closed-loop tremor compensation system which is based on the concept that higher FES-induced joint impedance may reduce the effects of more severe tremors. One of the major aspects within the design of such system is that the controller closely interacts with the subject. Due to that important feature, the final goal is not to completely suppress tremor (the case in which maximum joint active impedance would always be the best control action), but instead to provide the greater functional benefit, while minimizing total discomfort.

With respect to the control problem itself, the practical difficulties that appear when controlling musculoskeletal systems using FES must be pointed out. Indeed, controlling such systems using invasive technologies is already a difficult task due to the complexities of muscle action, but several other practical issues arise when using superficial electrodes. For instance, small differences in the electrodes positions highly affect the response obtained. It is even a greater issue if we consider electrical stimulation diffusion to other muscles. Together, these effects prevent the application of same model parameters on different experimental sections. Other time-varying effects may interfere also within a single trial, like changes in skin-electrode interface, muscle fatigue induced by FES. Due to those reasons, FES control and identification remain a challenging domain [13].

Further difficulties arise when FES is applied on subjects that have full control of the muscle, such as tremor patients, since involuntary contractions in reaction to the stimulation may greatly disturb the output. Unfortunately, these effects are hardly absent both for subjects who are already familiar with FES and those who have not yet experienced it.

Based on this context, the controller evaluated in this paper may be seen as a regulator designed to reject an estimated disturbance (the tremor). However, due to the issues described above, we have chosen a simple method to validate this new closed-loop approach: we have designed a simple PI controller with anti-windup, while this last feature is due to the actuator saturation with respect to physiological limits and subject comfort. The controller error is P_t, the tremor severity estimated by the online tremor tracking algorithm. The control law is implemented for a particular controlled muscle and the corresponding antagonist muscle input is given by

$$u_e = \frac{M_f}{M_e} u_f, \tag{7}$$

to ensure no residual torque will be applied. In the equation, u_e and u_f refers to the stimulation levels applied to extensor and flexor muscles, respectively. The ratio M_f/M_e is related to the maximum torques delivered by the antagonist muscles and is chosen based on the subject evaluation of the subjects with respect to the stimulation limits.

One of the particularities of such a controller is that it must be able to handle the following situation: since the controller error is always positive (there is no $P_t < 0$), a pure PI regulator will wrongly provide additional joint impedance even if tremor amplitude is within acceptable limits. The solution to avoid this problem is to suspend the stimulation if tremor severity drops below a threshold. If a measurement of the trembling muscle activity was available (from surface electromyography, for instance), a separate estimate of tremor intensity could be computed and such routine would be unnecessary.

IV. Experimental evaluation

A. Subjects and FES normalization

In preliminary trials, tests were conducted on 4 subjects with no neurological impairment, and tremor on the target joint was induced by an independent stimulator. Next, the performance of the proposed closed-loop strategy was evaluated on 1 female tremor patient.

Concerning the healthy subjects, 1 female and 3 male subjects took part in the study. The target joint was the wrist, particularly the dorsi/palmar flexion. FES-induced tremor was produced either by stimulating flexor muscles, such as the *Flexor Carpi Radialis* (FCR) or the *Palmaris Longus* (PL), or extensor muscles, such as the *Extensor Digitorum Communis* (EDC). Antagonist muscles chosen to attenuate tremor, such as the *Flexor Carpi Ulnaris* (FCU) and the *Extensor Carpi Ulnaris* (ECU).

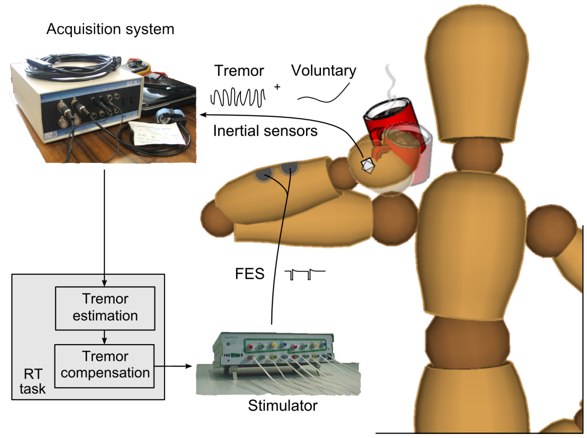

Fig. 2. General diagram illustrating the experimental setup used in this work.

Due to inter and intra-subjects variations concerning electrically controlled muscles, every experimental session was preceded by a procedure to identify the appropriate stimulation parameters for each muscle. Considering that the stimulator applied in this work allows online update of all three traditional FES parameters, the following rules were applied:

- Frequency was fixed for every experiment (30 Hz).
- Amplitude was also fixed and its value was chosen by the subject based on the discomfort produced. Typical values ranged from 15 to 25 mA.
- General stimulation level was controlled by the stimulation pulse-width (PW). Minimum (PW_{min}) and maximum (PW_{max}) values obtained according to the person's subjective evaluation were used to normalize FES control:

$$PW = (PW_{max} - PW_{min})u + PW_{min}, \tag{8}$$

where u, $0 < u < 1$, is the control variable.

B. Setup

The experimental setup may be represented by the Fig. 2. The main components are the stimulating, sensing and processing units. The stimulator is an 8-channel stimulator, the Prostim, designed jointly by the LIRMM and Neuromedics. The main sensor used in the control loop is the IDG-300, an angular rate sensor from Invensense. Both tremor tracking and tremor attenuation algorithms are executed in a 50 Hz-loop. The whole system is electrically isolated to ensure the subject's safety. As an additional hardware used on the trials involving healthy subjects, a commercial stimulator from CEFAR, the Physio 4, was used. It produces biphasic square pulses, opposed to the biphasic pulses with capacitive discharge generated by Prostim.

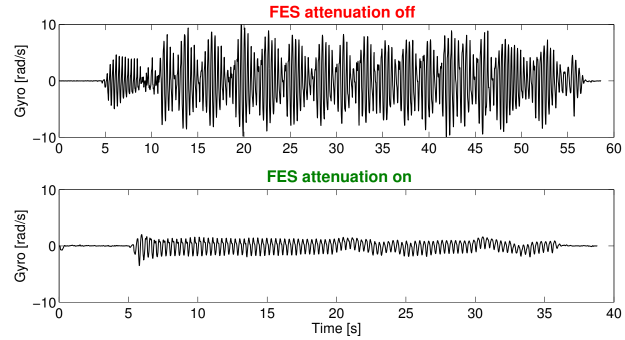

Fig. 3. **Subject A**. The top figure illustrates the effects of FES-induced tremor only (starts at 5 *s*). The bottom figure illustrates another trial, where FES-induced was kept at the same level, but the closed-loop FES compensation was activated.

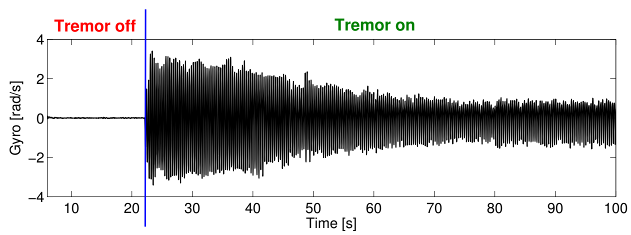

Fig. 4. **Subject B**. Progressive reduction on tremor intensity with closed-loop FES compensation. FES-induced tremor starts at 22 *s*.

C. Results

The proposed tremor compensation strategy was evaluated using two different methods. Either we have compared tremor severity with and without the FES compensation system in distinct moments, or the attenuation strategy was turned on for a brief period during a trembling motion.

Concerning the experiments involving subjects with no neurological impairment, illustrated in Figs. 3, 4, 5, and 6, FES-induced tremor frequency was constant during the tests. Variations in tremor amplitude have occurred due to variations throughout time of the subjects' involuntary resistance to the FES-induced motion. The illustrated data (one for each subject) was chosen to support the discussion that is presented in the following subsection.

After validation of the closed-loop strategy on healthy subjects, the same tremor patient whose open-loop results are illustrated on Fig. 1 has participated in one preliminary experiment. The results are shown in Fig. 7. The satisfactory performance of the method was also validated, even considering that the patient presents a mild postural tremor.

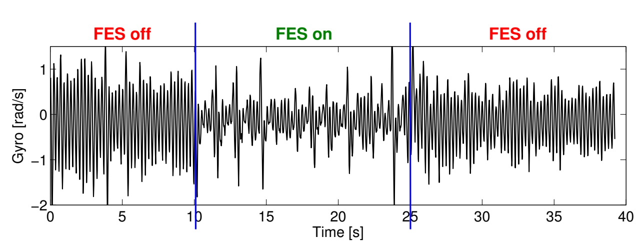

Fig. 5. **Subject C**. FES-induced tremor is highly variable, but mean amplitude clearly reduces when the closed-loop FES compensation system is active (between 10 and 25 *s*).

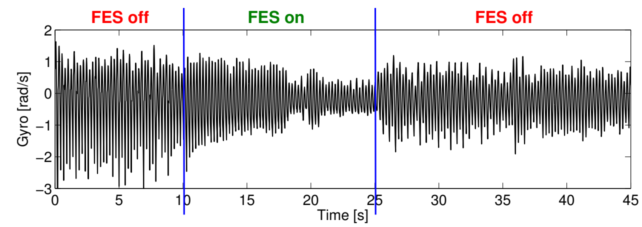

Fig. 6. **Subject D**. The closed-loop FES compensation system (active between 10 and 25 *s*) produces a reduction on tremor amplitude and, once it is stopped, tremor reestablishes.

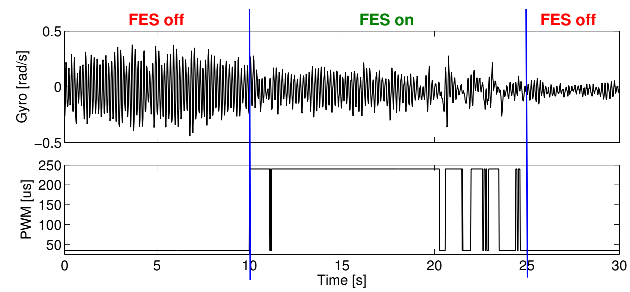

Fig. 7. **Patient 1**. Effect of the closed-loop FES compensation system on a mild tremor at the thumb. The lower figure illustrates the stimulation level applied to the concerned muscle.

D. Discussion

In other studies [5], we have already conducted preliminary validation using a quantitative evaluation of average results recorded in different trials. Then, here we focus on a qualitative analysis of the approach, considering more experimental data is now available. Based on this analysis, the first aspect that has to be pointed out is that the possibility of using this closed-loop strategy to attenuate tremor has been validated, since a reduction on tremor amplitude was observed in every subject. However, a satisfactory performance with respect to tremor intensity requires that all parts of the solution work properly. Indeed, the tremor characterization algorithm has been already evaluated independently [11]. Hence, the discussion concentrates on the advantages and drawbacks of the tremor compensation approach based on FES-induced joint modulation.

One important issue refers to the transient response of the controller. For instance, based on Fig. 3 we may conclude that tremor amplitude is reduced to an appropriate level with a satisfactory response time. On the other hand, that would not be the conclusion when analyzing the data in Fig. 4. In this case, the performance was highly affected by the fact that subject B had no prior experience with FES, and thus the FES limits set subjectively in the initialization procedure prevented a better performance. On tests involving other subjects with previous experience with FES, such as subject C, this effect may also be observed. In this case, the results indicate that the joint impedance provided by the FES system was enough for compensating the weaker components of tremor, while faster peaks on tremor were barely attenuated.

In other trials, particularly the one illustrated in Fig. 7, but also in Figs. 5 and 6, another issue is that an overall reduction on tremor amplitude may be observed even after the compensation system is turned off. One of the possible explanations for this fact is that the subjects involuntarily mimic the behavior of the compensatory FES system once its effects stops. The reason for such phenomena may be also related to fatigue or similar effects, since the trembling muscles are often also stimulated by the attenuation system. Either way, subjects have not particularly complained about pain or fatigue during or after the experiments.

We may also highlight some problems related to the use of FES-induced tremor. For instance, since only one muscle is stimulated, a strong stimulation level may cause the limb to deviate from its resting position. Indeed, in some experiments with healthy subjects, tremor had to be kept in low amplitudes, since increasing the stimulation level would naturally reduce tremor intensity due to wrist overextension. Another key issue is the diffusion of the stimulation to different muscles, which is intensified when using FES-induced tremor.

Considering specifically the trial with the tremor patient, the behavior of the controller was affected by a combination of the PI gains (which have been chosen previously targeting stronger tremors), the FES limits set subjectively by the patient, and the low tremor intensity presented in that case. Due to those facts, there was a lack of range of possible stimulation levels, causing the system to be reduced in practice to an on/off scheme triggered by the detection of tremor. Even in this case, however, the benefit of the compensation system was evident.

V. Conclusions and Future Works

The design of a tremor compensation system based on electrical stimulation is a complicated task. Pathological tremor often presents great inter-subject variation and time-varying intra-subject dynamics. Furthermore, muscle command using FES is complex, particularly with surface electrodes. More important, the system must be designed to provide functional support for the patient, with unconditional safety and reasonable comfort.

In this paper, we have described the design of a system capable of providing tremor attenuation using FES to co-contract a pair of antagonist muscles, thus increasing the impedance of the target joint. Such a system is currently able to estimate tremor features in real-time, while filtering the components from voluntary motion, and compute the appropriate FES parameters that modulate joint impedance, while minimizing the residual torque delivered to the joint. The approach, which had been already validated on open-loop on tremor patients, has been validated in closed-loop on 4 healthy subjects and 1 tremor patient.

Our future efforts include further development of the described strategy, particularly the design of more sophisticated experimental protocols and controllers that may minimize the drawbacks of the current compensation system. Additionally, we intend to persist in the evaluation of the proposed tremor attenuation system on tremor patients, focusing also on the choice of those tremor types and muscular groups that could be more indicated for the proposed solution.

VI. Acknowledgments

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