EXPERIMENTS ON FES CLOSED-LOOP ELBOW JOINT CONTROL

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Abstract— Functional Electrical Stimulation (FES) is the term used to describe the application of electrical impulses to produce movement restoration or assistance. Despite consistent development in recent years and its advantages with respect to competing tecnologies, FES technology has not achieved exgensive use in home and clinics. Among the causes for such scenario, one of the most important refers to the poor performance of controllers applied to FES systems. For this reason, in this work we propose an innovative PI controller for FES applications in which straightforward modifications are incorporated to reduce intra and inter-subject variability. Preliminary experimental evaluation conducted on two healthy subjects has provided satisfactory results, and also directions for further developments.
Keywords— Functional Electrical Stimulation, Elbow Joint Control, Assistive and Rehabilitation Robotics

Resumo— Estimulação Elétrica Funcional (em inglês, FES) é o termo utilizado para descrever a aplicação de impulsos elétricos para a restauração do movimento e assisência. Apesar de consistente desenvolvimento em anos recentes e suas vantagens em relação a tecnologias concorrentes, a tecnologia FES ainda não alcançou uso extensivo em ambiente residencial e clínico. Entre as principais causas para esse cenário, uma das principais refere-se ao limitado desempenho de controladores utilizados em sistemas FES. Por essa razão, neste trabalho é proposto um inovador controlador PI para aplicações FES em que simples modificações são incorporadas para reduzir a variabilidade entre experimentos no mesmo indivíduo e indivíduos diferentes. Uma avaliação experimental preliminar conduzida em dois voluntários saudáveis produziu resultados positivos, e também apontou direções para futuros desenvolvimentos.
Keywords— Estimulação Elétrica Funcional, Controle da Articulação do Cotovelo, Robótica Assistiva e de Reabilitação

1 Introduction

Electrical stimulation refers to systems where electrical pulses are applied to the body, either for function or therapy. The technology encompasses devices such as the cardiac pacemaker and the cochlear implant. Instead, the term Functional Electrical Stimulation (FES) is often applied to systems which attempt to restore lost or impaired neuromuscular functions, such as in paraplegia, by the application of electrical pulses to neural pathways or directly to muscles. One related term is neuroprostheses, which is often used to describe all systems designed for replacing or augmenting a function that is lost or diminished due to injury or disease of the nervous system (Popovic and Sinkjaer, 2000).

Relevant FES applications for physical rehabilitation or assistance require satisfactory control of joint movement in order to provide a functional benefit to the user. However, most FES systems today in real settings apply either open-loop control or simple closed-loop control strategies (Lynch and Popovic, 2008). For such reason, those systems often demand continuous user intervention, reducing the overall therapeutic effect. The lack of control systems providing a better performance is actually one the major reasons for the limited number of FES applications available today on worldwide markets. Indeed, many potential applications of electrical stimulation, such as movement restoration in Spinal Cord Injured (SCI) subjects and FES-assisted rehabilitation, depend on the use of effective closed-loop control systems, which would enable compensating the effects of imprecise modeling and disturbances.

Controlling muscle action using FES is not a straightforward problem due to several issues. FES is based on the principle of delivering electric pulses to the muscle motor point. These pulses may then induce muscle action and consequently muscle force and joint movement. However, the force generated by the muscle is not solely a linear function of the natural or artificial stimuli it receives. Instead, it is a nonlinear function of neural input, muscle length and velocity, level of fatigue, and more. Furthermore, the joints of the human arm are often driven by pairs of antagonist muscles. Hence, stimulation on one muscle eventually diffuses to its antagonist, creating an irregular behavior. Finally, all these difficulties increase when using surface electrodes, which is the case in the this paper.

Concerning the control strategies already evaluated for closed-loop FES control, one of the simplest control strategies that have been applied is the Proportional-Integrative-Derivative (PID) controller (Abbas and Chizeck, 1991). More complex model-based control techniques have also been studied, such as robust control (Hunt et al., 2001), but most experimental efforts have resulted in poor performance when multiple sessions or multiple subjects participated using the same controller parameters. Within the national scenario, two research groups have conducted works of great interest, including the development of customized stimulators. In (Catunda et al., 2012), a single joint controller based on single muscle stimulation was described. In this case, since motion was performed on the saggital plane, gravity produced the movement counteracted by the FES-actived muscle. (Prado, 2009) has described software and hardware development for an embedded closed-loop FES system, but experimental results were limited. Both works, which are based in PID controllers for controlling joint motion, have achieved primising results, but still some limitations were detected which prevent further use of FES systems in more practical scenarios. Those issues have motivated our development for the current work.

In this paper, we propose a closed-loop FES control system based on a PI controller, but structured with features that may improve inter-subject performance. The basic controller framework is presented in Section 3, following a brief problem formulation in Section 2. Next, a preliminary evaluation of the method based on controlling elbow on the horizontal is presented. The evaluation, conducted on two healthy subjects, included response to square wave trajectories and disturbances. Finally, the last section presents the concluding remarks and the future works.

2 Method

2.1 Problem formulation

Based on the current experimental issues concerning closed-loop FES systems, particularly using surface electrodes, a structured experimental scenario was chosen to enable evaluation of low-level single joint FES controllers. Thus, the tests featured in this paper are based on controlling elbow joint motion only by stimulating Biceps bracchi and Triceps bracchi muscles. Furthermore, in order to reduce other effects that may affect joint motion, such gravity-induced motion, movement is executed on the horizontal plane.

As the actuator unit, arbitrary stimulation signals may be used in such experiments. These different waveforms may represent different attempts to emulate the features of natural action potentials that induce muscle action. However, due to large availability of stimulators providing square biphasic waveforms, this class of stimulator is selected for the experiment. For real-time control, online modulation of selected stimulation parameters is required, and stimulation pulse width is chosen as the control variable, while the other parameters (frequency and amplitude) are kept fixed.

Finally, concerning the sensing system, in this experimental scenario only motion sensing is used. Since many FES applications are based on portable stimulation systems which may be used in nonstructured environments, particular interest is given towards portable sensors, such as inertial units. Furthermore, we have chosen not to apply sensors of muscular activity, such as surface electromyography, since for their use would additional calibration phases would be required, reducing the system usability for everyday use.

2.2 Proposed controller

The control strategy proposed in this paper must take into consideration that two different actuators (pair of antagonist muscles) are used to provide opposing torques to the controlled joint. Furthermore, it is desired that the controller performance is robust to subject-specific parameters, such as maximum muscle force. For these reasons, the output of the controller is normalized to a range of values, i.e. $-1 \leq n_c \leq 1$.

Using the normalized control variable n_c, computing the individual muscle activation level is straightforward. The sign of the control output defines which channel will be activated. For each stimulated muscle, m_{pw} defines a minimum stimulation pulsewidth, while the maximum pulse width range v_{pw} designates the maximum stimulation level. Based on these two parameters, the stimulation pulse width sent to each muscle, is computed as follows

$$n_c \geq 0 \Rightarrow \begin{cases} pw_B = 0 \\ pw_T = m_{pw} + v_{pw} n_c \end{cases} \tag{1}$$

$$n_c \leq 0 \Rightarrow \begin{cases} pw_B = m_{pw} + v_{pw} n_c \\ pw_T = 0 \end{cases} \tag{2}$$

where B and T refers to Biceps bracchi and Triceps bracchi, respectively. It may be noted that the antagonist muscles are not activated simultaneously within this framework, i.e. the potentially stabilizing effect of muscle co-contraction is not used in this controller.

As for the controller itself, it consists of a PI controller with the back calculation anti-windup method, while the last feature is important to reduce risk of overstimulating during long periods on the maximum saturated value. The controller parameters are selected using conventional techniques in order to provide small steady-state error, and sufficiently fast and nonoscillating response. Those specifications were also chosen in order to minimize user discomfort. Based on these requirements, the following constants are used in all tests, for all subjects: $k_p = 0.025$ and $k_i = 0.01$. Finally, due to the actuation based on antagonist muscles and their corresponding asymetries, the integral term is reset whenever there is a change in the error term.

3 Experiments

3.1 Materials

The closed-loop control system evaluated in this paper is mainly based on three devices, as illustrated in Fig. 1: a stimulator, wireless inertial sensors, and a portable PC.

In order to use a stimulator approved for clinical use into a closed-loop control system, a stimulator enabling real-time update of stimulator parameters is required. In this experiment, we have used the RehaStim (Hasomed, Germany) an 8-channel stimulator which features USB connection and contains a software module for research applications. The stimulator provides current biphasic electric pulses, which are known to provide a good compromise with respect to performance and potential tissue damage, and allows online update of frequency, amplitude and pulse width. Furthermore, the stimulation level controlled using the RehaStim could be performed using either amplitude and the pulsewidth modulation. In this paper, pulse width modulation was preferred, since greater sensitivity may be achieved[1].

In order to measure the elbow motion, an inertial sensor composed of 3-axis accelerometer, gyroscope, and magnetometer was used. The selected sensor was the 3-Space wireless sensor (YEI Technology, USA), which features onboard quaternion-based Kalman filtering algorithms to estimate the sensor attitude. The sensor was attached to the subject's hand, providing real-time information on the forearm orientation with respect to an initial position.

The controller was thus implemented in a Windows PC using Matlab. Due to the low-pass nature and the delays associated with muscle response, slower sampling periods have not appeared to affect the overall controller performance. In the experiments described next, a sampling period of $25ms$ was used.

3.2 Experimental protocol

In order to validate the methodology, tests were performed in two healthy female subjects. The subjects have experimented surface electrical stimulation before, and thus the involuntary reaction observed in some subjects was reduced, as expected. The tests were divided into two main phases: manual initialization to define stimulation parameters, and closed-loop FES joint control based on square wave reference trajectories.

[1]The RehaStim enables 1 μs for pulse width modulation and 2 mA for amplitude modulation.

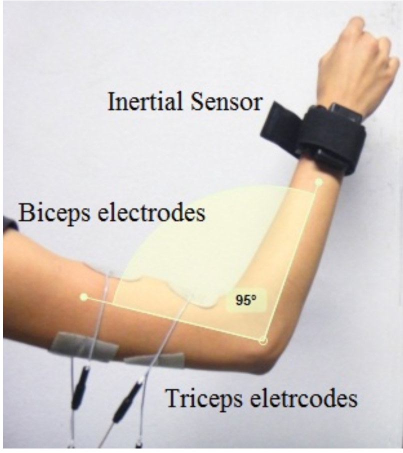

Figure 2: Photograph representing placement of sensor and electrodes, as well as the representation of the standard used for angle displacement (in light color).

Table 1: Individual muscle electric current (in $[mA]$) selected for each participating subject.

Subject	Biceps bracchi	Triceps bracchi
1	15	19
2	17	14

Before actual stimulation, the subjects were confortably seaten close to a table, where an elbow support was mounted in order to minimize effects of fatigue. The inertial sensor was then attached to the subject's right hand. Before each trial, the subject's arm was fully extended, and hence initially calibrated at 180^o, as illustrated in Fig. 2. The figure also illustrates the electrodes placed on the top of the antagonist muscles concerned with the motion of interest. For elbow motion, the Biceps bracchi and Triceps bracchi were stimulated, and square electrodes ($l = 5\ cm$) were used.

Once this initial setup was performed, the optimal parameters for the electrical stimulation was selected, as described in Section 2. The FES parameters were selected as to provide satisfactory motion response, while not causing any discomfort or pain to the participating subjects. In order to improve inter-subject use of the developed method, only one paremeter was set in this phase: the maximum stimulation amplitude. The control variable, the stimulation pulse width, ranged from 20 to 190 μs, while the frequency was fixed 40 Hz. The stimulation amplitude selected in this procedure are listed in Tab. 1.

After both initilization procedures were concluded, stimulation trials were conducted using reference trajectories. In each trial, the subjects were stimulated during 15 s. The reference trajectory used for every trial was a square wave oscil-

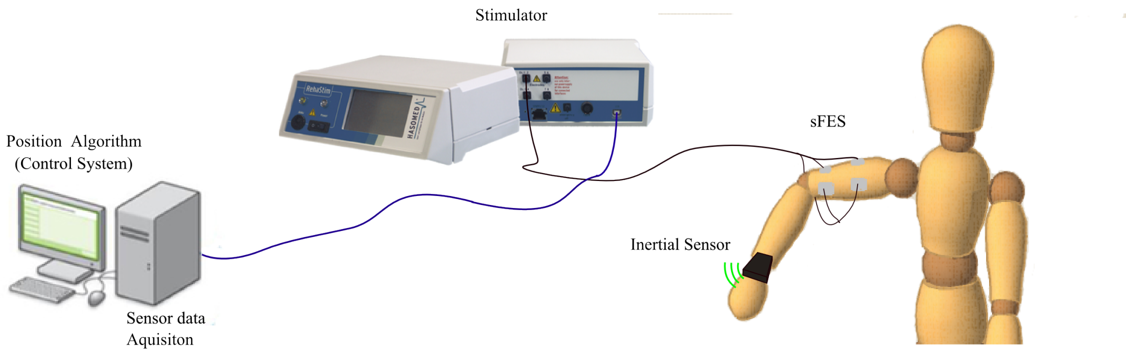

Figure 1: Closed-loop FES system for controlling elbow motion. Both stimulator and inertial sensor communicate with a PC, in which the proposed controller is implemented.

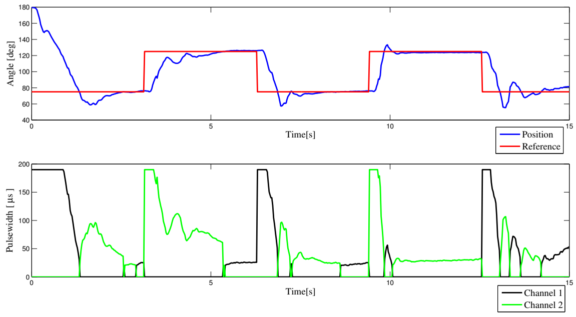

Figure 3: Subject 1. Elbow joint control without any disturbance. Biceps bracchi activation level is pictured in black and Triceps bracchi in green.

lating between 75° and 125°. A first sequence of trials were conducted using a reference movement period of 3 s. Also, no disturbance was applied to the system. During a second sequence of trials, controlled disturbances were applied to the joint position when the arm converged roughly to the reference position. In these later trials, a slower reference wave trajectory was used (5 s period), to enable stabilization after disturbance.

3.3 Results

The results obtained from the trials are illustrated in Figs. 3 to 6. Figures 3 and 4 refer to elbow joint control without any disturbance for the two participating subjects, while in the trials illustrated in Figs. 5 and 6 there were impulse disturbances applied to the joint position.

For the most part, the figures indicate coherent behavior in terms of joint position for all trials. The results are satisfactory for both trials with or without disturbances. Steady-state errors were observed only in Figs. 4 and 6. Both refer to Subject 2. Concerning the transient response, no large overshoot was detected during the experiments. On the other hand, a significant delay was present in every trial. It was indeed an expected phenomenon, which is further discussed in Sec. 4.

In order to further illustrate the system over-

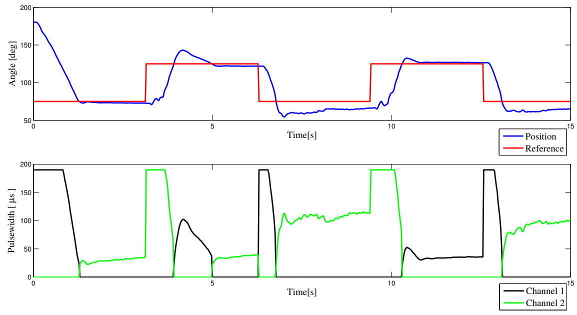

Figure 4: Subject 2. Elbow joint control without any disturbance. Biceps bracchi activation level is pictured in black and Triceps bracchi in green.

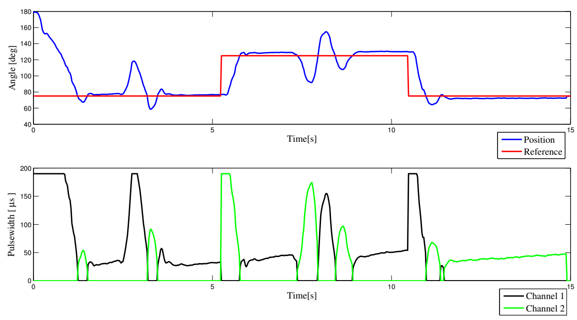

Figure 5: Subject 1. Elbow joint control and the effects of disturbances. A disturbance inducing positive displacement was applied at $t = 2,5\ s$, while another disturbance producing negative displacement was applied at $t = 7\ s$. Biceps bracchi activation level is pictured in black and Triceps bracchi in green.

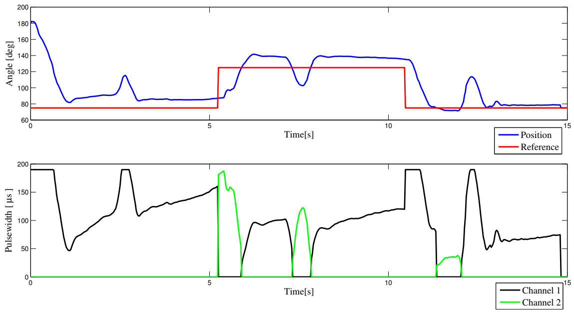

Figure 6: Subject 2. Elbow joint control and the effects of disturbances. A disturbance inducing positive displacement was applied at $t = 2,5\ s$ and $t = 12\ s$, while another disturbance producing negative displacement was applied at $t = 7\ s$. Biceps bracchi activation level is pictured in black and Triceps bracchi in green.

all performance, a video sample of the experimental session is available online[2]. The video shows both the elbow joint motion in images and the measured and reference angle trajectories.

4 Discussions

The experimental study described in the last sections indicates that the proposed PI controller provides proper performance. It may also be said that the controller might be robust enough for providing satisfactory results for different people, since more than one person parcipated in the experiments. Indeed, for adjusting the setup for a new subject, only one parameter must be adjusted for each stimulated muscle: the electric pulses amplitude in $[mA]$. This update must often be performed also when electrode position is changed on a same person, since muscle response to electrical stimulation is highly dependent on it. As mentioned, other difficulties observed in this kind of experiment are variations in muscle response due to muscular fatigue, involuntary contractions due to stimulation, and other factors. Those involuntary movements combined with the intrinsic properties of a FES-actuated muscle system (muscle electromechanical delay, low frequency normally used for the stimulation pulses, the delay of the stimulator in sending the pulses) induce a time delay in the system, as we can see in the results. Due to the summed up effects of those different phenomena, the system becomes nonlinear and challenging to control.

Nevertheless, the different errors observed in the Figs. 3 to 6 may also indicate that the controller parameters were not adequately selected. For instance, integral term used was could be increased to eliminate steady-state errors that occured for Subject 2. However, online tuning of PID parameters presents additional challenges in FES systems. The task is hampered, among other peculiarities of the system, by the tradeoff between a fast and precise response, and the person comfort during stimulation, as well as the diffusion of stimulation effects to other muscles. Another fixed parameter every subject refers to the pulsewidth range, and in the figures it may be noticed that the selected ranges are valid for both subjects, since the saturations in the control signals occurred just around abrupt changes of the reference. After these momentary saturations the signals converged back to a non-satured region, where finely tuned controlling is performed. In view of those difficulties, we may consider reasonable results were obtained for these parameters.

As a final remark, it is also important to discuss the nature of the reference movements evaluated in the experiments. Our choice of using simple square waves is in fact related to an important research subject in motor control (Kandel et al., 2000; Winters and Crago, 2000): the interdependence between feedforward and feedback while controlling goal-oriented moviments, such as the forearm motion. It is argued that complex trajectories not only involve a more consistent pre-planning of muscle activation levels, but also modulation of feedback gains. In this scenario, since no prior information concerning the desired trajectory is provided to the controller, a control strategy based on feedback only could be evaluated using simple point-to-point movements. Furthermore, most of FES applications described so far in the literature (e.g. FES-aided reahabilitation (Freeman et al., 2009) and assistance (Ring and Rosenthal, 2005)) involve such kind of reference trajectory.

5 Conclusions

Functional Electrical Stimulation (FES) refers to the use of electric pulses to generate limb motion in physical rehabilitation and assistance. Nevertheless, despite its potential in improving the quality of life of disabled persons, few FES systems are available for clinical or residential use today. The lack of control system providing improved performance, along with additional technological limitations of current systems, are the major issues that prevent the development of FES technology.

In this work, a FES closed-loop system was developed to control the elbow joint motion by stimulating of a pair of antagonist muscles. Using a PI controller and addtional modifications on the control structure, the proposed system was tested in two healthy subjects, considering a square wave as reference motion and the occurrence of eventual disturbances. The results showed the effectiveness of the controller to stabilize the system, with a

[2] `https://www.dropbox.com/s/9688z9ghenu4hge/sbai2013.m4v`

reasonable velocity and small error, even in the presence of disturbances.

The control system proposed here may be also applied in clinical applications and also to stimulate other body parts with minimal adjustments. Hence, future works involve experimental evaluation of the method in subjects with different degrees of motor impairments. Also, the research team plans to work on improving the current control strategy, possibly incorporating a previous optimization step to compute adequate stimulation parameters for given motor tasks and also the ability to control simultaneously joint motion and impedance.

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