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Extremum Seeking applied to Neuromuscular Electrical Stimulation

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Abstract: Extremum seeking (ES) methodology is applied to implement adaptive Proportional-Integral-Derivative (PID) closed-loop control for neuromuscular electrical stimulation (NMES). The proposed strategy is designed to control the patient's arm position in order to generate elbow extension/flexion movements. This method obviates the application of initial controller tests directly to patients since the tuning procedure is automatically performed in an online fashion. ES is used to tune the parameters of a PID controller so as to minimize a given cost function which is chosen to reflect the desired performance attributes. The ultimate responses obtained in the experiments with a healthy volunteer complied with the common specifications set in terms of the steady-state error, settling time, and the percentage overshoot.

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Keywords: functional electrical stimulation; adaptive systems; extremum seeking; PID control; trajectory tracking.

1. INTRODUCTION

Neuromuscular Electrical Stimulation (NMES) is a technique based on the artificial activation of the second motor neurons using exogenous electrical impulses (Sheffler and Chae, 2007). This activation may be used to increase muscle fatigue resistance, strength and in subjects with some neurological disorders such as stroke it can help them to make movements that they would not be able to perform.

NMES can be divided in two branches: the applications used as functional substitute and those ones intended to therapeutic intervention. For example, in a stroke patient with drop-foot (Seel et al., 2016), the NMES can activate the tibialis anterior muscle of the patient during swing phase. In this case, it is used as a functional substitute of a damaged central nervous system that is not able to recruit the necessary muscles during the gait. On the other hand, when a patient makes repetitive and voluntary training with his paretic arm it is shown that the central nervous system can be able to adapt and recover some functions, in a process called motor relearning (Sheffler and Chae, 2007). The sensorimotor experience is believed to be of paramount relevance to neural plasticity and motor relearning and it has been shown the NMES effects are enhanced when it is used concomitantly with voluntary effort (Lynch and Popovic, 2008), (Maffiuletti, 2010).

Most NMES devices used at clinics works in an open-loop approach and are adjusted at the beginning of the therapy (Lynch and Popovic, 2008). The amount of stimulation follows a pre-determined profile and demands user control to change stimulation parameters. This allows protocols aiming to enhance muscle contraction, sometimes concomitantly to the execution of intended contractions (Knutson et al., 2015). The drawback of this approach is that the device always gives the same amount of aid to the subject unless the therapist intervenes (Hara, 2008), (Freeman et al., 2009). Also, it has been shown that the open-loop devices are not well suited to promote an adequate association between the subject's intended movement and the artificial activation produced by NMES.

In this context, Proportional-Integral-Derivative (PID) controllers continue to represent a good option to closed-loop control the NMES electrical current amplitude based on the angular displacement of the arms because it has a simple implementation and its behavior is well known (Freeman et al., 2009). Although PID controllers are widely used in many distinct and general control processes, their effectiveness is often limited due to poor tuning. On the other hand, manual tuning is a time-consuming task and systematic methods rely on knowledge of the plant model or require special experiments to identify a suitable plant model. However, in NMES an exact plant model is not known, and it is not desirable to perform long system identification procedures with the patients in open loop. Note that the neuromuscular model is highly nonlinear and time-varying (Lynch and Popovic, 2008), which means those tests may be often unfruitful.

As a model-free real time optimization approach, extremum seeking is well suited for systems with unknown dynamics or those that are affected by high levels of uncertainty and or external dynamics (Krstic, 2014). Thus, the method does not rely on the knowledge of system mod-

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eling parameters being robust to parametric uncertainties and unmodeled dynamics. In particular, extremum seeking does not merely monitor the direction of the output response but explores the measured response to estimate the gradient of the map and update the control input in proportion to the gradient of the map. Extremum seeking has the dual benefit of rigorously provable convergence and the simplicity of implementation, by employing only an integrator as well as high-pass filter (Krstic and Wang, 2000). For dynamic systems, it is enough to select the extremum seeking probing frequency reasonably smaller than the highest frequency that can pass the system without significant attenuation. In a few words, any stable plant dynamics can be neglected at the price of some time dilation of the closed-loop system response. This choice also allows for the time-scale separation between plant and controller dynamics facilitating the convergence proof via singular perturbation and averaging theory.

The purpose of this paper is to develop an adaptive PID control scheme for NMES, aimed to upper limb unilateral exercises and evaluate its operation with healthy volunteers. The proposed method for online tuning PID parameters using extremum seeking (ES) within a closed-loop setting is shown to be importantly advantageous. The adaptive algorithm iteratively optimizes the controller parameters with respect to a cost function derived from the output error signal of the closed-loop system. This method is based on the performance of the closed-loop system during successive trapezoidal-response experiments.

It is worth mention that ES has already been used in NMES literature to generate the desired trajectory (Zhang et al., 2006) or identify stimulation parameters for set-point regulation (Stegath et al., 2007) in open-loop tests. On the other hand, we can even find adaptive feedback strategies based on iterative learning control (Freeman et al., 2009), (Seel et al., 2016) applied to NMES or rehabilitation. However, to the best of our knowledge, the present paper is the first work which proposes the use of ES as a tool for adaptation of NMES closed-loop controllers.

2. MATERIALS, METHODS AND EXPERIMENTAL PROTOCOL

A custom NMES device with a USB communication has been developed. Briefly, its analog module is a transconductance amplifier, which produces rectangular biphasic current with an amplitude controlled by a voltage at its input. A computer has been used to control the applied amplitude, pulse width and frequency of the electrical current stimulation. To restrain the arm movement of the subjects, a lightweight device has been built (Figure 1). It measures the elbow joint angle using a potentiometric goniometer (A) and allows mechanical adjusts to arm length (C) and lateral distance between the two limbs (D).

Patients were comfortably seated and had their arms adjusted to the device of Figure 1. Then self-adhesive square electrodes of 25 cm^2 were positioned at the distal portion of the biceps brachii muscle (BB) and triceps brachii muscle (TB). The motor point was detected using a small round electrode of 1 cm^2 and defined as the point were the smallest amount of current could produce a muscle twitch when under 1 Hz stimulation was used.

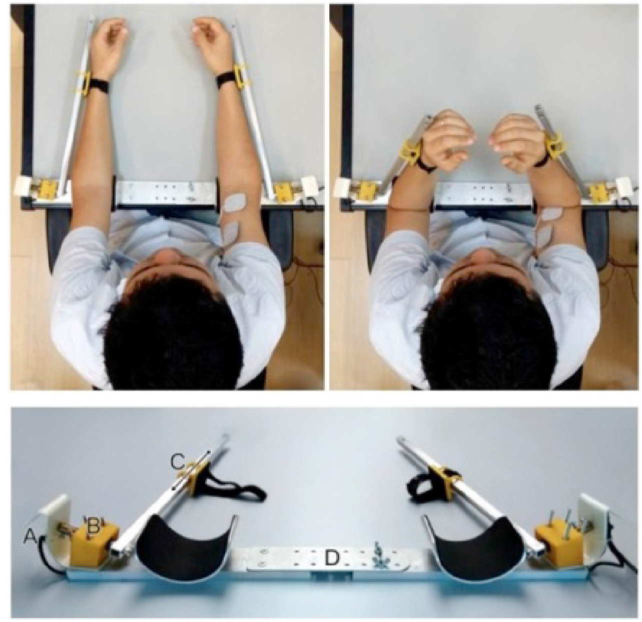

Fig. 1. Mechanical apparatus construct for NMES experimental tests. The point A in the image indicates a goniometer (simple potentiometer) linked to a steel axis B allowing angular displacement readings. Letter C shows that the wrist has an attachment with linear freedom of movement along the aluminium square rod, while D points out that there is an adjustment for the lateral distance of the elbow.

With the electrodes placed, each muscle is briefly stimulated using progressively increasing current up to the point that the subjects understood it was their limit before discomfort or when there was enough current to produce full elbow flexion or extension. All subjects are instructed not to overcome their limits because the results could be affected if they were not comfortable during the experimental protocols. The NMES pulses were balanced symmetrical biphasic with 400 μs pulse width at 50 Hz. The controller only modulated the current amplitude at each pulse.

Unilateral movements were made with one of the arms receiving NMES, while the output error signal

$$e(t) := r(t) - y(t)\,, \tag{1}$$

to be decreased was calculated using the difference between the reference signal (r) and the angular position of controlled elbow (denoted by y), measured with a goniometer.

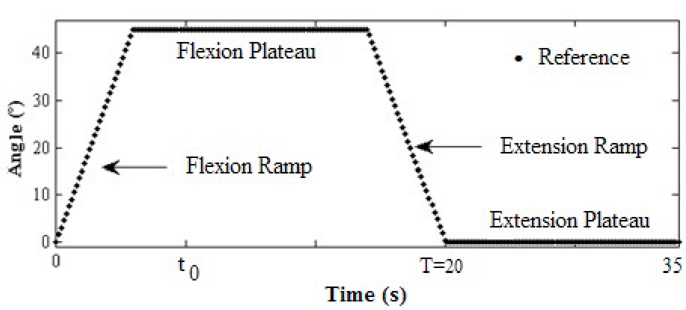

Fig. 2. Graphic of the reference signal and its divisions.

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