Model-based fatigue assessment

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Abstract

Muscle fatigue is a complex phenomenon that limits the application of functional Electrical Stimulation (ES), used to activate skeletal muscle in order to perform functional movements. The purpose of the present study was to track the development of neuromuscular fatigue under intermittent FES applied to the triceps surae muscle of 5 subjects paralyzed by Spinal Cord Injury (SCI). Experimental results gave evidence of neuromuscular fatigue development attributed to muscle contractile properties impairment. Classical parameters representing muscle contractile properties (peak twitch, Pt and twitch contraction and relaxation parameters) significantly decreased at the end of the protocol. These experimental data were used to identify the parameters of a previously developed physiological mathematical model describing all possible contractive states occurring in a stimulated muscle. The sigma-point Kalman filter was used for the identification of the model's parameters and simulation results prove that the model was capable to track fatigue and under the present stimulation conditions even predict muscle contractile behavior. This work reinforces clinical research with a tool allowing clinicians to monitor the current state of the stimulated muscle for its optimal solicitation.

Keywords*: muscle fatigue, contractile apparatus, Sigma-Point Kalman Filter, paraplegia, muscle model*

Introduction

Control of the electrically induced movement of the neuro-musculo-skeletal system, a highly complex, nonlinear and time-varying system, is a fundamental problem in FES research [1]. Development of mathematical models describing this complex system can assist in the design of efficient FES control strategies. Muscle fatigue, one of the major limitations in the clinical application of FES, further complicates the control task. The muscle contractile properties appear the most relevant parameter of fatigue development in subjects with SCI [2] and any attempt to track fatigue evolution should be focused on the study of this peripheral fatigue parameter.

When ES is applied to paralyzed muscles the stimulation sequence is not predefined and on / off periods are not known in advance. Considering that, for optimal control of paralyzed muscles, stimulation parameters should change according to muscle's current state, our approach to the problem of muscle fatigue is to find muscle's current state with the least laps of time, independently of the stimulation pattern. For this, mathematical models that are based on physiological parameters are necessary. A previously developed physiological muscle model that accurately predicts muscle response to different stimulation patterns [3] was used in the present study. The model's parameters were identified using experimental force data. The muscle mechanical response on a simple twitch was studied and its time-course under a pre-selected ES protocol was used to identify the model's parameters and to track fatigue. Fatigue studies classically use muscle contractile properties as index of peripheral fatigue development. This classical evaluation is pertinent for off-line analysis of muscle fatigue, but cannot be used for FES parameters modulation. The objective of the present study was to propose a method allowing the extraction of current muscle's state.

Material and Methods

Experimental design

Five motor complete SCI subjects volunteered to participate in the present study (ASIA A) which was approved by the ethical committee for persons' protection of Nîmes (2008-A00068-47/1). All subjects signed the consent form. Subjects came to the laboratory on two sessions separated by 2-3 days. On their first visit the intensities were set in order to obtain the maximal torque (Tmax) and the maximal mechanical response on a simple twitch (recruitment curves). Tmax was obtained through myostimulation of the triceps surae muscle (train at 30 Hz, 450 μs, 1 s on – 10 s off), while the twitch was delivered via neural stimulation (single twitch of 500-μs-duration) of the tibial nerve at the popliteal fossa. After this first visit, subjects returned for a second session during which the

aforementioned intensities were re-adjusted and the intermittent fatiguing ES protocol was performed.

Experimental protocol

The subjects' right triceps surae muscle was fatigued with 5 series of 5 trains (30 Hz, 450 μs, 2 s on – 2 s off, at intensity evoking 50% Tmax). Three twitches at supramaximal intensity (+10% intensity eliciting maximal twitch mechanical response) were delivered before and after every 5-train-series. Torque evoked by myo- and neural stimulation was continuously recorded.

Data analysis

From the muscle mechanical response the following contractile parameters were calculated: Peak Twitch (Pt), defined as the maximal value of torque evoked on a twitch, Contraction Time (CT), defined as the time elapsed from the beginning of the contraction until Pt and Half Relaxation Time (HRT), defined as the time necessary for torque to decrease to 50% of maximum. All parameters were statistically analyzed using a Friedman ANOVA test for repeated measures. Values after each stimulation series (post5, post10, post15, post20, post25) were compared to baseline values (pre). In the case of a significant effect of time over the variables, a post-hoc test was performed. Significance level was set at $P < 0.05$.

Presentation of the multi-scale physiological muscle model

The physiological muscle model used for identification and simulation of the muscle mechanical response is based on a multi-scale approach, from the sarcomere scale to the muscle scale [3] which results in the following differential equations for stiffness, force development and contractile element elongation:

$$\dot{k}_c = -(u + |\dot{\varepsilon}_c|)k_c + \alpha k_m \Pi_c(t) U_c$$

$$\dot{F}_c = -(u + |\dot{\varepsilon}_c|)F_c + \alpha F_m \Pi_c(t) U_c + k_c L_{c0} \dot{\varepsilon}_c$$

$$\dot{\varepsilon}_c = \frac{F_c u - \alpha F_m \Pi_c(t) U_c}{k_s L_{c0} + k_c L_{c0} - S_{\dot{\varepsilon}c} F_c}$$

where the chemical input u is defined as follows:

$$u(t) = \Pi_c(t) U_c + (1 - \Pi_c(t)) U_r$$

$$\Pi_c(t) = \begin{cases} 1 & \text{during contraction phase } \tau_c \\ \dfrac{\tau_r - t_r}{\tau_r} & \text{during transition phase} \\ 0 & \text{else} \end{cases}$$

Identification method

The input controls of the mechanical model are the recruitment rate α and the chemical input u. Under the present experimental conditions, α is considered to be 1, since the neural stimulation permitting to evoke the muscle mechanical response was delivered at supramaximal intensity, ensuring synchronous recruitment of all muscle fibers. The chemical input u is defined by 2 parameters U_c and U_r. The switching time from relaxation state to contraction state can be obtained by the twitch stimulation timing. The electromechanical delay can directly be measured as the time laps between stimulation and torque production. k_c, F_c and ε_c are time-varying states and only F_c is accessible from experimentation. L_{c0}, k_s, k_m, F_m, U_c and U_r are unknown parameters. In the present experiment we identified the time-varying parameters under isometric conditions and were interested in their fatigue-induced changes. L_{c0} and k_s are obtained from the literature [4]. Under isometric conditions k_m is not a sensitive parameter, while U_c is not significantly affected by fatigue. On the contrary, F_m and U_r (linked to Pt and HRT respectively), known to undergo the most prominent alterations under fatigue conditions [9], are the parameters to be identified by the muscle model in the present fatigue protocol. Finally, τ_c and τ_r are adjusted evaluating directly CT with which they are directly linked.

For the identification procedure of F_m and U_r the Sigma-Point Kalman Filter (SPKF) was used. After identification, F_m and U_r values were put in the muscle model in order to simulate muscle mechanical response during the fatiguing ES protocol. The time window used both for identification and simulation assessment is determined by the beginning of the twitch response up to roughly the time when 50% of Pt is obtained to be consistent with the comparison with classical HRT measurements.

Results

Evolution of the contractile properties during the intermittent ES protocol

Pt significant decreased throughout the ES protocol (P<0.001). Pt is classically used as index of peripheral fatigue development and is closely associated with cross-bridge binding events. At post25 it wad decreased by 13%. Parameters of the mechanical response (CT and HRT) did not significantly change throughout the intermittent ES protocol.

Identification and correlations with classical parameters

Identification of the muscle parameters was performed as explained in the previous section. F_m values were highly correlated with Pt values during the ES protocol. In tandem with this correlation, U_r had a high negative correlation with HRT. It shows that even if HRT evolves slightly, U_r is able to track these changes. Moreover, the negative correlation was expected because HRT is a time (s) and U_r a rate (Hz). These correlations were 0.98 and -0.95 for F_m-Pt and for U_r-HRT respectively.

Estimation results

Identification quality was evaluated by means of the normalized root mean square error (NRMSE). Error values for all subjects at the different stages of the protocol ranged from 0.022 to 0.052. Figure 1 shows an example of model estimation for different fatigue states.

Discussion

The present study aimed at tracking the phenomenon of neuromuscular fatigue under ES. For this, experimental data collected on subjects with SCI were used to identify the two free parameters of the previously developed muscle model [3]. We hypothesized that these two parameters would be the most sensible to the fatigue phenomenon. The triceps surae muscle was fatigued with an intermittent ES protocol and response to maximal neural stimulation was collected and analyzed for various mechanical parameters. When the model's free parameters (F_m and U_r) were identified using the collected experimental data, it gave the possibility to track the evolution of muscle's mechanical response throughout the protocol.

The evaluation of isometric twitches has been widely used in muscle fatigue studies and proved useful for identification of cellular mechanisms of muscle fatigue [5]. Pt and HRT were used to identify the model's free parameters (F_m and U_r). F_m represents the maximal force evoked by the muscle in tetanic contraction and Pt is considered as the maximal force on a single neural twitch, assuming that all muscle fibers are recruited simultaneously. U_r expresses the chemical kinetics during the relaxation phase of muscle contraction and HRT is the time needed for torque to reach 50% of its peak value on a simple twitch. The strong correlations between F_m and Pt and U_r and HRT further reinforce the relationship between the model's parameters and experimental data. To our knowledge this is the first time a muscle model was identified using torque obtained from experimental data whose physiological meaning is strongly implicated in the development of muscle fatigue.

Model estimation results of the force evoked by neural stimulation under fatigue conditions were rather satisfactory. We can thus accept that the model is able to track the fatigue developed by an intermittent ES protocol.

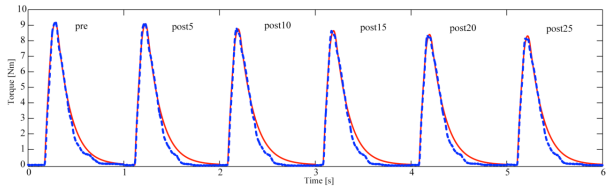

Figure 1: Estimation results on a representative subject. The second half of the descending part of the torque curve was not used for identification. Red line represents estimation values while the blue line shows measured values.

Conclusions

In the present study we managed to track the phenomenon of muscle fatigue using a physiology-based muscle model. These results can provide clinicians with a tool allowing them to monitor the muscle condition under ES application and to accordingly change stimulation patterns for optimal stress of the patients' musculo-skeletal system.

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