Feedback-based Control of Skeletal Muscle Electrical Stimulation Using ^{1}H and ^{31}P-NMRS to Monitor the Onset of Fatigue in Rat

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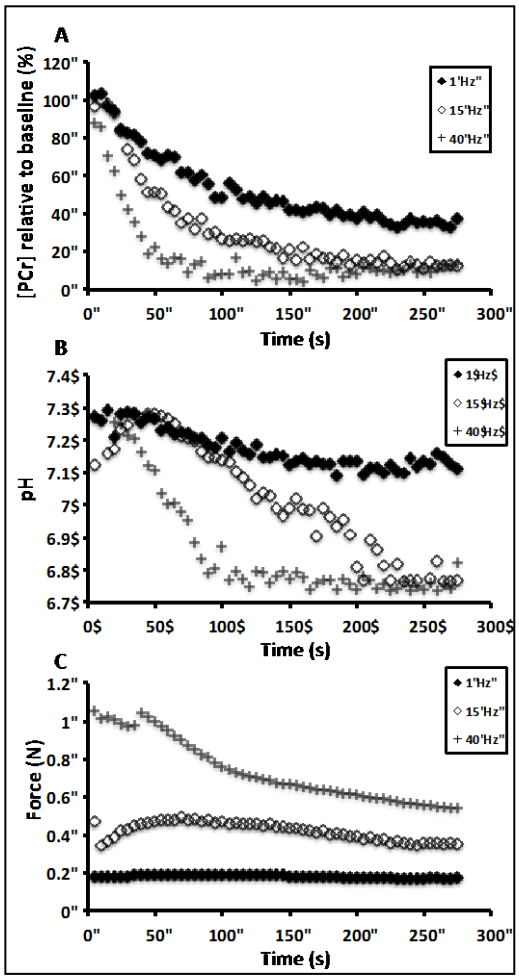
Introduction

Functional electrical stimulation (FES) is used in the physical therapy of SCI patients to help increase muscle mass and function. However, the increased susceptibility to fatigue observed in these patients is a limitation to the application of FES protocols. Downey *et al.* [1] developed a new control strategy, using leg extension angle during quadriceps stimulation as a feedback, to modulate electrical stimulation amplitude and frequency. ^{31}P NMR spectroscopy has long been used to investigate metabolic activity during and after muscle exercise. This technique can provide an accurate measure of pH, and of the relative changes in the phosphorylated metabolites (inorganique phosphate (Pi), phosphocreatine (PCr), adenosine triphosphate (ATP)) that are key to muscle exercise metabolism. Our goal is to develop acquisition/post-processing of 1H and 31P MR spectroscopy *in vivo* for a real-time monitoring of the onset of muscle fatigue in rat.



Experimental

Measurements were performed on anesthetized Sprague Dawley female rats (2% Isoflurane/oxygen) at 11.1 T (Agilent) in the AMRIS facilities at UF. A 1x2 cm^2 oblong surface ^{31}P coil was used to probe the posterior compartment of the lower hindlimb, and a 2-cm diameter surface ^{1}H coil was placed orthogonally for positioning and shimming. In these preliminary experiments, supramaximal muscle contractions were induced with subcutaneous electrodes adjacent to the sciatic nerve (10V-200 µs pulses) for 5 min at 3 different frequencies: 1Hz, 15Hz, 40 Hz. ^{31}P spectra were acquired at rest for 2 min, during exercise and recovery (20 min) with the following parameters: 50 µs square RF pulse, TR = 2 s, SW= 10 kHz, 8000 complex data points, NA=5. pH and PCr relative concentration were determined in the JMRUI software. A foot pedal connected to a force transducer (Interface, Inc) was used to record the force noninvasively during exercise.

Results and Discussion

The figure shows an example of (A) [Pcr], (B) pH and (C) force changes during exercise at different stimulation frequency. The low frequency protocol (1 Hz) induced only little changes in pH (above 7.15), and a slow decrease in [PCr] down to 40% of baseline values. changes in force time course were observed at higher frequency, as expected. While force values were low and steady throughout the exercise in the low frequency protocol, higher frequencies induced greater force production and, more importantly, showed a progressive decrease in force value. Concomittantly, pH values were drastically decreased and [PCr] depletion was faster and greater in the 15Hz and 40Hz protocols, with a nearly 100% depletion in the 40Hz protocol. Complementary analyses and experiments are underway to establish the relationship between changes in pH, [PCr] and the drop in force in our experimental conditions. These results will serve as calibration settings for the control algorithm and the modulation of the electrical stimulation parameters. This will allow for an appropriate management of fatigue and an extended duration of exercise in rat. Ultimately, this has the potential to improve skeletal muscle rehabilitation strategies based on FES, as commonly used in clinic in patients with spinal cord injury (SCI).

Acknowledgements

We acknowledge NHMFL for funding.