Motor Unit Control in Human Vastus Lateralis Muscle During Fatigue

A. Adam and C.J. De Luca
NeuroMuscular Research Center
Boston University
19 Deerfield Street
Boston, MA 02215, USA

***Abstract*—We investigated the motor unit firing behavior of the vastus lateralis muscle during a sequence of isometric constant-torque contractions maintained at 20% of the maximum voluntary contraction and repeated to exhaustion. Electromyographic signals were recorded via quadrifilar fine wire electrodes and decomposed into their constituent action potentials to obtain the motor unit firing times. In addition, we measured the whole-muscle mechanical properties during the fatigue protocol using electrical stimulation. In four out of five subjects, the firing rate of motor units first decreased within the first 10% – 20% of the endurance time and then increased. The firing rate increase was accompanied by an increase in the number of motor units recruited to reach and maintain the constant target torque. The elicited twitch and tetanic torque responses first increased and then decreased. In one subject, the initial decrease in firing rate was absent, but so was the increase in the torque response. Overall, the two processes followed the same time course and complemented each other. These data are consistent with an activation of the motor unit pool via a common drive that adjusts to compensate for the potentiation and diminution of the mechanical output of the muscle fibers.**

I. Introduction

The force level of a voluntary muscle contraction is controlled through two mechanisms: recruitment of motor units and modulation of the firing rate of active motor units. The general belief is that a motor unit, once recruited, tends to remain active during a constant-force contraction; although alterations in the recruitment of motor units during sustained contractions have been the subject of discussion for decades ([1]-[4], among others). This project was designed to systematically investigate changes to motor unit firing behavior during long-duration muscle activity. In addition, we set out to investigate if the inverse relationship between firing rate and recruitment threshold [5]-[7], also termed "onion skin property" [8], holds during fatiguing contractions.

II. Methods

A. Subjects

Five healthy young men [21.4 ± 0.9 (SD) yr] having no known neuromuscular disorders participated in this study. All subjects read and signed an informed consent form approved by the Institutional Review Board.

B. Torque and Electromyographic Recordings

Subjects were seated in a special chair to restrain hip movement and fix the dominant leg at a knee angle of 60 degrees flexion. Isometric knee-extension torque was measured via a lever arm and a pad positioned against the tibia. Using visual feedback subjects performed a sequence of constant-torque contractions maintained at 20% of the maximum voluntary contraction (MVC) and repeated to exhaustion. Each contraction started with a 5 s ramp up to 50% MVC and a brief hold phase after which the torque was decreased to the target value of 20% MVC and held constant for 50 s. A brief (6 s) period of rest at the end of each contraction was used to measure the electrically evoked muscle response and to allow the subject to prepare for the next cycle. Intramuscular electromyographic (EMG) signals were recorded from the vastus lateralis muscle via a quadrifilar fine wire electrode [9]. Three combinations of wire pairs were selected and differentially amplified to yield three separate EMG channels. These signals were subsequently decomposed into their constituent motor unit action potentials via the Precision Decomposition technique [9, 10] to obtain the motor unit firing times.

C. Electrical Stimulation

On three subjects, the voluntary fatigue protocol was repeated on a separate occasion with transcutaneous electrical stimulation but without intramuscular EMG recordings. A test stimulation train consisting of a brief train of 11 stimuli at 50 Hz was administered before, during, and immediately after the voluntary fatigue protocol. In two subjects, the 50 Hz train was followed, with a 1-s delay, by a single stimulus to measure the twitch response. All stimuli were constant-current, square-wave pulses (0.2 ms in duration) at supramaximal (110%) intensity.

D. Analysis

The motor unit recruitment thresholds were measured as described in a previous report [11]. Briefly, the recruitment threshold of a motor unit was calculated as the torque level at the first consistent firing (next firing within 250 ms) of the unit. The continuous-time mean firing rate signal was computed by passing the impulse train corresponding to the firing times of each motor unit through a unit-area Hanning window filter of 1.6 s duration [1]. The length of the window was chosen to capture slowly varying trends in the mean firing rate. The time-varying behavior of the mean firing rates during the plateau phase of the contraction were parameterized by the slope of a linear fit as well as the average value for each motor unit.

III. Results

The number of successive contractions performed up to exhaustion ranged from 6 to 10 (8.2 ± 2.0) in our cohort of five subjects. In four of the subjects the mean firing rate of motor units first decreased within the first 10% – 20% of the contraction series and then increased. The firing rate increase was accompanied by an increase in the number of motor units recruited to reach a 50% MVC torque peak and to maintain the constant target torque. The twitch and tetanic torque response declined in peak amplitude by 52% – 85% and 46% – 67%, respectively. However, in two out of three subjects the decline in amplitude was not monotonic, but briefly increased after the first contraction. This potentiation was only short lasting, as the peak torque declined below the initial value at subsequent one-minute intervals. Potentiation was absent in one subject, as was the decrease in the firing rates during the first contraction. The two processes, torque response changes and firing rate changes, followed the same time course and complemented each other. In all subjects, a negative correlation between the firing rates and the recruitment thresholds of motor units was observed at the start, middle, and end of the contraction series.

IV. Discussion

Our data suggest that when the vastus lateralis muscle is activated to maintain a constant torque output, its motoneuron pool receives a net excitatory drive that first decreases to compensate for the short-lived potentiation of the muscle force twitch and then increases to compensate for the diminution of the force twitch. However, the underlying inverse relationship between the firing rate and the recruitment threshold that has been reported for non-fatigued contractions is maintained. We, therefore, conclude that the CNS control of motor units remains invariant during fatigue in isometric isotonic contractions.

Acknowledgement

The assistance of T. Hassid, M. Sullivan, and J. Wu in processing the data is greatly appreciated.

This work was supported by the NIH Bioengineering Research Partnership Grant # 1R24HD38585 from the National Center for Medical Rehabilitation Research of the NICHD

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