MOTOR UNIT FIRINGS DURING VOLUNTARY ISOMETRIC RAMP AND BALLISTIC CONTRACTIONS IN HUMAN VASTUS MEDIALIS MUSCLE

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Intra-muscular electromyographic (EMG) signals in vastus medialis muscle were decomposed into their constituent motor unit action potential trains using a specially designed quadrifilar wire electrode during voluntary isometric ramp and ballistic contractions. Five male adults participated in our experiments as subjects and performed ramp trapezoidal, ramp triangular, and ballistic contractions. By using a newly developed wire electrode, intra-muscular EMG signals were successfully decomposed into the individual motor unit action potential trains. The firing behaviors analyzed by the decomposition technique were consistent with previous studies on small muscles. This new quadrifilar wire electrode is potentially a useful tool for detecting intra-muscular electromyographic signals in large limb muscles such as the vastus medialis.

KEY WORDS: Motor unit, recruitment threshold, firing frequency

INTRODUCTION: A technique for analyzing motor unit (MU) action potentials called “Precision Decomposition” was previously developed by De Luca and his colleagues (De Luca 1993; De Luca & Adam 1999; LeFever & De Luca 1982; LeFever et al. 1982). This technique allows identification of action potentials from individual motor unit firings during isometric contractions by using a quadrifilar needle electrode. By using this technique, many important findings have been reported on motor unit firing behavior in humans. Recently we developed a new electrode using fine wire instead of a needle. The purpose of the present study was to demonstrate our new electrode design records reliable and stable intra-muscular EMG signals from a large proximal limb muscle such as the vastus medialis, allowing these signals to be decomposed into individual motor unit action potential trains during maximal isometric ramp and ballistic contractions.

METHODS: Subjects and apparatus: Five healthy male adults (mean ± SD; age: 30.4 ± 6.3 years; height: 174.4 ± 4.4 cm; weight: 66.4 ± 5.4 kg) participated in the present experiments as subjects. Informed consent was obtained from all subjects before their participation. The subjects sat on an experimental chair with their right knee flexed at 90 degrees. Isometric knee extension force was recorded using a force transducer (LSM-100KBSA67; Kyowa, Tokyo, Japan) positioned at the distal end of the right leg (Fig. 1).

Tasks: The subjects were asked to produce isometric knee extension force in three types of force exertion: ramp trapezoidal, ramp triangular and ballistic exertions. The ramp trapezoidal exertion task consisted of increasing, maintaining, and decreasing force phases and was used to test whether the new wire electrode could detect reliable signals during a slow and low force exertion task. Subjects were required to increase force gradually up to 25% MVC in 2.5 seconds (10% MVC /s), then maintain that force level for 5 seconds, and relax gradually in 2.5 seconds (-10% MVC/s). In the ramp triangular exertion task, to test whether the electrode could detect reliable signals during high force exertion, subjects were required to increase force up to 100% MVC in 5 seconds (20% MVC/s), and then relax as quickly as possible. The purpose of the ballistic exertion task was to assess the electrode in a rapid force exertion task, during which subjects produced a brief force, as fast as possible, up to the target force set at approximately 50% MVC.

Recording of intra-muscular EMG signals: Intra-muscular EMG signals were obtained from the right vastus medialis muscle. The original precision decomposition technique used a quadrifilar needle electrode (De Luca 1993) to obtain the intra-muscular EMG signal. This electrode has four detection surfaces, each 50 μm in diameter, 200 μm apart on the corners of the port of a square configuration, located on the side of a needle. In the present experiment, intra-muscular EMG signals were obtained using a specially designed quadrifilar 'wire' electrode whose detection surfaces were the same as the original quadrifilar needle (Unique Medical, Tokyo, Japan, Fig. 2). The EMG signals were differentially amplified and digitized at a sampling rate of 51.2 kHz together with the knee extension force signal sampled at 500 Hz (Counterpoint; Dantec, Skovlunde, Denmark).

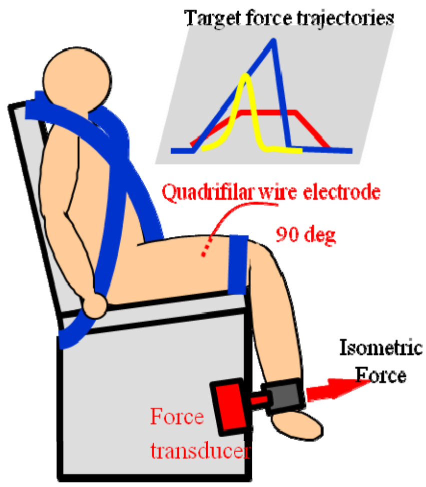

Fig. 1. Experimental setup of the present experiments

Analysis of motor unit firings: A precision decomposition technique (Counter point, Dantec, Denmark) was used to analyze intra-muscular EMG signals in vastus medialis muscle. The intra-muscular EMG signals were band-pass filtered from 1 to 10 kHz, and then decomposed into individual motor unit action potential trains by decomposition algorithms: template matching, template updating, superposition resolution and firing statistics. Mean firing frequency was calculated every 400 ms time bin in the ramp trapezoidal and ramp triangular exertion tasks. In the ballistic exertion task, the frequency was calculated as a reciprocal of instantaneous inter-firing intervals.

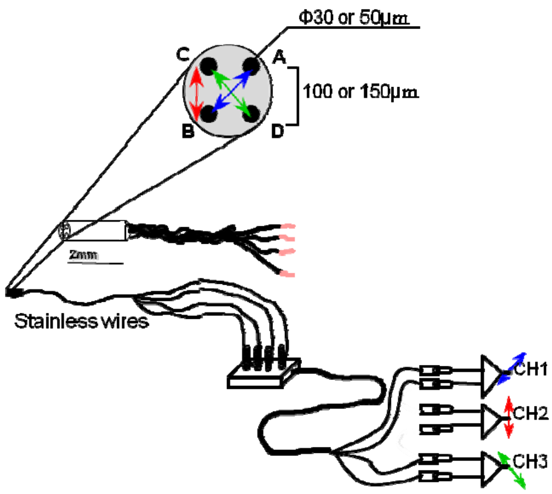

Fig. 2. Configuration of a specially designated wire electrode used in the present experiment

RESULTS: A total of 13 motor units (5 in the trapezoidal, 4 in the triangular and 4 in the ballistic tasks) from 5 subjects were successfully decomposed. Figure 3 shows the raw intra-muscular EMG signal (A), bar plot of the decomposed MU firings (B), mean firing frequency (C) and inter-firing interval time (D) for one trial in the ramp trapezoidal exertion task. In this case, three motor units were identified over the entire contraction. Their recruitment threshold forces were 7.5, 16.5 and 26.0% of MVC (Fig. 3B). Figure 3C shows the time courses of the mean firing frequencies of each motor unit. The mean firing frequency of the earlier recruited motor unit was higher than that of the later recruited MU. Figure 3D shows the time interval between continuous spikes. The motor unit with a higher recruitment threshold force showed a larger variation of the inter-firing interval.

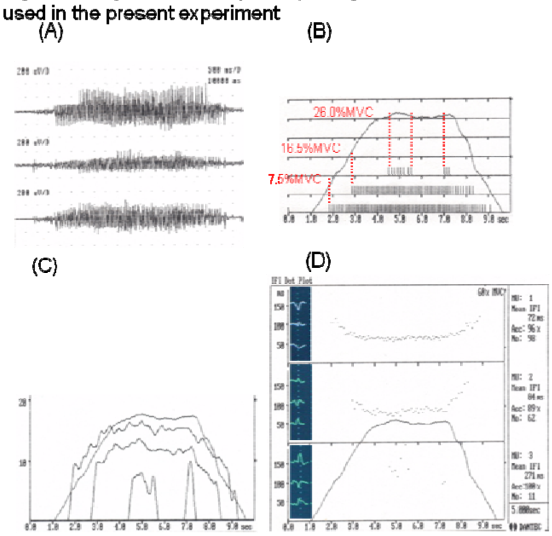

Fig. 3. Raw intra-muscular EMGs (A), bar plots (B), mean firing frequency (C) and inter firing interval(D) of a sample subject.

Figure 4 shows motor unit firing behaviors in the ramp triangular task. In these trials, relatively high threshold motor units were identified (53.0, 57.0% MVC). The relationship between the recruitment

threshold force and the variation of the inter-firing interval in this task was the same as in the trapezoidal exertion task; the higher the recruitment threshold, the larger the variation of the inter-firing interval.
Figure 5 shows bar plots of the motor unit action potential trains in one trial of the ballistic exertion task. In this trial, the peak force value was 46% of MVC and four motor units were identified. All the motor units identified were recruited at approximately 0% MVC and Table 1 shows their mean firing frequencies. A remarkably high mean firing frequency was observed in motor unit 1. The mean firing frequencies of earlier recruited motor units were higher than those of later recruited MUs (Table 1).

DISCUSSION: The main finding of the present investigation was that by using a quadrifilar wire electrode specially designed by the authors, intra-muscular EMG signals of a large proximal limb muscle, such as the vastus medialis, were successfully decomposed into their individual motor unit action potential trains, when subjects performed large and rapid knee extension force production. Although the number of motor units that were analyze in the present study were too small to effectively describe the features of the motor unit firing behavior due to technical difficulties, our results still provided useful information on motor unit firing behavior of large muscles exerting high forces.

Recruitment threshold of motor unit: Recruitment threshold of the motor unit has been defined as a force value at which that motor unit begins to fire during voluntary isometric ramp contraction. It is well known that in human finger muscles, such as first dorsal interosseus muscle, which require a fine control of force magnitude, most motor units fire at less than 50% of maximal voluntary contraction (Basmajian and De Luca 1985, Masakado et al. 1995). On the other hand, in the more proximal limb muscles, such as the deltoid and tibialis anterior muscles, motor units fire at approximately 70% of MVC (Basmajian and De Luca 1985; Erim et al. 1996). In the present experiment, intra-muscular EMG signals were analyzed from the vastus medialis, a large proximal limb muscle. The highest recruitment threshold of the triangular task was 57.0% of MVC (MU2 of Subject 2 in Fig. 4). This suggests that the motor units with high recruitment threshold could also exist in the vastus medialis muscle.
Firing frequency of motor unit: The earlier recruited motor units always fired at greater frequencies compared to the later recruited

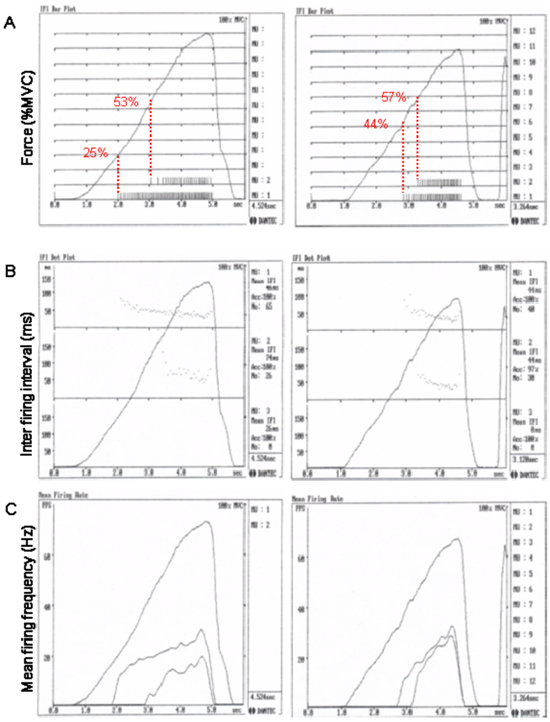

Fig. 4. Bar plots of inter firing interval(A), inter firing interval times(B), and mean firing frequencies (C) in the triangle task.

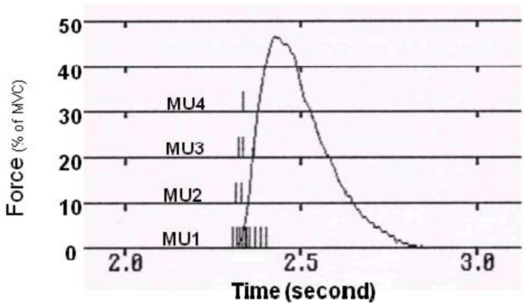

Fig. 5. Sample bar plots of motor unit action potential trains in the ballistic task.

Table 1. Mean firing frequencies of motor units identified for one trial identified in ballistic task.

MUs	Number of firings	Mean firing frequency (Hz)
MU4	1	—
MU3	3	42.6
MU2	2	52.6
MU1	10	96.8

motor units during the voluntary isometric contractions. Erim et al. (1996) called this property "*Onion Skin Phenomenon*". In the present experiment, the onion skin was clearly shown during the ramp trapezoidal (Fig. 3C), triangular (Fig. 4C) and ballistic tasks (Table 1). Therefore, our results are consistent with the observations from previous studies. These results suggest that the control of firing frequency of motor units in the vastus medialis muscle is similar to other limb muscles. To the knowledge of the authors, this reported recording of MU firing frequency during ballistic contraction of a large limb muscle is the first in the motor unit research field. A firm conclusion cannot be made since only one trial was successfully decomposed for the ballistic exertion task, but the mean firing frequency of all three MUs successfully decomposed were greater than 40Hz, and these values were much higher than those (20-30 Hz) for the ramp exertion tasks. Whether these low-threshold high-frequency MUs are the same MUs as those firing in the ramp exertion, or different from those recruited in the ramp exertion is a further question to be answered.

Quadrifilar wire electrode: This type of electrode affects the results of motor unit firing behaviors. In our preliminary experiments, we used a conventional quadrifilar needle electrode (De Luca 1993) to record intra-muscular EMG signals in the vastus medialis muscle. However, a reliable signal could not be obtained when using the needle electrode during isometric ramp and ballistic contractions as described above. In the present experiments, we used a specially designed wire electrode (Fig. 2). As a result we could obtain reliable signals. This suggests that the thick tip of the quadrifilar wire electrode plays a role like an anchor of a ship, so that the detection surface moves with the surrounding muscle fibers throughout the ramp and ballistic contractions.

CONCLUSION: In the present study a quadrifilar wire electrode was used to record reliable and stable intra-muscular EMG signals from the vastus medialis muscle, a large proximal limb muscle, during maximal isometric ramp and ballistic contractions. The signals were then decomposed into individual motor unit action potential trains. The quadrifilar wire electrode developed is potentially a valuable tool for recording intra-muscular EMG signals, especially in large limb muscles. Continued improvement in the rate of electrode sampling and decomposing of motor unit firing will serve to enhance our understanding of human muscle force control mechanisms.

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