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Technical Report

Technique for Detecting MUAP Propagation from High-Threshold Motor Units

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Summary: A technique was developed to identify the propagation pattern of high-threshold motor unit action potentials (MUAPs) in human skeletal muscles. A linear surface array and a selective needle electrode were used simultaneously for detection of myoelectric signals during a constant-force isometric voluntary contraction. The needle signals were decomposed into trains of single MUAPs and were used to trigger-average the surface signals. After averaging 16 channels of surface signals derived with the linear array electrode, we obtained the propagation of single MUAPs along the muscle fibers. The special quadrifilar needle electrode and the algorithm for decomposing the needle signals made it possible to detect high-threshold MUs recruited at ≤57.5% of the maximal voluntary contraction (MVC) during 75% MVC sustained contractions and consequently the propagation pattern of APs from those MUs. The position of the innervation zones within single MUs was estimated from the location of the conduction reversals in the surface myoelectric signals. With this technique, we were able to study the configuration of innervation zones of high-threshold MUs in conjunction with their recruitment threshold.
Key Words: Single motor unit—Decomposition—Innervation zone—Motor endplate—Tibialis anterior.

When muscle fibers run parallel to each other and to the skin surface, propagation of motor unit action potentials (MUAPs) can be detected with a linear surface electrode array placed along the muscle fibers (5). The MUAPs usually arise in the middle of the length of the muscle belly and propagate in opposite directions to the tendons. Thus, the position of the innervation zones (motor endplate regions) can be estimated from the source of the propagation. Moreover, when this technique is applied to APs originating from a single MU, the innervation zones of individual MUs can be estimated (4,6).

In studying the innervation zones of the biceps brachii, we noted that some MUs have innervation zones separated by ≤20 mm in the direction of muscle fibers (4,6). Normally each muscle fiber has only one motor endplate. The separate innervation zones detected by surface electromyography (EMG) are caused by muscle fibers, some of which form one innervation zone whereas others are innervated at different sites. In these studies, the single MUAPs isolated by visual analysis were limited to those originating from MUs with low recruitment thresholds. According to the size principle (2), MUs recruited at higher contraction force have a larger

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number of muscle fibers than MUs with lower recruitment threshold. Thus, MUs with higher recruitment threshold may have wider or more scattered innervation zones than MUs with lower threshold.

We developed a technique for detecting the propagation pattern of high-threshold MUs and for analyzing the configuration of innervation zones in conjunction with the recruitment threshold of MUs.

METHODS

We used a linear surface array electrode consisting of 17 silver contacts 10 mm wide and 1 mm thick arranged parallel to each other. The pitch of the contacts was 5.08 mm. Sixteen surface signals were derived bipolarly from adjacent contacts with a gain of 63 dB. These signals were digitized by a computer at a rate of 5 kHz.

We also used a selective needle electrode with four detection surfaces (50 μm diameter) at the side of the cannula (3,7). We derived three signals from pairs of detection surfaces or from one detection surface and the cannula. The needle signals were recorded on an FM tape and then digitized by a computer at 50 kHz. The sampled signals were decomposed into trains of single MUAPs with the aid of a computer. The decomposition was performed by a computer-based operator-interactive algorithm called Precision Decomposition (3,7). The algorithm scanned the ME signals and identified MUAPs. Each MUAP was then classified as being created by a particular MU by comparing its shape to candidate MU templates and considering the probability of each MU firing at the time the MUAP was detected. MU templates consisted of representative MUAP shapes for each MU. The templates were updated with each appropriate MUAP classification. Probability estimates for each MU were calculated based on the previous firing history of that MU and were updated with each MUAP classification to that MU. Superpositions of MUAPs were resolved into their component MU templates by special computer algorithms that at times required operator interaction to assist in determining the composition of unknown waveshapes. The firing time of the decomposed MUAPs was used as a trigger point for averaging the surface ME signals.

In addition to the ME signals, the contraction force was also recorded. During the contraction, a force trajectory was presented to the subject on a monitor screen. The force trajectory was a trapezoid (Fig. 1), which reached its plateau in 10 s, sustained the plateau for 10 s, and relaxed in 5–10 s. The level of the plateau was set at values between 50 and 75% MVC. The subjects were requested to track the trajectory by isometrically contracting the tibialis anterior muscle while the leg and foot were secured in a specially designed apparatus.

A trapezoidal shape was chosen for the force paradigm. This shape allows for a rising and falling

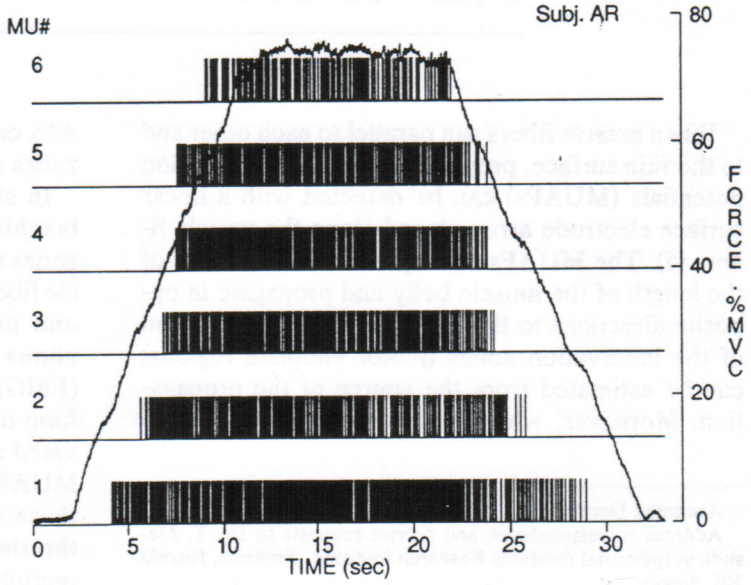

FIG. 1. Trains of single motor unit action potentials (MUAPs) decomposed from the signals shown in Fig. 3. In this record, six MUs were isolated. The force curve is also plotted. The target trajectory of force in this recording was 10 s at 75% maximal voluntary contraction (MVC) that was reached in 10 s and relaxed in 10 s.

segment that provides regions where recruitment and derecruitment can be observed as well as a constant-force segment where the trigger-averaging is to be performed. To extract a reliable waveshape of individual MUAPs, at least 200 trigger-averages are required. Given an average firing rate of 20 pulses per second, the duration of the constant-force segment was set to be 10 s. For convenience of defining the recruitment and derecruitment thresholds of MUs, the durations of the rising and falling segments were set at 5–10 s. The recruitment and derecruitment thresholds were estimated during the rising and falling phase of the force trajectory, respectively.

The muscle studied was the tibialis anterior. This muscle was chosen because the needle signals are relatively stable at high force contractions as compared with other muscles and the muscle fibers are long enough to detect propagation of MUAPs with the surface electrode.

The subjects were 4 healthy normal adults (3 men and 1 woman) aged 24–35 years. All gave informed consent before participating in the experiment. In all subjects, the right tibialis anterior was studied.

RESULTS

Figure 2 shows the schematic diagram of the electrode placement. The selective quadrifilar needle electrode was inserted at the middle length of the tibialis anterior near the proximal edge of the surface array electrode. Figure 3 shows a processed record of the signals detected with the needle electrode. The detected signals were decomposed into the trains of individual MUAPs. Figure 1 is a bar plot of the trains of MUAPs. In this recording, six MUs were isolated with sufficient accuracy. Precise values of the recruitment and derecruitment thresholds for these six MUs are shown in Fig. 4. A clear orderly recruitment and derecruitment was observed. In the individual MUs, the derecruitment thresholds were higher than the recruitment thresholds.

Figure 5 shows the raw surface signals recorded simultaneously with the needle signals shown in Fig. 3. The surface electrode was placed over the distal half of the tibialis anterior (Fig. 2). The signals of adjacent channels show a relative time shift indicative of the propagation of MUAPs along the muscle fibers. The source of the propagation can be located to the region between channels 5 and 6. In

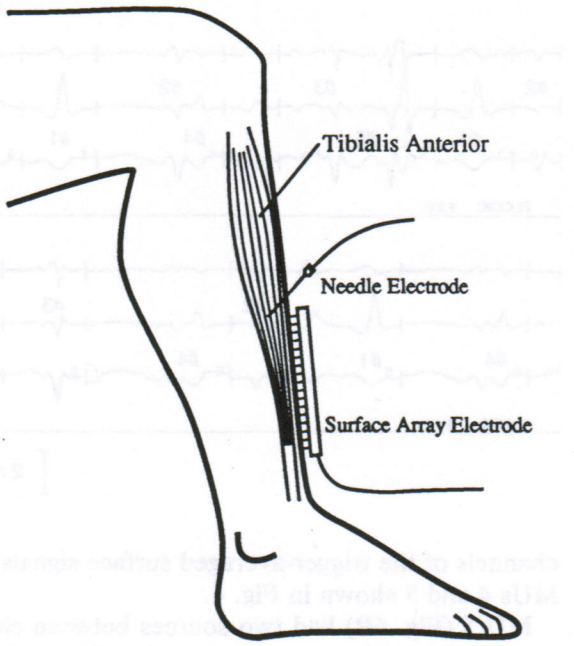

FIG. 2. Electrode placement. The surface electrode was placed over the distal half of the tibialis anterior. The needle electrode was inserted at the middle length of the muscle belly near the proximal edge of the surface electrode.

the adjacent channels, the potentials propagated in opposite directions. A second smaller source existed between channels 8 and 9. The two sources indicate the existence of innervation zones under the corresponding recording contacts. The volume conduction of the current from the muscle fibers may affect the waveshapes and duration of the surface ME signals but does not change the spatial symmetry in the distribution of the current as long as the volume conductor has uniform conductivity in the muscle fiber direction. Therefore, the focus of the conduction reversals is not affected by the volume conductor between the active muscle fibers and the skin surface. In the more proximal area of the tibialis anterior, we could not detect a clear pattern of the propagation, probably because of the complex configuration of muscle fibers.

Figures 4 and 6 show the surface MUAPs averaged by using the decomposed AP trains as the trigger signals. Figure 4 shows the averaged surface signals from channel 9 for the six MUs. In each graph, the waveshapes are drawn with three lines. The center line shows the average value, and the top and the bottom lines show the average value ± 3 SD. The small SD shows the successful extraction of single MUAPs. Figure 6A and B shows all the 16

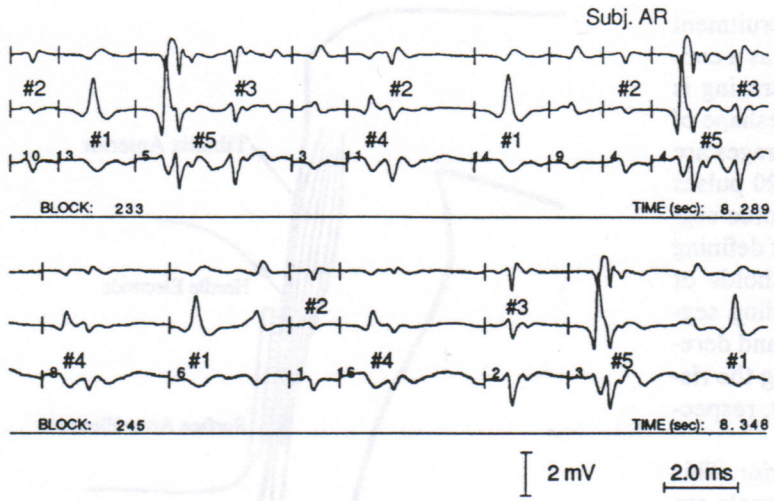

FIG. 3. Myoelectric signals obtained with the selective needle electrode. Three channels of signals were derived simultaneously. Two consecutive blocks of the recording are shown. The top two traces in each block represent the signals derived from a pair of contacts located at the side of the cannula; the third trace represents the signals derived between one of the contacts and the cannula. Signals in an inactive period containing no potentials exceeding the predetermined threshold (typically 1 mV) were not stored in the computer. Vertical lines in traces represent this inactive period, and numbers on the third trace indicate duration of the inactive period in milliseconds. The numbers in each segment of the traces indicate motor units (MUs) extracted by the decomposition algorithm. Each MU has the same waveshapes in its repeated firings.

channels of the trigger-averaged surface signals for MUs 4 and 5 shown in Fig. 4.

MU 5 (Fig. 6B) had two sources between channels 5 and 6 and between channels 8 and 9. Similarly MUs 1 and 6 (Fig. 4) had two sources at the same location. MUs 3 and 4 (Fig. 6A) had no distal source; it had a source only in the neighborhood of

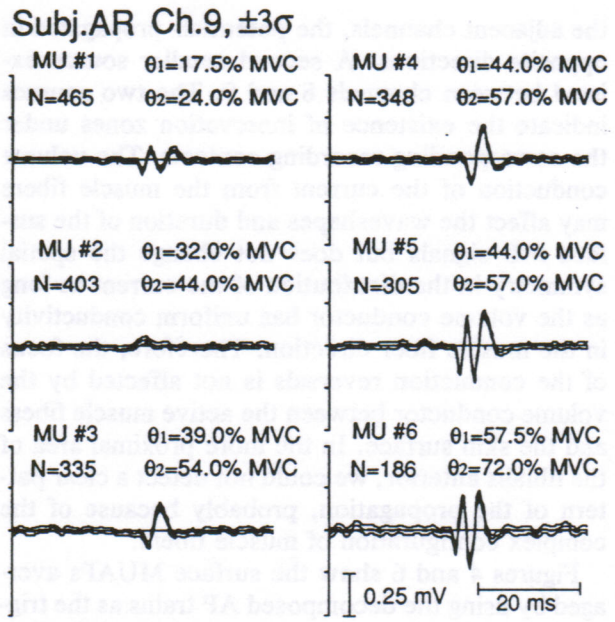

FIG. 4. Trigger-averaged surface signals for each motor unit (MU) isolated in Fig. 1. The surface signals of channel 9 are presented. The signals from the other channels are shown in Fig. 6 for MUs 4 and 5. θ_1 and θ_2 are recruitment and derecruitment thresholds of each MU; N, number of firings used to trigger-average the surface signal. Each MU action potential is drawn in three traces. The center trace of each graph shows the average value; the top and bottom traces show the average value ± 3 SD. The amplitude of MU 2 was too small to permit estimation of the propagation source.

channel 5. The initial small downward deflection in the channel 5 signal followed by a larger upward deflection indicated, however, that more than two innervation zones existed, with a small separation around channel 5. Other innervation zones may exist in the more proximal region of the muscle, but could not be detected by the present method because a clear propagation of MUAPs is not observable in the proximal muscle belly (5). No MU was detected that had only the distal innervation zones between channels 8 and 9; i.e., the distal innervation zone was always accompanied by the proximal innervation zones. In all the present records, the potentials propagating in the proximal direction had complex waveshapes and the propagation distance was smaller as compared with the distal region. The amplitude of MU 2 was too low to permit estimation of the innervation zones.

In the most distal channel, MU 5 (Fig. 6B) had a peak different from the ones originating from the source positioned between channels 8 and 9. Although the origin of this peak is unclear, it may be caused by the difference in the conductivity between the muscle and the tendon. In this recording, the distal edge of the surface array electrode was close to or on the tendinous region of the tibialis anterior.

MUs with two separate sources were found in two of four subjects (Table 1). This result does not mean that the other two subjects did not have MUs with separate innervation zones. In one subject (N.P., Table 1), the raw surface ME signals showed two separate sources ~15 mm apart along the muscle fibers, but the trigger-averaged surface MUAPs showed no clear separate sources within single

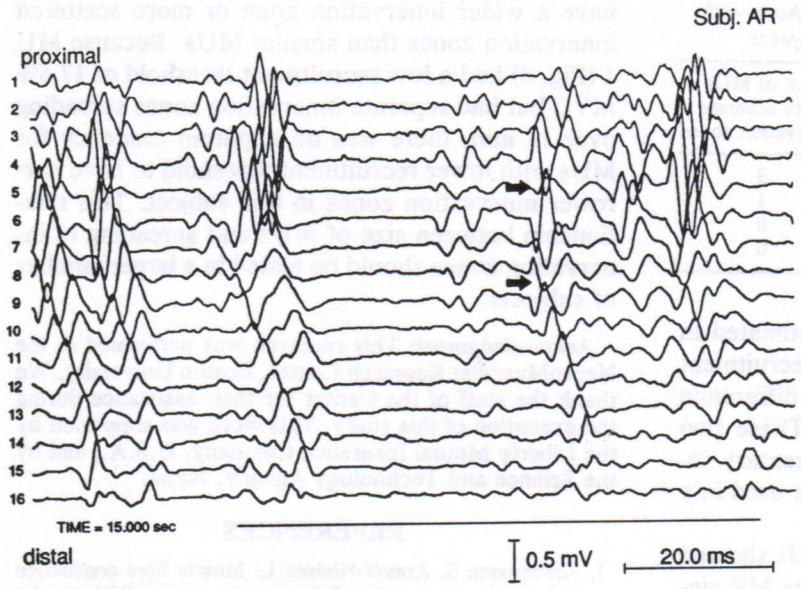

FIG. 5. Raw surface myoelectric signals recorded from the distal portion of the tibialis anterior. These signals were derived simultaneously with the recording of the needle signals shown in Fig. 3. The time shift between the signals of adjacent channels indicates the propagation of motor unit action potentials (MUAPs) along the muscle fibers. In this record, there were two sources of the propagation (arrow): one near channel 5 and the other between channels 8 and 9.

MUs. The detection of MUs with separate innervation zones depends on the position of the needle and the surface electrodes and on the chance that the needle electrode is placed close to the fiber of MUs to be detected.

DISCUSSION

With the aid of the selective needle electrode and the decomposition technique, we were able to estimate the position of the innervation zones of single MUs with recruitment thresholds ≤57.5% MVC. These MUs were detected during a voluntary contraction of 75% MVC. With the present technique, we cannot analyze MUs with recruitment threshold >75% MVC because a duration of 10 s is necessary to obtain a sufficiently large number of MUAP discharges and consequently to extract a reliable waveshape of averaged surface ME signals. Normally, maintaining the contraction force >75% MVC >10 s is difficult. If the surface ME signal has a large amplitude for a given MU, the number of averagings can be reduced, e.g., from 200 to 100. The duration of contraction can then be set <10 s and, as a result, the contraction force can be >75% MVC.

Another approach for detecting the propagation of single MUs was developed by Andreassen and Arendt-Nielsen (1), who used an intramuscular microstimulation of single motor axons and derived the surface potential with a tripolar electrode array. The size of MUs was estimated from the parameters of the twitch force elicited by the microstimulation. In this method, only one MU is analyzed at a time, whereas our present method can analyze several MUs in a single recording during a normal volun-

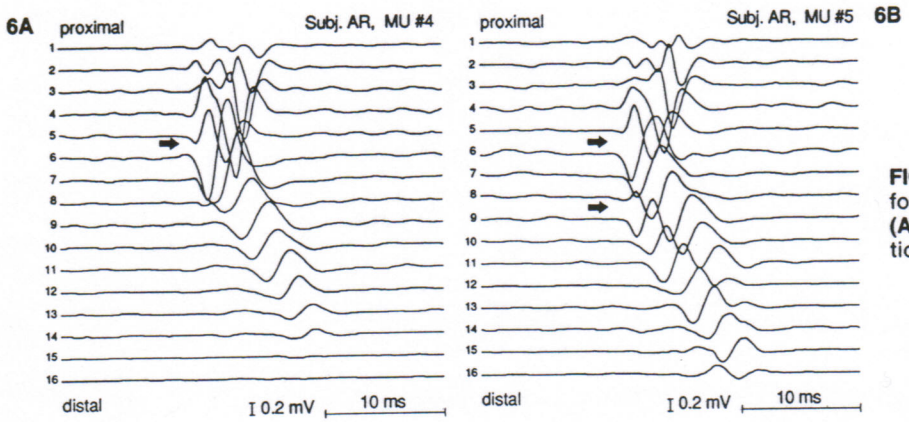

FIG. 6. Trigger-averaged surface signals for all 16 channels of motor units (MUs) 4 **(A)** and 5 **(B)** in Fig. 4. Source of propagation (arrow).

TABLE 1. *Number of MUs detected and those with separate innervation zones in four subjects*

Subject	No. of MUs detected	No. of MUs with separate innervation zones
A.R.	6	3
M.A.	7	1
T.M.	7	0
N.P.	5	0

tary contraction. The size of MUs is estimated in our method from the recruitment and derecruitment thresholds, which constitutes another difference from the method of microstimulation. These two different methods will provide complementary information on the size of MUs and can be used in a supplementary fashion.

In the present study, the individual MUs showed their characteristic waveshapes of surface ME signals and different configuration of innervation zones. In some MUs, two separate innervation zones were identified, although a narrow innervation zone spreading <5 mm was noted in the other MUs. In a previous study, MUs in the biceps brachii were shown to have innervation zones that spread ≤20 mm along the muscle fibers (4,6). A similar range (>15 mm) of spreading was found in the tibialis anterior, indicating that this degree of spreading is not rare in these large skeletal muscles.

Whether the spreading area of the innervation zone has any relation to the recruitment threshold or the size of MUs may be of interest. According to the size principle, large MUs have a larger number of muscle fibers and a larger territory in the cross-section of a muscle. Therefore, large MUs may have a wider innervation zone or more scattered innervation zones than smaller MUs. Because MU 1 (Fig. 4) had a low recruitment threshold of 17.5% MVC but had separate innervation zones spreading over 15 mm, there was no apparent tendency for MUs with lower recruitment threshold to have narrower innervation zones in this subject. This relationship between size of MUs and spreading of innervation zones should be tested in a larger number of subjects.

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