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Properties of Spike Potentials Detected by a Surface Electrode in Intact Human Muscle

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Abstract A clearly discriminable train of spikes was detected by ordinary silver disc electrodes fastened to the skin surface overlying *m. vastus medialis* during voluntary contraction in man. Some properties of these surface spikes were obtained. (1) Motor unit potentials detected by the inserted electrode located in the muscle closely under the fascia were found to be synchronized with the surface spikes. (2) The conduction velocity was around 3.5 m/s. (3) A starting point of the excitation, *i.e.*, "end-plate," was located at a point one-third of the observed length from the distal end in this particular case. (4) The conduction velocity showed a linear relationship with muscular temperature and $Q_{10} \simeq 2.0$ in the range of 17–31°C. (5) The amplitude of the surface spikes decreased monotonously with increasing the distance between the source and electrode. (6) Wave forms and threshold values were highly reproducible. (7) Similar surface spikes have been found in six other muscles in the subject S.M. and in *m. vastus medialis* in five other subjects.

Electromyography was introduced for detecting electrical activity of the intact human muscle by PIPER in 1912. The electrical activity can be led off either by surface electrodes fastened to the skin surface overlying the muscle, or intramuscular electrodes. Recording with the surface electrodes gives information about the total electrical activity within a certain area in the vicinity of the electrodes due to the considerable distance between the active fibers and the electrodes. An intramuscular fine electrode (ADRIAN and BRONK, 1929) has widely been employed for detecting the electrical activity of the motor unit. With this method the responses are observed as a discriminable train of spikes.

During a study of shivering in man, a clearly discriminable train of spikes was detected unexpectedly with ordinary silver disc electrodes fastened to the skin surface overlying the muscle. Further investigations showed that these discriminable spikes were also detected during voluntary activation of the muscle. In the present study, we attempted to observe the properties of these spikes led off

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by the surface electrode.

METHODS

The subjects of this study were healthy male adults. (One subject, most of the experiment, was one of the authors, S.M.)

The subject sat on a high stool which allowed free movement of the lower legs. The tension during knee extension was detected by a strain gauge (Nihon-Kohden, Tokyo, RTB-100K) connected to the ankle. The output of the strain gauge was fed into a carrier amplifier (Nihon-Kohden, Tokyo, RP-3).

For detecting electrical activity, we used surface and intramuscular electrodes. Two silver discs, with a diameter of 10 mm each, were fixed at a center-to-center separation of 20 mm by elastic adhesive plaster to a given position on the skin surface overlying the *m. vastus medialis* in line with the general direction of the muscle fibers. The disc closer to the starting point of the excitation was connected to the positive, and the other disc to the negative, input of a differential amplifier. Contact was completed with electrode jelly. The inserted electrode was prepared in the laboratory following KURATA's method (1974). Two copper wires (diameter of 0.1 mm each) insulated with polyurethan were joined. The bipolar electrode thus prepared was inserted into a one-third hypodermic-injection needle and bent at a point 2 mm from the tip. After the electrode was inserted into the muscle with the aid of the needle, the latter was removed. For an indifferent electrode, a silver plate 30 mm in diameter was placed on the skin surface of the knee joint where there was no underlying muscle. Signals from both the surface and inserted electrodes were amplified by conventional differential amplifiers (Nihon-Kohden, Tokyo, RB-2) with a time constant of 0.03 s. The input impedance of each amplifier was 5 MΩ.

Mechanical and electrical signals were simultaneously displayed on a cathode ray oscilloscope (Nihon-Kohden, Tokyo, VC-7) and photographed with a continuously recording camera (Nihon-Kohden, Tokyo, PC-2B).

In one of the part of the experiment, the temperature of the muscle was measured with a thermistor (Shibaura Electronics, Tokyo, MGP-III), embedded in the tip of an injection needle, with a diameter of 1 mm, inserted into the muscle.

RESULTS

Relationship between the spikes recorded by the surface and inserted electrodes

We attempted to locate spikes detected by the inserted electrode synchronized with those detected by the surface electrode from *m. vastus medialis*. After fixing the surface electrode in a position in which the largest amplitude of the spikes was detected, the intramuscular electrode was pushed into the muscle *via* the skin at a point 10 mm from proximal side of one of the disc electrodes. We attempted

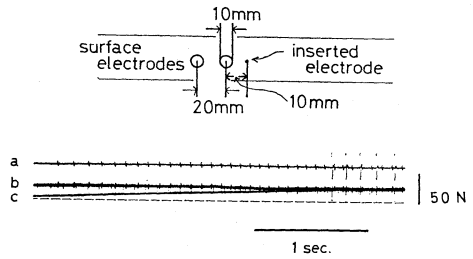

Fig. 1. Synchronized potentials detected by surface and inserted electrodes. Trace a: signal from the surface electrode. Trace b: signal from the inserted electrode. Trace c: tension of knee extension. Broken line shows zero level of tension.

to locate the spikes synchronized with surface spikes by moving the inserted electrode to and fro in the direction of the wire axis. Only when the tip of the electrode was located in the muscle closely under the fascia were the synchronized potentials detected. Spikes detected in the deeper part of the muscle were not synchronized with those detected on the surface. Figure 1 shows the typical synchronized potentials recorded from both surface and inserted electrodes. When the subject extended the knee joint gradually, spikes appeared at a tension of 5 N and over. Both trains of spikes were synchronized with each other. Other large synchronized potentials appeared at a tension of about 20 N and over. It was difficult to discriminate the synchronized potentials at a tension of about 50 N and over because of the interference of spikes from other sources.

Conduction velocity of the spikes

The time difference between both spikes was a function of the distance along the muscle axis between the surface and the inserted electrode. The time difference was determined by measuring the period between the negative upward peak of the spikes (inset of Fig. 2). The distance between the surface electrodes and the inserted electrode was defined as the distance between the inserted electrode and the mid point of two disc electrodes on the skin surface. Figure 2 shows a rectilinear relationship between two parameters. From this kind of measurements, the conduction velocity of the spike potential could be calculated: the results were, for example 3.3, 3.5, 3.6 and 3.7 m/s. Figure 2 also shows that the spike potential is conducted in both directions. The intersection of the two lines indicates the starting point of excitation, *i.e.*, "end-plate." The "end-plate" was located at a point one-third of the observed length from the distal end in this particular case. Because of the finite size of the surface electrodes and the broad distribution of the end-plates, the intersection occurred in the negative region of the ordinate.

Conduction velocity at different temperature

We attempted to investigate the effect of temperature on the conduction

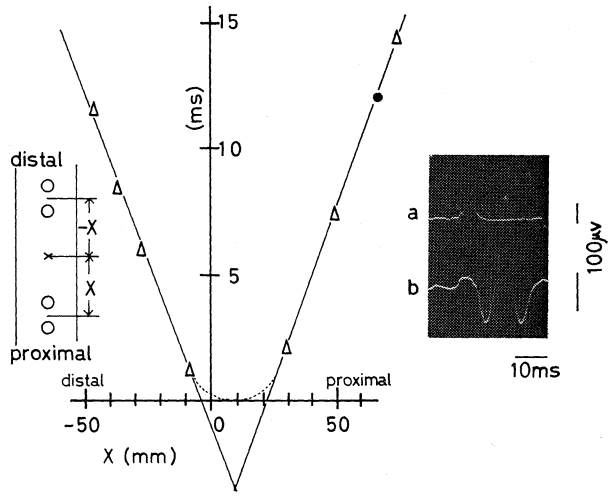

Fig. 2. Relationship between time difference and electrode distance (X). Ordinate: the time difference in ms of responses detected by the surface and inserted electrodes. Abscissa: the distance (X) in mm between the inserted electrode (×) and the surface electrodes. The zero point on the abscissa corresponds to the position of the inserted electrode. The lines were drawn by a method of least square of fitting. Conduction velocities were calculated to be 3.7 m/s (distal) and 3.6 m/s (proximal). Inset is the record of both spikes. This record corresponds to the filled circle on the plot. Trace a: the signal from the inserted electrode. Trace b: the signal from the surface electrode. Upward deflection means negative voltage.

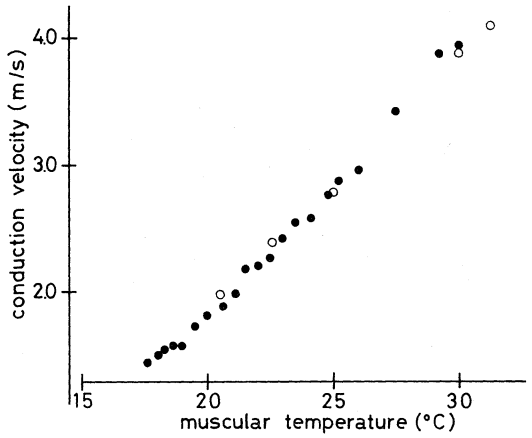

Fig. 3. Relationship between conduction velocity and temperature. ●, data point during cooling phase; ○, data point during warming phase.

velocity of the spike. In this experiment we used two pairs of surface electrodes, 38 mm apart, fixed on the skin. The conduction velocity was calculated from the time difference between negative peak points of both spikes and the distance between two pairs of electrodes. The position of a pair of electrodes was defined as the mid point of two discs. The temperature was changed in the muscle by the following means: the skin surface overlying the muscle was covered with the ice wrapped in a plastic sheet after fixing two pairs of electrodes. The temperature of the muscle was measured by a thermistor inserted into the muscle just under the fascia at the mid point between the two pairs of electrodes. To avoid the effect of heat conduction, the needle containing the thermistor was wrapped in adiabatic material. The temperature decreased gradually from 31 to 17°C in 30 min after ice was applied. After the ice was removed the temperature rose again to 31°C in 20 min. During this process the spikes were recorded. Figure 3 shows a relationship between the conduction velocity and the temperature. Two parameters showed a linear relationship and the rate was about 0.2 m/s·deg. This rate was maintained during both cooling and recovering phase.

Shape of spikes at the vicinity of "end-plate"

Figure 4 shows spike potentials detected by the surface electrodes. In trace b, one of the disc electrodes, connected to the negative input of the differential amplifier, was put in a position corresponding to the intersection of the two lines in Fig. 2. This steeply rising phase can be interpreted as follows: considering

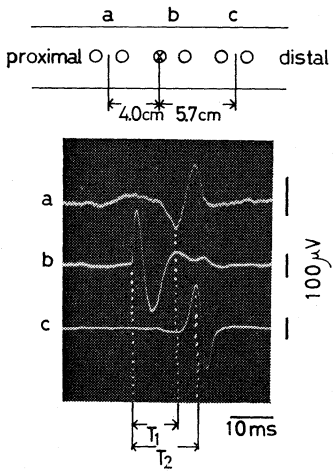

Fig. 4. Spike potential detected simultaneously from surface electrodes at three different positions along the direction of conduction. × shows the position of the "end-plate." The conduction velocity, calculated using the distance between a and b (4.0 cm) or b and c (5.7 cm) and T_1 or T_2 on this record is 3.7 m/s. Upward deflection means negative voltage.

the effect of the volume conductor, the shape of the rising curve of an ordinary spike potential is smooth because of the current flow into the excited part in front of the electrode. On the other hand, if the electrode is put just on the "end-plate," there is no current flow into the electrodes before the excitation starts. Traces a and c recorded at the distal and proximal parts from the "end-plate" respectively. In this case, the proximal disc electrodes of each pair of electrodes were connected to the negative, and distal discs to the positive, inputs of the differential amplifiers. The inversion of the phase of two potentials can be interpreted as a result of the conduction of the excitation in the opposite directions from the "end-plate."

Spike amplitude and source to electrode distance

To obtain the distribution of the source, we used two pairs of surface electrodes. One pair was used as reference electrodes placed on the skin just over the source of the excitation at which the amplitude of the spike was maximum. The other pair was used as test electrodes on the proximal part of the reference electrode as indicated in Fig. 5. We displayed both spikes on the oscilloscope triggering by the spike from the reference electrode. When the spike from test electrode was synchronized with one from the reference electrode, we recognized that the source of both spikes were same. When the test electrodes were placed just on the source, maximum amplitude was observed. The amplitude decreased at the medial and lateral side of the source (Fig. 5).

Reproducibility and generalization of the spike

To confirm the reproducibility of the experiment, we examined the threshold

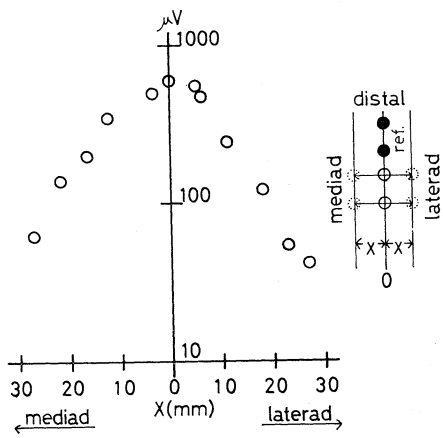

Fig. 5. Relationship between amplitude of spike and source-to-electrode distance. Ordinate: peak-to-peak amplitude of the spike on the logarithmic scale. Abscissa: distance of *X*. The zero point on the abscissa corresponds to the position of the reference electrode. The inset indicates the position of the reference (● ●) and the test electrodes (○ ○).

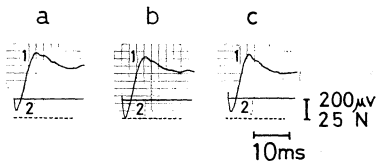

Fig. 6. Spike potentials recorded by internal trigger mode of an oscilloscope in three independent experiments. In each photo: trace 1, spike potential; trace 2, tension. The broken line shows the zero level of tension. a, b and c were recorded on March 4, 6 and 7, 1978, respectively. Downward deflection means negative voltage.

values, *i.e.*, the tension at which the spike was recruited, and the wave forms recorded at the same point on the skin but on different days. Figure 6 shows the wave forms which were obtained from three experiments performed on different days. The threshold values obtained from each experiments performed on different days were 24.0 ± 1.9 *N* ($n=24$), 24.4 ± 2.5 *N* ($n=22$) and 22.1 ± 2.0 *N* ($n=19$), respectively. Wave forms and threshold values were highly reproducible.

Finally, to generalize our findings, we attempted to find out the surface spikes

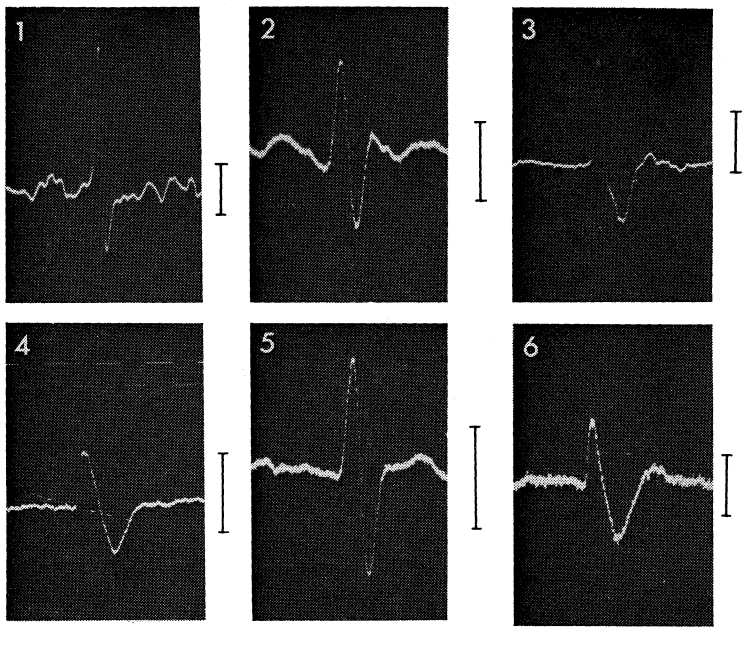

Fig. 7. Examples of surface spikes recorded from some muscles and subjects. 1, *m. tibialis anterior* in S.M.; 2, *m. biceps brachii* in S.M.; 3, *m. flexor pollicis brevis* in S.M.; 4, *m. vastus medialis* in Y.O.; 5, *m. vastus medialis* in H.K.; 6, *m. vastus medialis* in Y.U. Calibration bars indicate 100 μV and 10 ms, respectively. Upward deflection means negative voltage.

as mentioned above in other muscles and other subjects. We have found them in *m. vastus lateralis, m. tibialis anterior, m. biceps brachii, m. flexor digitorum superficialis* and *m. flexor pollicis brevis* in this subject, S.M., in *m. vastus medialis* in five other subjects. Figure 7 shows some examples of the records of above findings.

DISCUSSION

It has generally been accepted that surface electrodes sample the electrical activity of the whole muscle. Recently YEMM (1977) reported that the activity of a few units was visible as a discrete wave form on the surface signal in the masseter and temporal muscle. According to his method, however, a signal averager was triggered by pulses derived from a succession of spikes of a single motor unit from the needle electrode signal. In the present experiment, on the other hand, the spikes from the surface signal could be discriminated clearly without any averaging procedure and synchronized with spikes of a single motor unit from the inserted electrode signal. The surface responses mentioned above would give similar information as the responses detected by an inserted electrode.

The first investigation on conduction velocity in the skeletal muscle was performed on the human forearm with surface electrodes by HERMAN (1878) who reported the velocity of 10–13 m/s. PIPER (1909) also found the velocity in the forearm to be 10 m/s. DENSLOW and HASSETT (1943) made measurements of the conduction velocity on motor unit potentials in the voluntarily activated human muscle using an inserted electrode and reported a velocity of 1.3–12.5 m/s. No consideration was taken of the site of the end-plate in relation to the recording electrodes and therefore the above results do not represent the velocity in the muscle fibers. BUCHTHAL *et al.* (1955a) used a method in which they stimulated a small group of fibers in *m. biceps brachii* in man by an intramuscular needle electrode and picked up evoked potentials with 3–5 concentric needle electrodes. They found a rectilinear relationship between the arrival time of the potentials recorded from different electrodes and the distance between the electrodes. The conduction velocity in these measurements was found to be about 4.0 m/s. BUCHTHAL *et al.* (1955b) also found a velocity of 4.7 m/s in voluntarily activated muscles. The surface electrode samples the electrical signal from the wide part of the muscle. Because of the property of the surface electrode, the surface spike is the sum of the spikes of each single muscle fiber. The conduction velocity found in our investigation is the mean value of each muscle fiber belonging to the same motor unit. By considering the difference of the muscle and the room temperature, the present results, of around 3.5 m/s, are in agreement with above findings.

WILSKA and VARJORANTA (1940) found a nearly linear relationship between temperature and conduction velocity in the muscle fibers of the abdominal muscle of the frog. In isolated frog whole muscle preparations BUCHTHAL and ENGBAECK

(1963) investigated the velocity in the temperature range of 14–25°C and found a positive correlation with a $Q_{10}=1.6$. In intact human muscle Buchthal and Rosenfalk (unpublished data, sited by BUCHTHAL and STEN-KNUDSEN, 1959) found a $Q_{10}=2.0$ in the range of 30–37°C. In the present case, we also found a $Q_{10}\simeq 2.0$ in the range of 17–31°C. This value has a good agreement with above result.

LORENTE DE NÓ (1947) investigated in the nerve fiber and reported that the spike amplitude decreased in an exponential manner by increasing the distance between the source and the electrode in an isotropic conduction medium. HÅKANSSON (1957) also investigated in muscle fiber and found a same relationship with the nerve fiber. This tendency is in agreement with one which was investigated by the inserted multielectrode by BUCHTHAL and STEN-KNUDSEN (1959). Although, in our case, the exact distance between the source and the electrodes could not be obtained, the spike amplitude decreased monotonously with increasing distance between the source and the electrodes. This result suggests that the location of the muscle fibers belonging to the attending motor unit is not diffused but localized. From the evidence that the spike is undiscriminable at the tension above 50 *N*, it can be interpreted that some other motor units are located at the same place in a mixed manner.

The present method seems to be very useful for studying the voluntary control and/or the muscular activity because of simplicity and good reproducibility.

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