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Location of Electrodes in Surface EMG

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1. Introduction

Motor unit action potentials (MUAPs) from motoneurons are transmitted to muscles through end-plates and then propagated to the tendons. These bioelectrical signals are detected via electromyography (EMG), which is performed using electrodes.

The electrodes used in EMG are primarily surface electrodes and inserted (wire or needle) electrodes, of which surface and wire electrodes are mainly used for kinesiological studies. Surface electrodes are widely used because of noninvasive attachment, painless usage, suitability for detecting muscle activation by generation of EMG signals and simplicity, although detection is usually limited in surface muscles. Surface EMG is a practical and noninvasive procedure that has potential usage in sports and rehabilitation medicine.

The signal amplitude of surface EMG is analyzed to estimate the level of muscle contraction, while the frequency component is used to estimate performance of muscle activation. For example, a change in EMG signal amplitude is regarded as a change in the strength of muscle activation, and a shift of the surface EMG signal towards a lower mean frequency is correlated with decreasing muscle fiber conduction velocity due to muscle fatigue. However, the detected EMG signal amplitude and mean frequency are influenced by the location of surface electrodes, although the action potentials in a muscle are generated at the same time. For these reasons, the location of surface electrodes is very important for accurate evaluation of muscle activation.

In this chapter, the propagation or conduction of action potentials is illustrated to understand the EMG signal recorded by surface electrodes. Proper electrode locations are suggested with theoretical and practical methods.

2. Surface EMG signals according to the propagation of action potentials

EMG can explain the superimposed waveform of MUAPs, which are detected by electrodes. The EMG signal can be prepared by the summation of theoretically generated MUAP waveforms. The EMG signal observed by electrodes can also be estimated.

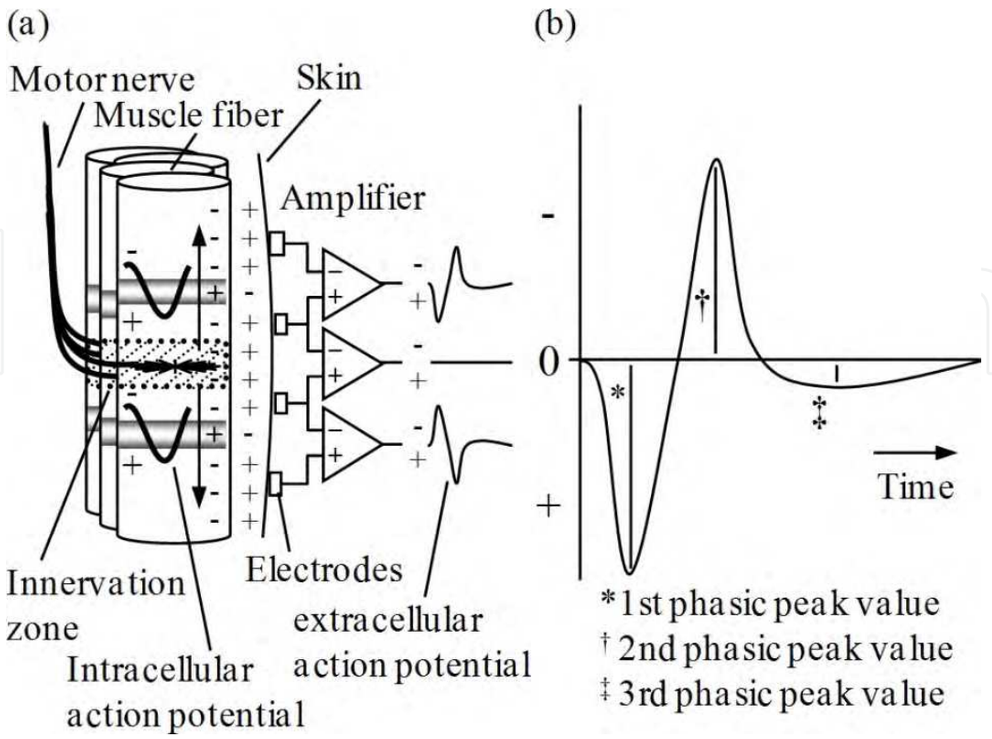


Fig. 1. Theoretical waveform of an MUAP measured using a surface electrode.
The action potential from the innervation zone (IZ) is propagated bilaterally along the muscle fibers. The direction of the waveform will reverse depending on whether the surface electrode is proximal or distal to IZ (a). The normal MUAP is triphasic, consisting of larger first- and second-phase peaks and a smaller third phase peak (b; Nishihara et al., 2010).

2.1 Detection of MUAP waveform with surface electrodes

Rosenfalck recorded action potentials during muscle contraction in individual muscle fibers of frogs, rats and humans, and performed a detailed calculation of the predicted action potentials when the signals were detected by bipolar electrodes placed on the skin surface (Rosenfalck, 1969). In humans, the basic action potential is triphasic; the first two phases are similar in amplitude, whereas the terminal phase has a peak-to-peak amplitude, which is only 5%–10% of those of the first two phases (Fig. 1).

If only a single MUAP is generated, whether the peak in each phase starts in a positive or negative direction theoretically depends on whether the recording bipolar electrode is proximal or distal to IZ (Hilfiker & Meyer, 1984; Zalewska & Hausmanowa-Petrusewicz, 2008).

The waveform of an MUAP is propagated from the end-plate to the muscle tendons. If the end-plates are concentrated in one location, then the direction of the positive or negative side of the MUAP waveform will reverse depending on whether the position of the electrode that is recording muscle activity is proximal or distal to IZ (Masuda & Sadoyama, 1991). The waveform of a MUAP will be canceled or attenuated in IZ.

When measuring a surface EMG signal during voluntary contraction, many MUAPs can interfere with each other, thus making it more complicated to identify a single whole MUAP from a raw waveform display.

2.2 Relationship between the direction of electrodes and muscle fibers

Action potentials from motoneurons are propagated along muscle fibers. Bipolar surface electrodes are usually placed in the approximated direction of muscle fibers and used with a differential amplifier, which suppresses signals common to both electrodes.

The potential at one electrode is subtracted from that at the other electrode, and then the difference is amplified. Subsequently, the common noise of both electrodes is eliminated.

Multichannel electrodes arranged along the direction of muscle fibers can be used to investigate the muscle fiber conduction velocity or propagation of the action potentials. However, many EMG channels must be used for a single muscle (Nishizono et al., 1979). Multichannel surface array electrodes or grid electrodes would facilitate the stable observation of action potentials because these electrodes are attached to a plate that fixes the electrodes in close proximity to each other (Fig. 2; Zwarts & Stegeman, 2003).

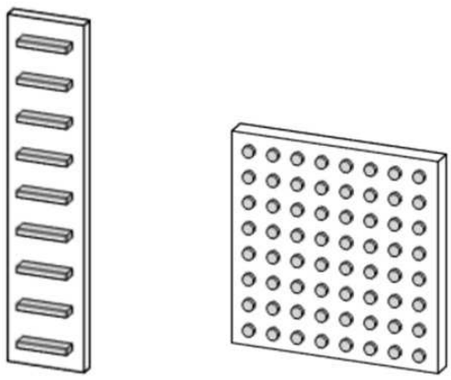


Fig. 2. Multichannel surface array electrodes (left) and grid electrodes (right).
The gray rectangles and circles represent electrodes attached to the boxes.

The propagated MUAPs are attenuated depending on their distance from the surface electrodes, the location of subcutaneous tissue, and the electrical impedance of the skin (Fig. 3). Usually, MUAPs generated at a distance from the electrode are greatly attenuated. The higher frequency components of the interfered waveform are more difficult to detect when surface electrodes are placed over subcutaneous tissue; in addition, it is difficult to identify the propagation of MUAPs. The propagation pattern from raw EMG signals may be observed during lower level of voluntary muscle contraction (Fig. 4).

The propagations are estimated by detecting time shifts of pulses, which are considered as one MUAP although they appear across EMG signals of several channels (Fig. 4). The time shifts of pulses indicate that the surface electrodes are approximately located along the direction of muscle fibers. The pulses shift maximally when the electrodes are placed along the direction of muscle fibers that are anatomically arranged in the same direction. Close to the tendons of a muscle, however, the amplitude of the EMG signal is reduced and the time shifts of pulses are unidentifiable.

Appropriate analysis techniques are needed to estimate the propagation of EMG signals in higher level of muscle contraction because many motor units are activated and the generated MUAPs interfere with the observed raw waveforms of EMG.

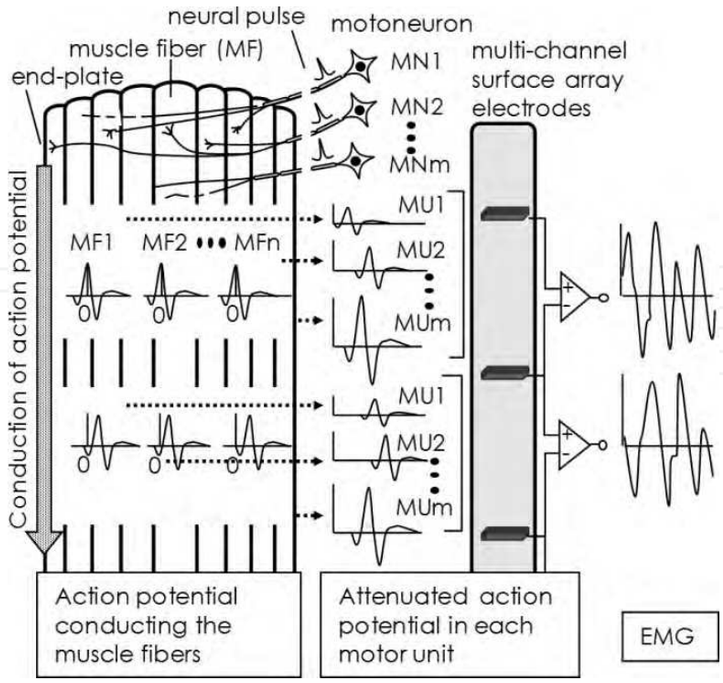


Fig. 3. Theoretical EMG signal from action potentials propagated along muscle fibers. The action potentials propagated along muscle fibers are attenuated according to the distance between the muscle fibers and the surface electrodes and are superimposed in surface EMG (Nishihara et al., 2003).

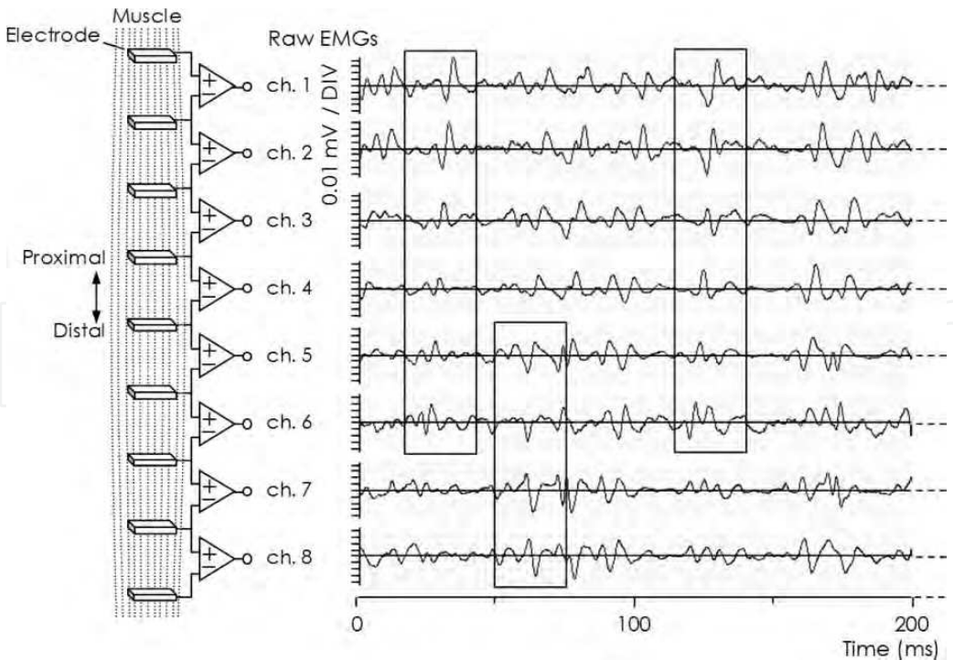


Fig. 4. Example of raw EMG signals detected by multichannel surface array electrodes. The propagations are estimated by detecting the continuous time shifts across several channels (rectangular boxes).

2.3 Cross-correlation method to estimate the propagation of action potentials

The cross-correlation method has been widely applied to estimate action potential propagation by multichannel surface EMGs using automated computer programs (Yaar & Niles, 1991). The correlation coefficient ($R\tau$) used to calculate the time shift is calculated from the reference EMG (X) and comparison EMG (Y) using the following equation (1):

$$R\tau = \frac{\sum_{i=0,j=i+\tau}^{N,N+\tau} (X_i - \overline{X}) \cdot (Y_j - \overline{Y})}{\sqrt{\sum_{i=0}^{N} (X_i - \overline{X})^2 \cdot \sum_{j=i+\tau}^{N+\tau} (Y_j - \overline{Y})^2}} \quad (1)$$

where $R\tau$ is a normalized value ranging from −1 to +1. The peak value of $R\tau$ displaced from time 0 is the time shift reflecting the conduction time between the two EMG signals (Fig. 5). A time shift could be assumed to occur according to the muscle fiber conduction. If the surface electrodes were attached in the proper direction, the peak value of $R\tau$ would be close to 1, which is relatively high.

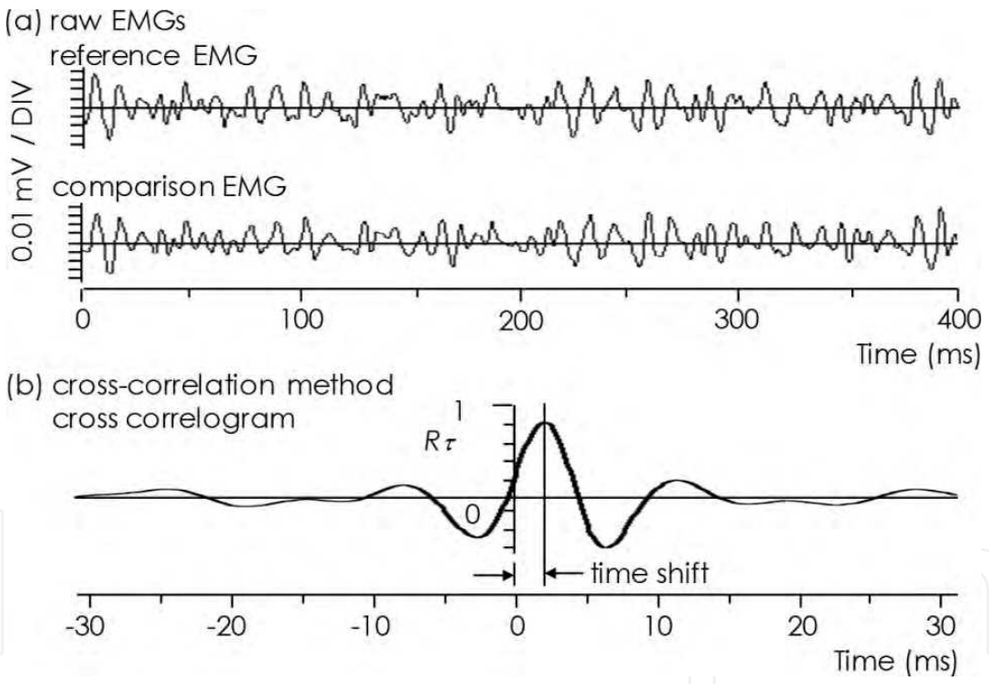


Fig. 5. Sample records of raw EMG signals (a) and the time shift estimated by the cross-correlation method (b).

The time shift estimated using the cross-correlation method by calculating the time between zero and the peak of the cross-correlogram of an EMG signal (Nishihara et al., 2003).

2.4 Peak averaging method to estimate the propagation of action potentials

The propagation pattern from a raw surface EMG signal can be observed by detecting the peaks in a surface EMG and averaging them using computer programs (Nishihara et al., 2003; Isho et al., 2011).

The smallest value at which the pulses were not detected from resting muscle EMGs was set as the threshold to avoid the detection of a noise component. When a positive peak value was larger than the set threshold in the EMG signals, the amplitude and time were registered as the peak of positive pulse. The negative peak value of the EMG signals is processed as the peak of negative pulse using the same method.

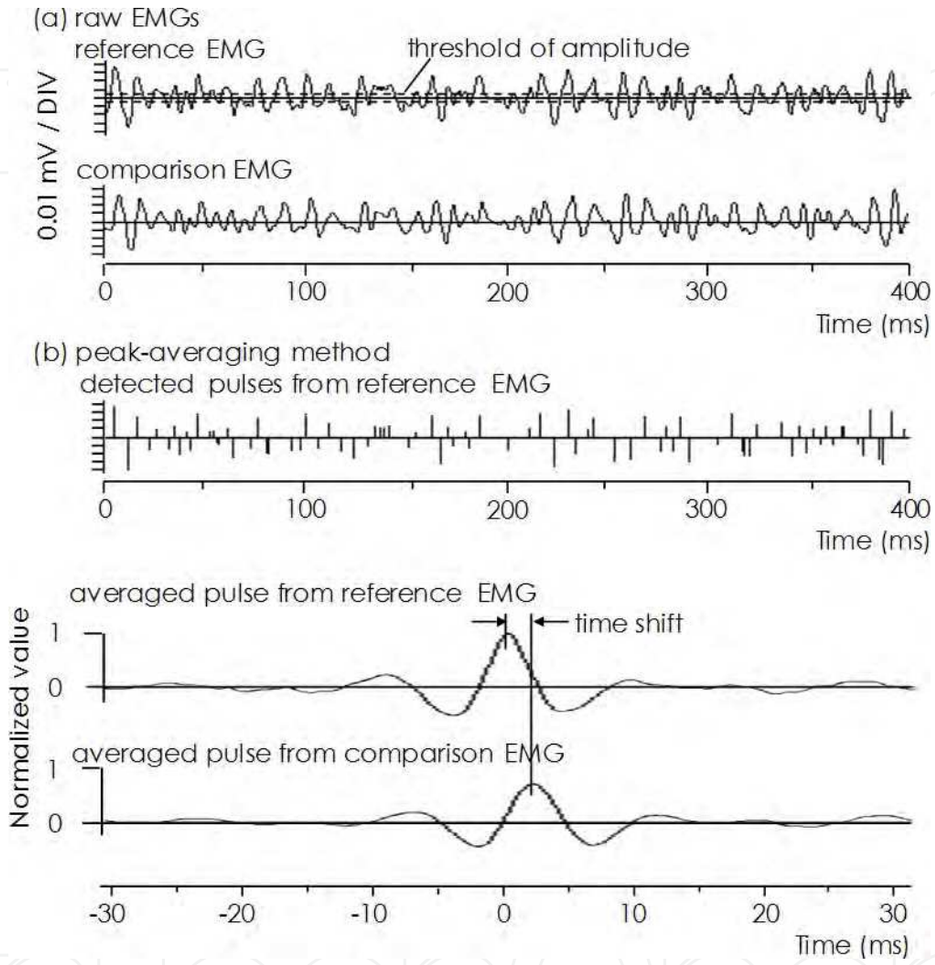


Fig. 6. Sample records of raw EMGs (a) and action potentials estimated using the peak averaging method (b).
The time shift is the time difference between the peak averaged pulses obtained using the peak averaging method (Nishihara et al., 2003).

Pulses from a reference EMG were superimposed at time 0 and averaged to minimize the irregular components of other interfering action potentials and noises. The value of the averaged pulse (*PAi*) at the point *i* on the reference EMG is obtained using the following equation (2):

$$PA_i = \frac{\sum_{j=1}^{N} \frac{1}{A_j} \cdot X_{T_j+i}}{N} \tag{2}$$

where N is the number of detected pulses in EMG with the reference electrodes, X is the reference EMG, Aj is the peak value of a detected pulse j in X, and Tj is the time at which a peak detected pulse j is obtained in X.
The peak value of PAj is 1, and its peak point of time is 0.
An averaged pulse is obtained simultaneously from a comparison EMG with an averaged time delay. The waveform of the comparison EMG is averaged with the same Aj and Tj of the detected pulse j in the reference EMG (not in the comparison EMG). Thus, the averaged pulse PBi at point i from the comparison EMG is obtained using the following equation (3):

$$PB_i = \frac{\sum_{j=1}^{N} \frac{1}{A_j} \cdot Y_{T_j+i}}{N} \tag{3}$$

where Y is the comparison EMG.
The time shift estimated by investigating the time difference between PAi and PBi is calculated from the time difference between the peaks or cross-correlation of PAi and PBi (Fig. 6).
This method permits simple observation of the propagation of action potentials across multichannel array electrodes.

3. Surface EMG signals in IZ

Action potentials were generated in the end-plates used for signal transmission from motoneurons. These end-plates are usually concentrated in areas such as IZ. The propagation pattern was investigated using the peak averaging method, and the location of IZ was also estimated by analyzing this propagation pattern.

3.1 EMG recording

Multichannel array electrodes were attached to the medial aspect of the belly in the direction of fibers of the biceps brachii muscle and the array was secured to the skin with surgical tape. The array electrodes comprised nine wires (material: silver/silver chloride, width: 1 mm, length: 10 mm) attached at 5-mm intervals to a transparent acrylic resin box.
A weight band was attached to the wrist of the subject. Isometric elbow flexion was performed for one second to the extent of <10% maximum voluntary isometric contraction, and an EMG signal was recorded. The adequacy of the distance between the array electrodes and the tendons was checked by palpation.

3.2 Estimation of IZs

The averaged pulses from the recorded EMG signal were calculated as shown in Fig. 7. If the array electrodes are shifted towards the adjacent muscles, the time shifts are not clear, and hum components, which are easily mixed if the reference electrode is incompletely attached, are detected as pulses. This results in many dummy averaged pulses appearing in each channel. In that case, the locations of electrodes must be corrected.
The origin of the propagation is considered as IZ. If the directions of electrodes and muscle fibers are substantially different, these time shifts of averaged pulses would not be clearly shown, or the peak correlation coefficient obtained would be of a relatively low value (equation (1)).

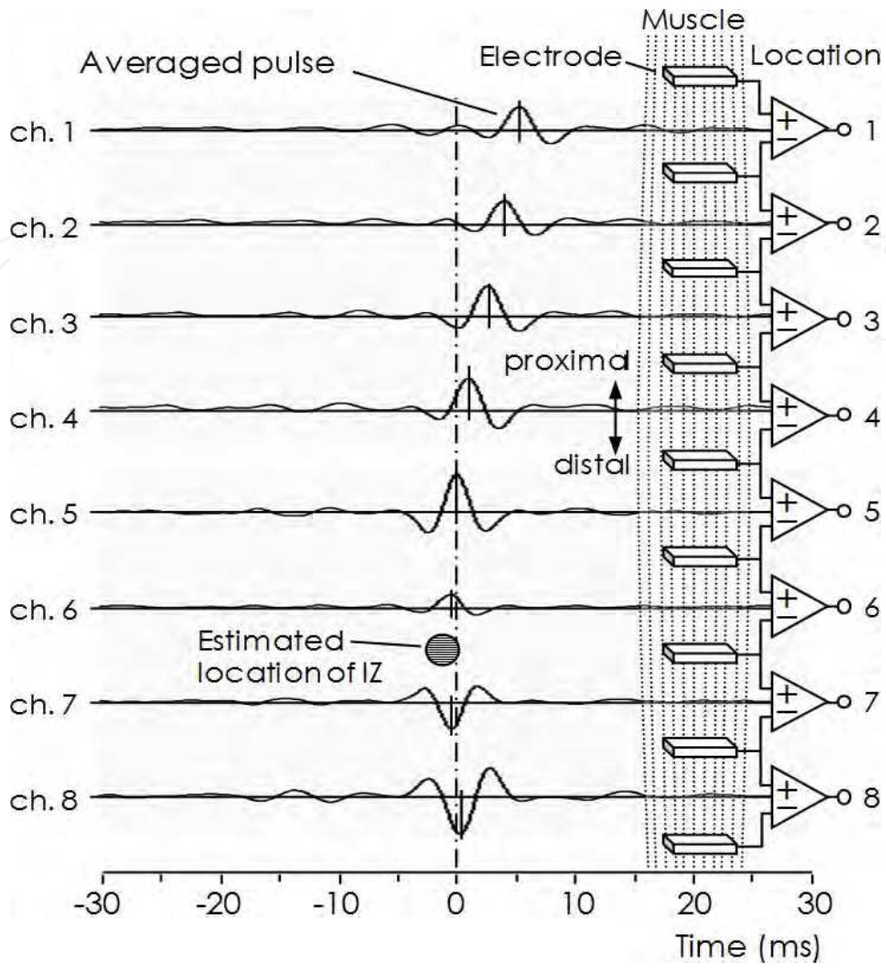


Fig. 7. Example of the generation of averaged pulses.
The EMG signal is the same as that in Fig. 4. Channel 5 was selected as the reference EMG. Detected pulses from the EMG signal are averaged, and these averaged pulses indicate the direction of propagation in muscle fibers. In this subject, the estimated location of IZ is between channels 6 and 7 (Nishihara et al., 2009).

4. IZ locations and directions of muscle fibers across several muscles

IZs are usually located around the muscle belly, or in other words, around the center of muscle fibers. However, determining the locations of IZs is difficult by the muscles. The muscles have been classified by the structures.

4.1 The structure of muscles according to the direction of muscle fibers

Muscles are classified on the basis of the direction of muscle fibers rather than the overall direction of the muscle (Fig. 8). The biceps brachii muscle is a typical example of a fusiform muscle, because it has a relatively uniform direction of muscle fibers with IZ located around its center in most cases. However, IZs were dispersed in many cases in spite of the biceps brachii muscle being used for the study in all cases (Fig. 9).

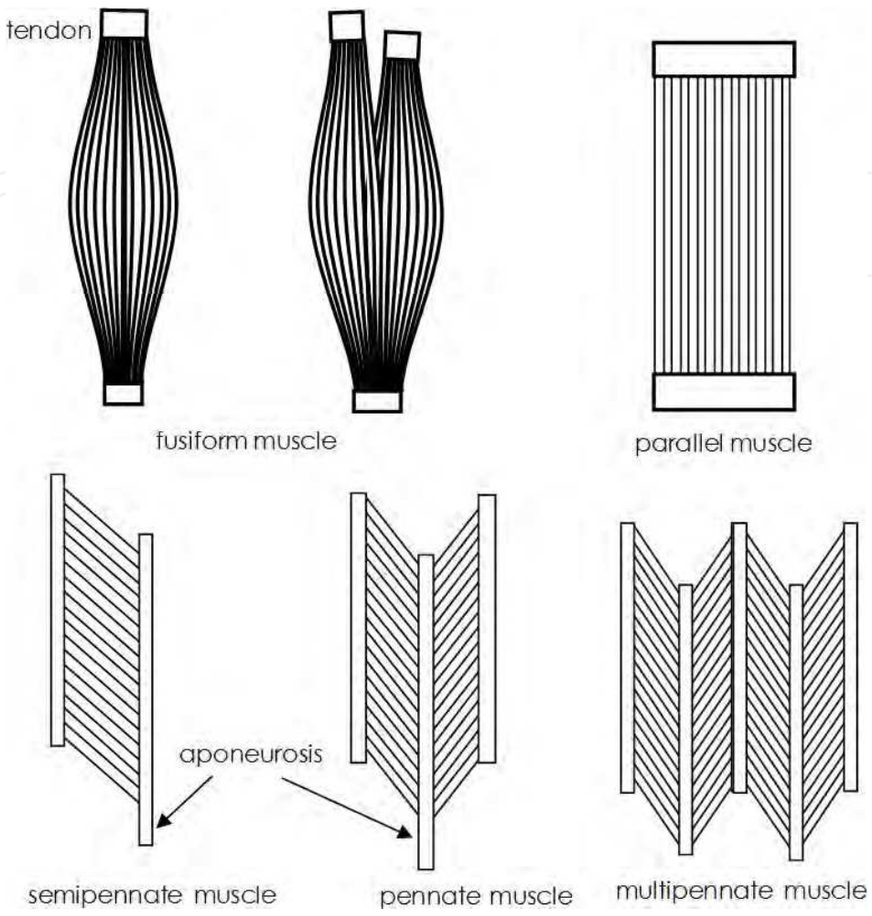


Fig. 8. Classification of muscles based on the directions of muscle fibers.

The direction of fibers is irregular in many muscles; consequently, IZs of these muscles are scattered around them (Saitou et al., 2000). Therefore, it is very difficult to attach surface electrodes in the exact direction of the muscle fibers of such muscles. In this case, the EMG signal does not comprise the waveform of generated MUAPs as illustrated in Fig. 1. The time shifts of averaged pulses from the gluteus medius muscle are not very clear compared to those from the biceps brachii muscle (Fig. 10). Clear time shifts do not appear even when the directions of array electrodes are rotated up to 30° (not shown in this figure).

The deltoid muscle is divided into three sections: anterior, intermediate, and posterior. In particular, the intermediate section of the deltoid muscle has a typical pennate structure. The direction of the muscle fibers in this section of the deltoid muscle are irregular compared to that of the biceps brachii muscle. The time shifts across the channels of the averaged pulses are not very clear; therefore, it is difficult to investigate the location of IZ (Fig. 11; Nishihara et al., 2008).

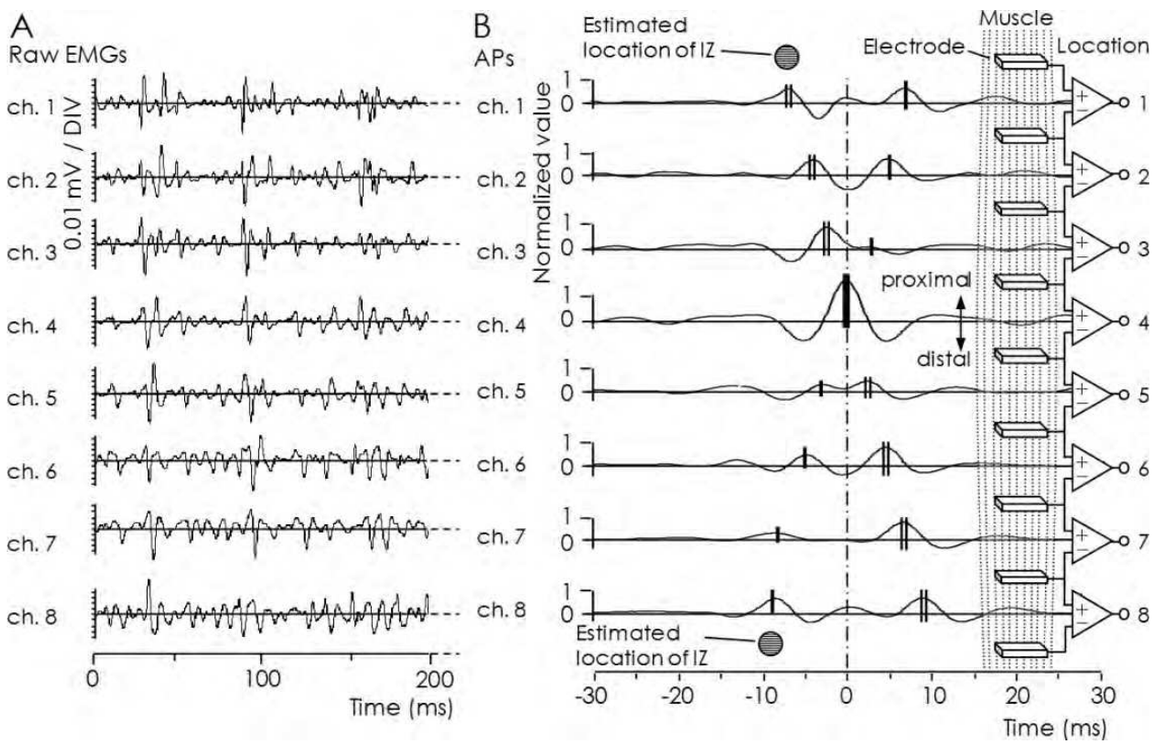
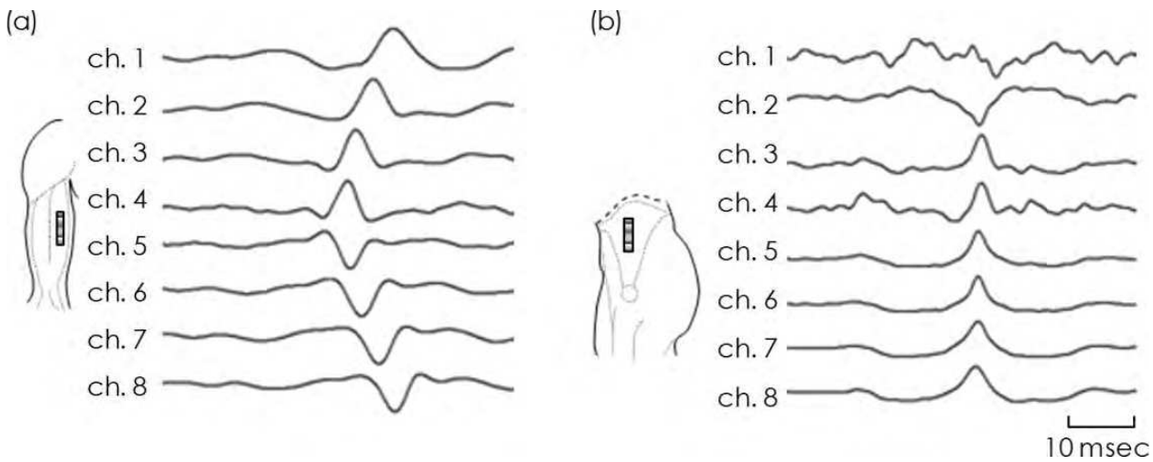
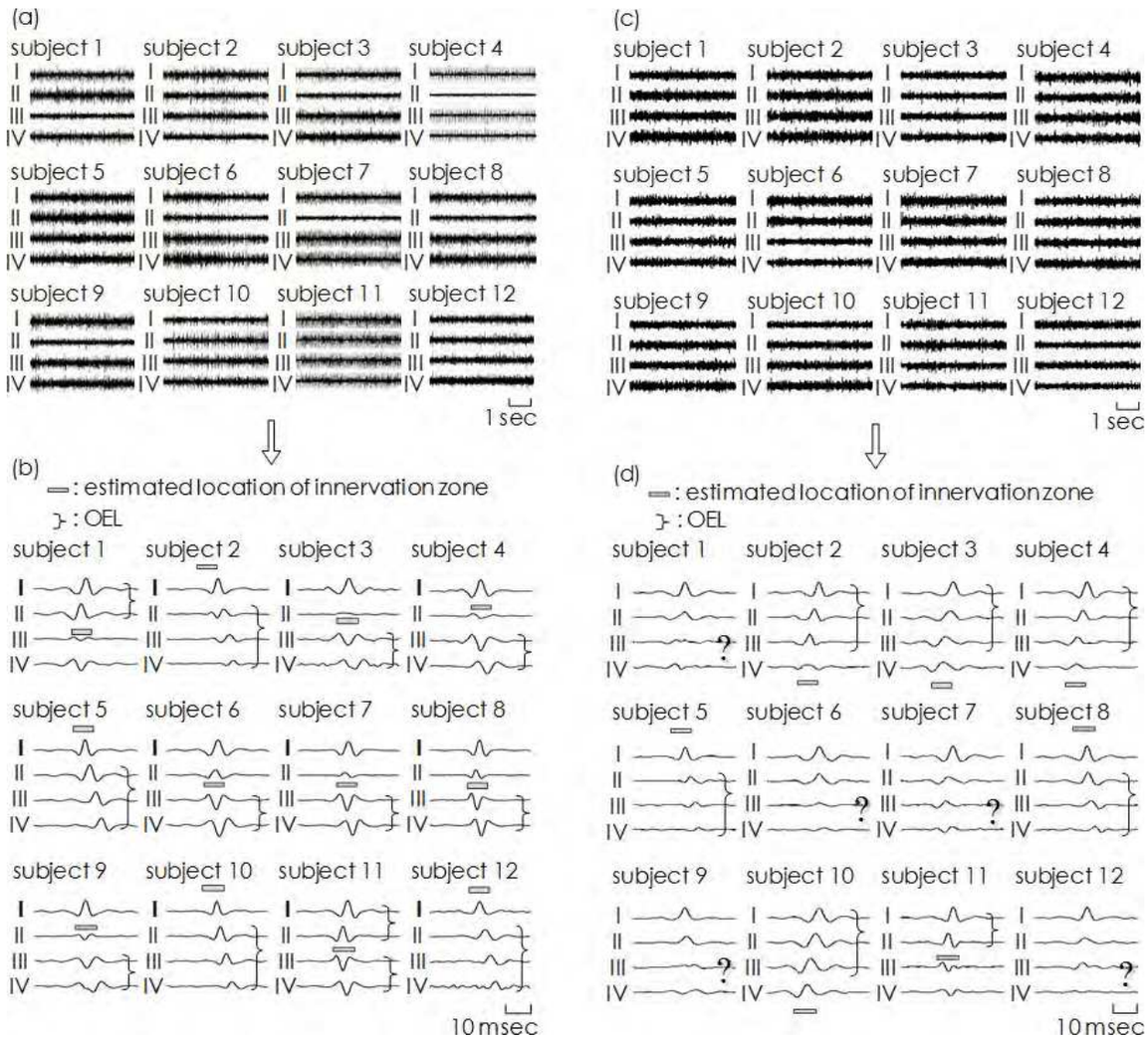


Fig. 9. An example of dispersed IZs in the biceps brachii muscle.
The calculation method is same as that described in Fig. 7. (A) Channel 4 is selected as the reference EMG. (B) The estimated locations of IZs are proximal at location 1 and distal at location 8 in this subject.



(a) The time shifts of averaged pulses across the various channels are revealed in the biceps brachii muscle. (b) However, the time shifts of averaged pulses are not revealed in the gluteus medius muscle. The gray rectangles demonstrate the locations of array electrodes, which were attached at 10-mm intervals.

Fig. 10. An example of calculating the averaged pulses of different muscles.



(a) Raw EMG signals of the biceps brachii muscle are shown. Particularly small amplitudes are exhibited in channel 3 in subject 1 and channel 2 in subjects 3, 4, 7, 8 and 9. (b) Calculated averaged signals of the muscles with pulse detection in EMG for channel 1 (shown in bold). (c) Raw EMG signals of the intermediate section of the deltoid muscle are shown. (d) Propagation patterns are shown for seven subjects. The propagation patterns of the other five subjects were not estimated because central peaks in the averaged signals could not be obtained for all four channels, or peaks in the averaged signals of neighboring channels did not exhibit time differences in the propagation of action potentials along electrodes. The optimum electrode location (OEL) is investigated on the basis of the location of IZ (Nishihara et al., 2008). Note the lower amplitudes of the raw EMG signals around channels of IZ locations.

Fig. 11. Analysis of EMG signals for the biceps brachii muscle (left) and deltoid muscle (right).

4.2 EMG signals near IZ

The changes in EMG signal amplitudes near IZs can be estimated if multichannel electrodes are used. For example, EMG signals with smaller amplitudes are observed using the raw EMG signals of the biceps brachii muscle as shown in Fig. 11, and the data for these

channels agree with those of the channels near estimated IZs. The EMG signal amplitude can be calculated from the root mean square (RMS) of the EMG signal. The RMSs of EMG signals are obviously attenuated near IZ as shown in Fig. 12. Sufficiently large RMS values can be obtained at locations far from IZs.

IZs of the deltoid muscle are not very clear compared to those of the biceps brachii muscle (Fig. 11, d). However, this does not imply that the EMG signal of the deltoid muscle more correctly reflects the level of muscle activation than that of the biceps brachii muscle. Small RMS values are shown in some channels of subjects, although the locations of IZs are not estimated in the deltoid muscle (Fig. 12, right half). The EMG signal amplitudes may be attenuated by the different electrode directions relative to the axes of the muscle fibers rather than the small, scattered IZs in the deltoid muscle.

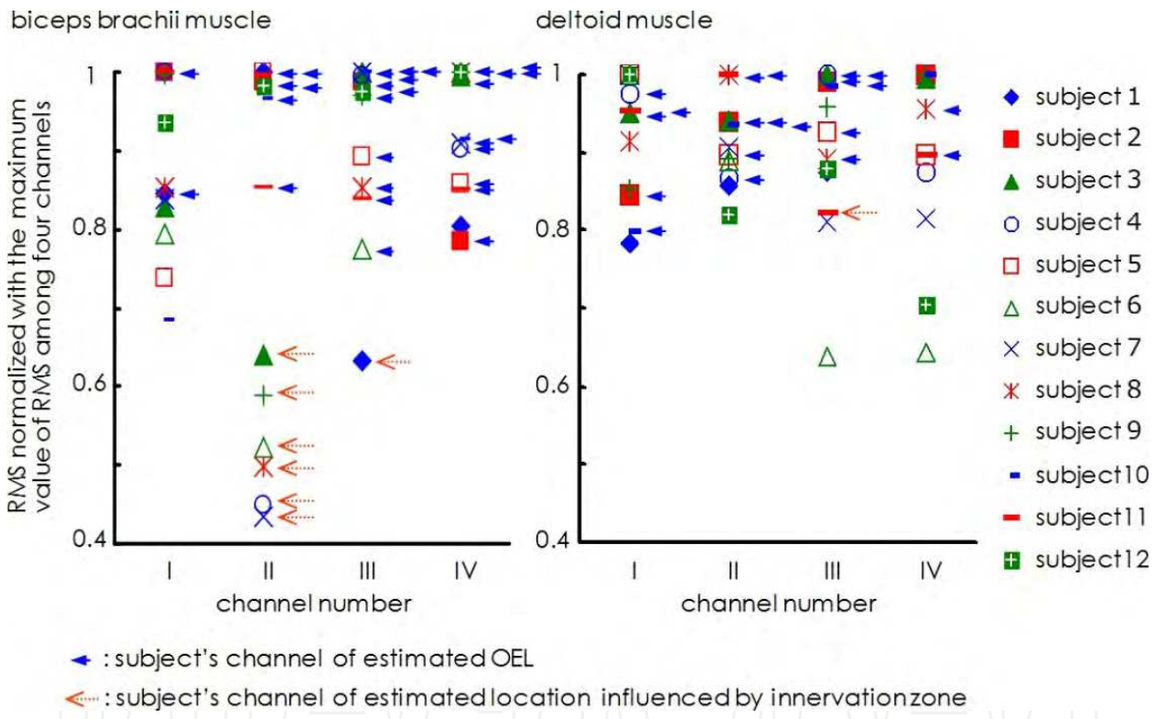


Fig. 12. RMSs of raw EMG signals for the subject channels depicted in Fig. 11.
The EMG signals shown in Fig. 11 a and c are used. The subject's channel of estimated location, which was influenced by IZ, gave particularly small values (indicated by the large arrow with dotted line) compared with the subject's channel of estimated OEL (indicated by the small arrow with solid line). Small values were recorded in the channels of subjects whose deltoid muscle was not evaluated (channels 3 and 4 of subject 6 and channel 4 of subject 12).

5. Conclusion

These results demonstrate that EMG signals are affected by location of electrodes. Proper location of electrodes can be suggested by these findings.

5.1 Identification of targeted muscle

The location of electrodes has to be carefully determined for the targeted muscle. Superficial muscle could be identified with manipulation. When the electrodes were shifted towards the adjacent muscles, the unassumed action potentials from different muscles were mixed with the EMG signal. The electrodes were also easy to place on the tendon of the muscle. In that case, low-amplitude EMG signals that do not reflect muscle activity could be observed. Muscle and tendons can be distinguished by palpation.

5.2 Identification of the direction of muscle fibers

The direction of electrodes affects the EMG signal when the direction is differing from the directions of muscle fibers. The direction of the electrodes must align with that of muscle fibers. An ideal situation would be when one whole MUAP is detected by one electrode and the next one by the other electrode. The muscle fibers need not always be in the direction of the muscle. However, if muscle fibers are diagonally directed, obtaining sufficient space to attach bipolar electrodes may prove difficult.

5.3 Attaching the reference electrode

The reference electrode must be attached firmly to eliminate noise components such as hum. The reference electrode has to be located on electrically neutral tissue such as a bony prominence. The propagation pattern is not revealed by the peak averaging method (Fig. 7) if large noise components are included in the EMG signal.

5.4 The relationship between electrode and IZ locations

Propagation has to be regarded relative to the location of electrodes because their placement can affect the signal amplitude and frequency components in surface EMG. As previously mentioned, to correctly quantify muscle activity, electrodes must be placed along the course of muscle fibers between tendons in the targeted muscle. The cutaneous area, which is useful for observing the surface EMG signal, could be very limited in this restricted rule. For this reason, the electrodes should be located near the muscle belly. However, the EMG signal is easily affected when the electrodes are located near IZs, which are concentrated in the muscle belly (Fig. 11). A stable EMG signal is necessary for the reliable investigation of voluntary muscle activation.

The channels located near the estimated IZs agree with the channels of the smallest amplitude or RMS of the EMG signals (Fig. 12). As a result, it is suggested that electrodes should be placed at a sufficient distance from IZ for detection of the surface EMG signals during voluntary muscle contraction.

Moreover, IZ is known to shift with changes in muscle length due to muscle activity. In other words, when electrodes are attached to the skin and EMG for muscle activity is recorded, the positional relationship between the surface electrodes and IZ can shift markedly. Electrodes must also be attached after considering the moving IZ during EMG recording (Nishihara et al., 2010).

5.5 Effect of muscle structure

The aforementioned rules are based on the assumption that all muscle fibers are aligned in the same direction and IZs are concentrated in the muscle belly of the targeted muscle. The anatomical structure of the targeted muscle must be investigated before attaching the electrodes. However, in muscles with irregularly oriented muscle fibers, such as pennate

muscles, the proper direction of electrodes could be not determined. There are limitations to consider regarding the optimum surface electrode locations while investigating the activity of these muscles using EMG signals.

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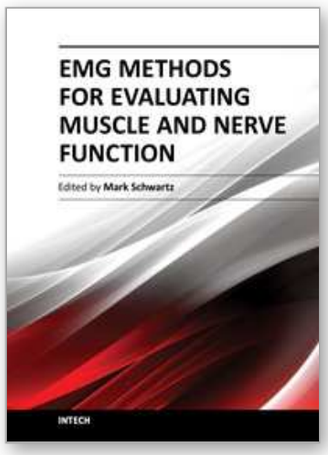

EMG Methods for Evaluating Muscle and Nerve Function
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