A Procedure for Decomposing the Myoelectric Signal Into Its Constituent Action Potentials— Part I: Technique, Theory, and Implementation

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***Abstract*—A technique has been developed which enables the decomposition (separation) of a myoelectric signal into its constituent motor unit action potential trains. It consists of a multichannel (via one electrode) myoelectric signal recording procedure, a data compression algorithm, a digital filtering algorithm, and a hybrid visual-computer decomposition scheme. The algorithms have been implemented on a PDP 11/34 computer. Of the four major segments of the technique, the decomposition scheme is by far the most involved. The decomposition algorithm uses a sophisticated template matching routine and details of the firing statistics of the motor units to identify motor unit action potentials in the myoelectric signal, even when they are superimposed with other motor unit action potentials. In general, the algorithms of the decomposition scheme do not run automatically. They require input from the human operator to maintain reliability and accuracy during a decomposition.**

INTRODUCTION

THE motor control system is a complex neural system with a myriad of pathways. One of its output pathways consists of the ensemble of α motoneurons which activates the skeletal muscle fibers. One way to study this output pathway in humans is to record the action potentials associated with firings of individual motor units (MU's) by means of indwelling (needle or wire) electrodes inserted into a muscle. An MU consists of a group of muscle fibers distributed throughout a muscle, which are all innervated by the same α motoneuron. The detected waveform associated with one twitch of the MU is known as the motor unit action potential (MUAP). During a muscle contraction the MU's fire repetitively, generating motor unit action potential trains (MUAPT's). An indwelling electrode will typically detect the activity of several fibers in its vicinity. Some of these fibers may belong to the same MU, whereas others may not. The signal thus obtained consists of a superposition of the MUAPT's from all the MU's having fibers in the vicinity of the electrode. This signal is referred to as the myoelectric (ME) signal. Refer to De Luca [5] for a more detailed review of the electrophysiology.

The shape and amplitude of each MUAP waveform will generally differ from MU to MU due to the unique geometric arrangement of the fibers of each MU with respect to the recording site. MUAP waveforms from different MU's may, however, be nearly similar in amplitude and shape when the muscle fibers of two or more MU's in the detectable vicinity of the electrode have a similar spatial arrangement. The shape of the MUAP waveforms within a MUAPT will remain constant if all the initial relationships between the electrode and the active muscle fibers remain constant: that is, if the geometrical arrangement between the recording electrode and active muscle fibers does not vary; if the relative time difference between the initiation of each constituent fiber action potential is constant; if the properties of the recording electrode do not change; and if there are no significant biochemical changes in the muscle tissue [5].

The possibility of correctly detecting and identifying individual MUAP's from each MUAPT contained in the ME signal has interested several investigators in the past. The different techniques that have been employed may be generally categorized as either visual identification by a human [4], [6], [12]-[14], [17], [22], [23], [26] or automatic identification by electronic apparatus [1], [3], [7]-[11], [16], [20], [21], [24], [27]-[30]. The major problem with totally visual analysis procedures is the tremendous amount of time required to make the MUAP identifications and precise firing time measurements. The criteria upon which the automatic identifications are based may be categorized as either feature extraction (the peak amplitude, rise time, area, or other characteristic of the MUAP waveform) or signal space representation (usually referred to as correlation, matched filter, template, or square-error separation techniques). One of the major problems with most automatic detection schemes is the inability to resolve waveforms produced by the superposition of two simultaneously occurring MUAP's. Most automatic detection schemes also cannot accommodate a slow change in a MUAP waveform's shape or amplitude throughout a contraction.

This paper describes a system which has been developed to overcome some of the previous limitations. It consists of a

Manuscript received December 17, 1980; revised November 6, 1981. This work was supported in part by the National Institute of Arthritis, Metabolism and Digestive Diseases under Grant AM 19665, the Insurance Institute for Highway Safety, the United C. P. Research and Education Foundation Inc. under Grant R 723-76, the Charles A. Dana Foundation Inc., the Hearst Foundation Inc., and the Liberty Mutual Insurance Company.

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multichannel ME signal recording procedure, a data compression algorithm, a digital filtering algorithm, and a hybrid visual-computer detection scheme.

Overview of the Data Acquisition and Analysis Procedures

The overall objective of the development of the data acquisition and analysis system which will be described is to obtain a more detailed understanding of the voluntary control of MU's in human muscles. The specific information to be obtained through the use of this system is a time record of the firings of each of several simultaneously active MU's during force varied and attempted constant-force isometric contractions. The performance goal for this system was to accurately (error free) detect each firing of up to eight MU's during a single contraction with forces as high as 100 percent of a subject's maximal voluntary contraction. Each of the component procedures of this system, from experimental setup to final data analysis, has been developed to achieve this goal. The resulting system is complex, requiring several successive operations on the data. The time involved may often exceed one h/s of recorded ME signal to accurately detect the activity of several MU's in contractions above 50 percent of maximal level. The results obtained by using this system have demonstrated that a greater understanding of the motor control system is made possible by this highly accurate analysis of concurrently active MU's [18].

The following are brief descriptions of each of the component procedures. A more detailed description of the important aspects of these procedures and their theoretical bases are presented in latter sections.

Force Regulation Procedure

Contractions were performed isometrically against a force transducer. Appropriate apparatus was used to stabilize and support the joint being controlled. The vertical position of a horizontal line on an oscilloscope was controlled by the measured force. The subject attempted to match a second target line whose position was controlled by a microprocessor which caused it to move up, down, or remain stationary. The contractions investigated to date have included linear increases and decreases in force at several different rates as well as attempted constant-force contractions. Abrupt changes in force were avoided so that MU firings throughout a contraction could be studied.

Myoelectric Signal Recording Procedure

Three channels of ME signals were recorded from a modified DISA (13k80) bipolar needle electrode which contains two electrode surfaces within the cannula. The heavy cable, which is normally attached to this electrode, was replaced with three 15 cm long, 0.078 μm diameter, polyurethane insulated copper wires. These flexible wires greatly reduced external force on the needle, thereby minimizing the electrode movement with respect to the muscle fibers during a contraction. The wires of the electrode were connected to unity gain FET buffer preamplifiers (constant current, source follower configuration). This arrangement minimized the shunt capacitance (<6 pF),

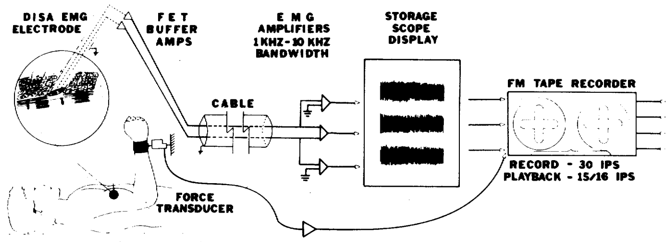

Fig. 1. Schematic representation of the myoelectric signal and force recording system.

permitting wide-band recordings. This type of electrode was chosen because:

1) It allows three channels of ME signal recording from different recording electrode configurations in the same physical proximity of a group of muscle fibers.

2) It can be easily repositioned in the muscle without reinsertion. This permits electrode adjustment for obtaining high quality recordings and for sampling MU's from differing populations within the muscle.

3) It can routinely detect 3 to 8 MUAP waveforms simultaneously, each with a signal to noise ratio sufficiently large to permit a reliable analysis of the MUAPT's.

A schematic representation of the ME signal and force recording arrangement is displayed in Fig. 1. The three channels of ME signals recorded from the needle electrode are: one bipolar between the two platinum wire recording surfaces, and two monopolar between the cannula and each of these surfaces. Although this provides one redundant channel of information, the signal to noise ratio is slightly improved. The differential amplification was performed by three amplifiers having a 6 dB/octave rolloff at 1 and 10 kHz. The procedure of setting the lower 3 dB point at 1 kHz rather than a lower frequency such as 100 Hz was consistently observed to reduce the duration of MUAP waveforms produced by muscle fibers near the electrode, and to substantially reduce the amplitude of slower rise-time MUAP waveforms produced by muscle fibers more distant from the electrode. The outputs of the amplifiers were recorded on an FM tape recorder at 30 in/s. With this arrangement it has been possible to obtain action potentials with peak-to-peak rise times as short as 100 μs. Three simultaneously recorded channels of ME signals recorded with this arrangement may be seen in Fig. 2. This figure demonstrates the main advantage of multichannel recordings. Note that the first two MUAP's in the bipolar channel appear to be deceptively similar in shape and amplitude. However, by observing the corresponding waveforms in the two monopolar channels, it can be distinctly concluded that the two adjacent MUAP's are associated with different MU's. Other similar examples may also be observed in Fig. 2.

Data Sampling and Compression

The recorded ME signals were transferred to digital storage using a PDP 11/34 computer. Due to the signal processing method used to detect MU firings, a sampling rate several times higher than the Nyquist frequency must be used to reduce alignment errors. (Refer to the Appendix for additional information.) A sampling rate of 50 kHz was chosen

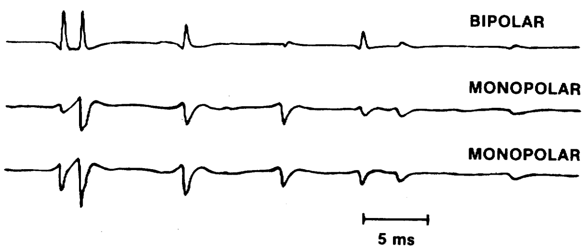

Fig. 2. Three simultaneously recorded channels of the myoelectric signal detected by the modified bipolar needle electrode. (See text for details). Note the distinctly different shapes and amplitudes of the motor unit action potentials as they appear on the different channels. It is of particular interest to observe the similarity of the first two motor unit action potentials on the bipolar channel, in contrast with the substantially dissimilar shapes of the corresponding events in the other two monopolar channels. Similar examples appear throughout the remainder of the record.

since some of the MUAP waveforms obtained using the wide-band recording technique have frequency spectra that range up to 10 kHz. The high sampling rate was achieved by playing back the ME signal 32 times slower than it was recorded, and sampling at a rate of 1.5625 kHz. A computer program to sample and store the data was written which stored only the segments of data containing positive or negative peaks above a preset threshold. This threshold was selected by the operator dependent upon the level of background noise in the data. The remaining portions of data intervals between stored segments were stored only as a number of skipped samples. This method reduced the storage requirements to 5 to 20 times less than uncompressed storage without sacrificing any significant information. A comparison of uncompressed and compressed ME signals is shown in Fig. 3.

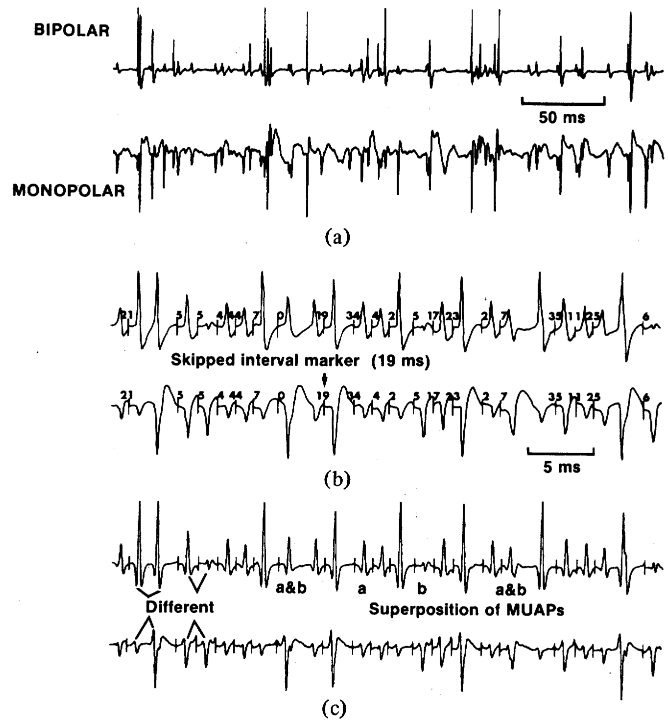

Fig. 3. The appearance of the myoelectric signal at various stages of the signal processing procedure. Only two of the three channels are presented for simplicity. (a) The top set presents the signal recorded with a bandwidth of 1–10 kHz. (b) The middle set presents the same record after undergoing compression. The numbers above the vertical separating lines (skipped interval markers) represent the time in ms which contained no useful information and was removed. (c) The bottom set presents the same record after it was digitally filtered with a bandwidth of 2 kHz (12 dB/oct) to 7 kHz (48 dB/oct) and zero phase. It is this latter set which is decomposed by the computer algorithm.

Signal Conditioning (Filtering)

The simple high-pass filter (6 dB/octave) at 1 kHz in the amplifiers was very effective in substantially reducing the amplitude of slow rise-time MUAP waveforms recorded from fibers more distant from the electrode. See Figs. 2 and 3(a). However, in approximately 50 percent of the signals analyzed to date additional filtering was found to be necessary to further reduce the superposition of MUAP waveforms. A symmetric, Hamming window, finite impulse response digital filter was found to be appropriate for the required task [25]. This type of filter has no phase distortion which could add undesirable extra phases (ringing) to the MUAP waveforms. Typically, the following parameters were found to be appropriate: a lower 3 dB point of 2 kHz with a 12 dB/octave rolloff and an upper 3 dB point of 7 kHz with a 48 dB/octave rolloff. An example of the effect of filtering on an ME signal utilizing these filter parameters is shown in Fig. 3. Various other filter parameter values have, however, been found to work better with some other ME signal recordings.

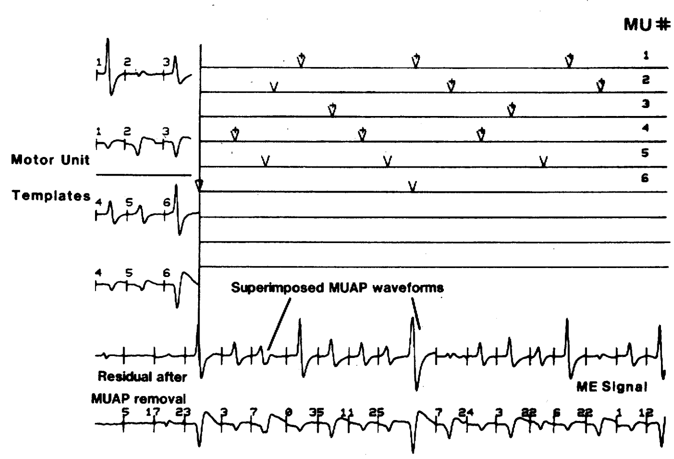

Fig. 4. A typical video terminal display of the decomposition procedure. The display of the third ME signal channel is optional. The *V* markers indicate the occurrence of a motor unit action potential. A plus (+) sign above the marker indicates that particular motor unit action potential waveshape was used to update the corresponding template displayed on the left side of the display. Note the decomposition of two superimposed motor unit action potentials.

The Decomposition Algorithm

The original goal was to develop a totally automatic computer algorithm to perform all of the data analysis; however, this has not been possible. The present computer program may be run automatically. However, the reliability and the number of MUAPT's which can be extracted is considerably less than when run interactively by an operator.

Fig. 4 shows a portion of the information displayed to the operator during the analysis of a segment of a record. For clarity, only two channels of ME signal are presented. The variety of features highlighted in this figure are discussed in the following sections. The basic operation of the decomposition algorithm may be described by the following four sequential steps.

Step 1: Locate the next MUAP waveform in the ME signal.

Step 2: Determine which one (if any) of the previously detected MU's has produced this MUAP waveform. Alternatively, the MUAP waveform may be skipped or designated as belonging to a newly recruited MU.

Step 3: Use this MUAP waveform and its time of occurrence to update the template and the firing statistics of the MU whose firing has been detected. The MU template is an estimate of the MUAP waveform which will be produced by a firing of the MU. If this MUAP waveform is produced by a newly recruited MU, the MUAP waveform is used as the initial estimate of the MU template. Both the MU templates and firing statistics are used in the decision-making process in the previous step.

Step 4: Remove this MUAP waveform (numerically subtract the template) from the ME signal, and return to Step 1. By subtracting the estimate of the MUAP waveform produced by the detected MU, other MU firings (usually producing lower amplitude MUAP waveforms) with which it is superimposed may also be detected. Thus, the program would ideally process the ME signal until the entire signal above a specified threshold is accounted for.

Each of these steps contributes to the overall efficiency and accuracy of the algorithm, as will be discussed in the following detailed description.

An Example of the Results Obtained by Using the System

A typical decomposed data set is presented in Fig. 5. The top plot, Fig. 5(a), presents the interpulse intervals of six concurrently active MU's whose ME signal was recorded with one needle electrode. The force of the contraction generated by the muscle while the ME signal was recorded is superimposed and shares the same horizontal time scale. Fig. 5(b) presents the corresponding mean firing rates of the same six MU's. These mean firing rates were calculated by passing an impluse train corresponding to the MU firing times through a low-pass filter with a symmetric, unit-area, impulse response. A Hanning window was used as the filter impulse response because it achieves a minimum stopband attenuation of 41 dB and has a nonuniform weighting, giving greater importance to the firings closer to the instantaneous time for which the mean rate is computed.

Although the data displayed in Fig. 5 appear to be proper and their behavior are consistent with previously reported similar data of many investigators (see De Luca [5] for a review) it remains to be verified that the decomposition program described in this paper is, in fact, functioning reliably and accurately. This aspect will be discussed in the accompanying paper [19].

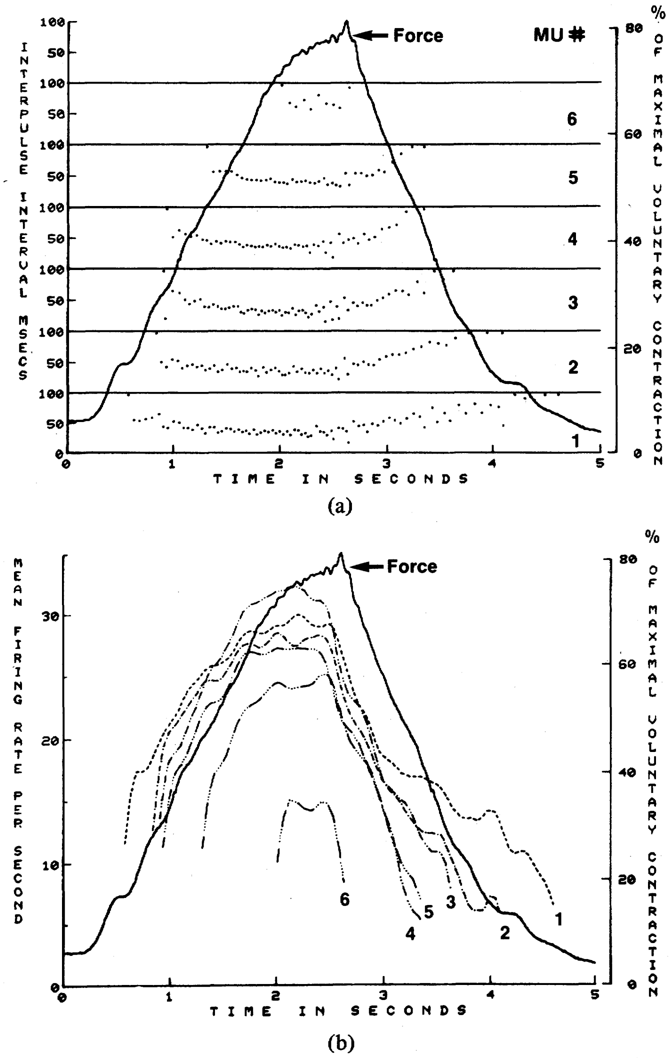

Fig. 5. (a) Interpulse interval records of six concurrently active motor units decomposed from a myoelectric signal recorded from the middle fibers of the deltoid muscle while the subject was exerting an isometric abduction generating the displayed force. Each interpulse interval record has a separate vertical scale ranging from 0 to 100 ms. Each point corresponds to a motor unit action potential discharge, with the vertical displacement corresponding to the value of the interpulse interval between each adjacent motor unit action potential. (b) The firing rates of the motor units corresponding to the top plot. See text for details of calculations.

Detailed Description and Theoretical Discussions

Basic Method for the Detection of Motor Unit Firings

The detection of the occurrence of a particular MU's firing is based upon the *maximum a posteriori* probability receiver theory which is discussed in detail by Van Trees [31], Wozencraft and Jacobs [33], and others. Although the computations involved are quite similar, there are substantial differences in the *a priori* information and assumptions. The assumptions from which the theoretical computations are derived are as follows:

1) One and only one of M signals is present, from known time t to time $t + T$.

2) The exact waveform (template) of each signal is known. Each of these templates is of time duration T.

3) The probability of each signal's presence is known.

4) The received waveform is perturbed only by additive, zero mean, Gaussian distributed, white noise with a known spectral density of $N_0/2$.

The *maximum a posteriori* decision algorithm may be summarized as follows. Let "i" represent one of the M possible signals. The *a priori* probability for the occurrence of this signal is denoted by P_i. The template for this signal is represented by the array $\vec{s_i}$. The template is the exact waveform which would be received (appear in the ME signal) in the absence of noise. The received waveform is denoted by the array $\vec{r}$. These arrays may be either single channel or multiple channel since the mathematical derivation does not depend on the number of channels. All arrays throughout this discussion will therefore represent the set of MUAP waveforms on all three ME signal channels. Among these M possible signals $(\vec{s_i})$ the one (ith) for which the following computation results in the least value is detected as the one that had been transmitted (MU that fired):

$$|\vec{r} - \vec{s_i}|^2 - N_0 \ln (P_i).$$

The first term represents the squared signal space distance between the received waveform and the ith template. The second term weights this decision by P_i. If all the P_i terms are equal, this term has no effect. If they are unequal, the level of the noise (N_0) controls the influence of the probabilities on the decision.

The extremes of the decision-making process performed by these computations may be thought of in the following terms. If the received waveform is near (in signal space) to one of the templates and far from all the others, the P_i terms are essentially ignored and the signal with this template is chosen. If, however, the received waveform is approximately the same distance from two or more of the templates, and far from the others, the decision will be based more heavily on the relative magnitude of the P_i values of the near signals. This situation will occur most often in an ME signal when the MUAP waveforms produced by two or more MU's are very similar. If the waveforms are distinct, this problem would be avoided. For this reason, multiple channel ME recordings are used to attain greater signal space distances between waveforms produced by different MUAP's.

In reality, none of the assumptions used in the derivation of the *maximum a posteriori* algorithm applies precisely to the recorded ME signals. The major differences and the steps taken to deal with these differences are as follows:

1) None, one, or more of the M signals may be present in addition to possible unknown signals, all of which may be superimposed in the same time interval with various relative time offsets. The inclusion of an acceptance region (to be discussed later) for the detection of an MU firing was necessitated by this problem. The beginning and duration of the time intervals are also unknown. A peak detection algorithm and variable length templates are used to deal with this problem.

2) Only an estimate of the template of each of the M signals is known. A continual update of the template estimate is used to cope with this problem. An MU's action potential waveform may also vary substantially from one occurrence to the next. These variations are greater when the MUAP waveform actually arises from two or more of the MU's fibers at approximately the same distance from the electrode and, thus, of similar amplitude contribution. The variable latencies (often referred to as end-plate jitter) in the onset of the individual muscle fiber action potentials may produce large uncorrelated changes in the compound MUAP waveform from one firing to the next. An example of this occurrence is presented in the raster display in Fig. 1 of the accompanying paper [19].

3) The random process is nonstationary and only an estimate of the probability of each signal's presence can be made. Also, since this computation is based upon the last firing-time of each MU, an immediately preceding incorrect detection will significantly affect this estimate. Therefore, errors are not independent. This problem is dealt with by using an acceptance region to make a false detection highly unlikely, and using a probability weighting function which includes the possibility of missed detections. The use of the visual detection by the operator also significantly reduces the number of detection errors, thus increasing the accuracy of the probability estimates.

4) The perturbing noise is not white. When few (less than three) MUAPT's are present in the ME signal, much of the noise actually results from variations in an MUAP waveform from one firing to the next. When a greater number of MUAPT's is present, the additional noise is also produced by many low amplitude MUAP waveforms. Although the number of these low amplitude MUAP waveforms is sufficient to produce a significant noise level, there is not a sufficient number to permit the noise to be modeled as shot noise. The algorithms for determining which MU has fired have therefore been modified. The computations used are similar to those previously discussed, differing primarily in the first-squared error term.

During the preliminary data anlysis it was found that the absolute change in a MUAP waveform from one firing to the next was roughly proportional to the waveform amplitude. Thus, the computation of the squared error to signal-power rato (E/S) for each template is the criterion used, rather than squared error (used in the *maximum a posteriori* equation). The resulting expression to be minimized with respect to the ith MU is thus

$$\frac{|\vec{r} - \vec{s_i}|^2}{|\vec{s_i}|^2} - w \cdot \ln (P_i).$$

In this expression, $\vec{s_i}$ is a shortened version of the template of the ith MU. The tails of the templates (MUAP waveforms) are not used. This permits accurate detection of one MU's firing when the MUAP waveform of another MU is slightly superimposed (overlapping on the tails). To actually perform this computation for each MU, the peak (greatest absolute value) of each MU template $\vec{s_i}$ is aligned with the peak in the waveform $\vec{r}$. Since the peaks do not occur at the same point in the different templates, and the templates are usually of differing length, the $\vec{r}$ used for the computation for each MU consists of a slightly different set of points (although many are the same). If the $\vec{r}$ used for each of the $\vec{s_i}$ were the same, the squared error term could be expanded to derive a matched filter (Van Trees [31]; Wozencraft and Jacobs [33]).

The value of P_i in the probability weighting term is determined from the "detection" hazard function computation discussed below. The noise level weighting value w (N_0 in the *maximum a posteriori* equation) is unitless in this equation since the E/S error term is a relative error. Rather than estimating the value of w from the ME signal, the value is set by the operator to control the degree to which the probability weighting affects the decision, typically at a value of 0.02.

A Priori Probability Weighting

The time sequence of firings of each MU is modeled as a renewal process with Gaussian distributed intervals. Both the mean ($\bar{t}_i$) and variance (σ_i^2) of the distribution for each MU are permitted to vary with time. The method used to estimate these parameters is based upon a recursive (Kalman) filter. These computations use the current values (old) and the most recent interpulse intervals (IPI's) as follows:

$$\bar{t}_i\,(\text{new}) = (1 - 1/N) \cdot \bar{t}_i\,(\text{old}) + (1/N) \cdot \text{IPI}$$

$$\sigma_i^2\,(\text{new}) = (1 - 1/N) \cdot \sigma_i^2\,(\text{old}) + (1/(N-1))\,(\text{IPI} - \bar{t}_i(\text{new}))^2$$

The value of N used is typically 10.

The relative probability of occurrence of a MUAP from each MU can be approximated from these parameters using computations derived by LeFever [18] and referred to as the detection hazard function ($z_i(t)$):

$$z_i(t) = \frac{(1-p) \cdot \sum_{n=1}^{\infty} n^{-1/2} \cdot p^{(n-1)} \cdot \exp\left(-(t - n \cdot \bar{t}_i)^2/(2n\sigma_i^2)\right)}{(2\pi\sigma_i^2)^{1/2} \cdot (1-p) \cdot \sum_{n=1}^{\infty} p^{(n-1)} \cdot Q((t - n \cdot \bar{t}_i)/(n\sigma_i^2)^{1/2})}$$

where

$$Q(x) = \int_x^{\infty} \frac{\exp(-u^2/2)}{(2\pi)^{1/2}}\,du$$

where p is the probability of a missed detection (typically set by the operator at 0.1). Since the error function $Q(x)$ cannot be evaluated in closed form, a numerical approximation is used [18]. For each MU, the value of P_i, used in the probability weighted error computation, is determined by evaluating the detection hazard function for the time interval since the last detected firing of that ith MU, t_i. Thus

$$P_i = z_i(t_i).$$

The Motor Unit Templates

Each MU's template (see Fig. 4) is an estimate of the MUAP waveform (amplitude and shape on all three channels) which will be produced in the ME signal due to the next discharge of the MU. Prior to the analysis of an ME signal record, both the number of different MU's whose firings can be detected and their corresponding MUAP waveforms are unknown. Therefore, all templates must be created during the decomposition.

When either the operator or computer (only in fully automatic mode) has decided that a waveform in the ME signal is produced by an action potential of a "new MU," a new template is created. The term "new MU" is used nonrigorously. The new MUAP waveform may be from an already firing, although previously undetected, MU which has increased in amplitude (due to electrode movement) until it now exceeds the scan threshold. If the amplitude of this MUAP waveform is significantly greater than the scan threshold, a newly recruited MU has probably been detected. If not, subsequent analysis of the firing pattern will permit the distinction between a newly recruited and an already firing MU to be made.

The best estimate for the new template is the new MUAP waveform itself. Subsequent estimates are made using computations similar to that for estimating the mean interpulse-interval. The new estimate of the template is computed using the following formula:

$$\vec{s_i}\,(\text{new}) = (1 - 1/N) \cdot \vec{s_i}\,(\text{old}) + (1/N) \cdot \vec{r}.$$

The value of N depends upon the number of previously detected waveforms used to estimate the template, beginning with the value one and reaching a maximum of (for example) four on the fourth or subsequent update. An update is only performed if the normalized signal space distance of the ME signal waveform $\vec{r}$ from the entire template $\vec{s_i}$ (including the MUAP waveform tails) is below a preset threshold. Thus, if

$$\frac{|\vec{r} - \vec{s_i}|^2}{|\vec{s_i}|^2} < 0.15 \qquad \text{(typical value)}$$

an update of the estimate will be made. If not, the program proceeds immediately to the routine which removes the MUAP waveform from the ME signal.

When the operator makes the assignment (detection) of a waveform in the ME signal as the firing of a particular MU, he must specify whether the assignment template should be updated. In addition, he also has the option of completely replacing the template with the received waveform. A plus (+) sign, as shown in Fig. 4, indicates that the ME signal waveform was used to update the template. After the update of the template estimate has been completed, the new template is used to remove the MUAP waveform from the ME signal.

Confirmation of a Detected Motor Unit Firing

The random superposition of two or more differing MUAP waveforms may produce a complex waveform that may actually be closer in signal space (within the time window of the templates) to some other previously identified MUAP not actually present, even in the absence of noise. The peak that has been detected may also have arisen from only the background noise. Alternatively, the MUAP detected may actually be produced by a newly recruited MU, for which no template has been established. For these reasons, a detection is confirmed only if the signal space location of the ME signal waveform is within predetermined boundaries about the best-match template, that is, if the waveform in the ME signal is sufficiently similar to the template on both an amplitude and shape basis. This signal space region will be referred to as the acceptance region.

The *acceptance region* can be specified by using a two dimensional representation to compare the ME signal $\vec{r}$ with the template $\vec{s_i}$ of the tentatively detected MU firing. The ME signal is represented by two scalar values: A, its relative amplitude colinear with the template; and XN, its relative amplitude orthogonal to the template (caused by dissimilar shape and/or noise).

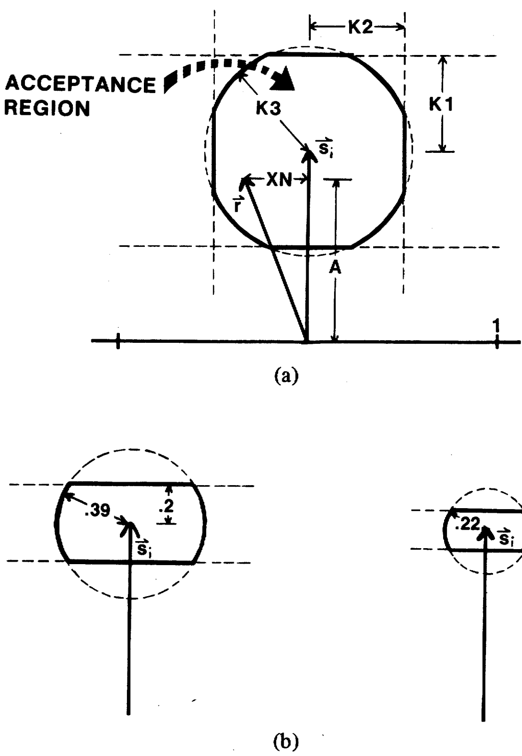

Fig. 6. (a) Generalized schematic representation of the acceptance region for an automatic detection of motor unit discharges. (b) Normal acceptance. (c) Tight acceptance region. All coordinates are normalized such that $|\vec{s_i}| = 1$.

These are computed as follows.

$$A = \frac{\vec{s_i} \cdot \vec{r}}{|\vec{s_i}|^2}$$

$$XN = \left(\frac{|\vec{r}|^2}{|\vec{s_i}|^2} - A^2\right)^{1/2}$$

Various two dimensional acceptance region could be established based upon these parameters. The program will confirm a detection if all of the following conditions are met:

$$|A - 1| < K1$$

$$XN < K2$$

$$(XN^2 + (A - 1)^2)^{1/2} < K3$$

The resulting acceptance region is shown in Fig. 6(a). The acceptance region used most often is shown in Fig. 6(b). The "tight" acceptance region, usually specified when differing MUAP waveforms are very similar, is shown in Fig. 6(c).

If the ME signal vector falls within the acceptance region, a detection is confirmed. If, however, the ME signal vector is beyond the acceptance region, the computer informs the operator (when the interactive mode is selected) of the best match, and then waits for instructions. The operator may then confirm the detection, specify one of the other MU's as the correct detection (according to arguments discussed in the accompanying paper by LeFever *et al.* [19]), or pursue one of the other options discussed below. When an MU firing is detected (either automatically or by the operator) a V is plotted at that point on the MU's firing time line as shown in Fig. 4.

Options Available Upon Failure to Match a Template

When the best template match to the ME signal waveform falls beyond the acceptance region, the number of the MU which achieved the closest match is displayed adjacent to the peak in the ME signal on a graphics video terminal. The operator must then select one or more of numerous interactive alternatives. See LeFever [18] for a detailed description.

The Superposition Algorithm

The purpose of the superposition routine is to resolve an ME signal waveform, formed by the summation of multiple MUAP waveforms. Only combinations of two waveforms and, thus, two templates are considered, since the computation time is prohibitive for more. The specialized recording techniques and predecomposition signal processing reduce the likelihood of a triple superposition to such a low level (usually less than 0.5 percent) that the use of such an algorithm cannot be justified. The scheme employed by the superposition decomposition algorithm is similar to the single template match criteria with the addition of a procedure which attempts to fit a second MU template to the residual error between the ME signal and each first MU template.

This is implemented as follows. Each template is aligned with the detected highest peak in the ME signal waveform, as would be done for a single match. An error buffer for each template is created by subtracting the template from the ME signal waveform (error buffer $= \vec{r} - \vec{s_i}$). An attempt is then made to resolve the remaining waveform in the error buffer with one of the other templates. The minimum-squared error which can be achieved between the error buffer of the ith MU and any other jth template ($|\vec{r} - \vec{s_i} - \vec{s_j}|^2$) is then used in place of the $|\vec{r} - \vec{s_i}|^2$ term in the probability-weighted error computation. A firing of the ith MU which minimizes this computation is then tentatively detected as would be done for a single match. The detection is confirmed if the value of the error term for this ith MU is below a preset threshold. (This is a simple form of an acceptance region.) The algorithm proceeds as though the MU firing had been detected by a single match. The template is subtracted from the ME signal, but is not updated. The second superimposed (jth) MUAP is detected after the program returns to scan the remaining ME signal, usually by the single match procedure. Quite often this remaining signal is sufficiently close to the template of this second MUAP to be used for updating.

Implementation and Programming Notes

The computer used in the implementation of this system was a DEC PDP 11/34 with a floating point processor option, 64K bytes of memory, an AD11 A/D converter, and a KW11 real time clock. A Tektronix 4012 computer terminal was used as the interactive "video" display. The programs were written primarily in Fortran with some subroutines written in assembly language to reduce the required processing time. The ME signal sampling and compression program was written almost entirely in assembly language. The digital filtering program used direct convolution (implemented in assembly language) rather than FFT techniques because a relatively short (usually 51 points) finite length impulse response was used. The decomposition program contains approximately 1800 lines of Fortran code and uses assembly language subroutines to perform the squared error computations.

Discussion

The technique described in this paper has been used to decompose ME signals recorded from the First Dorsal Interosseous and Deltoid muscles during constant-force and force-varying isometric contractions up to 80 percent of the maximal voluntary contraction. Up to eight concurrently active MUAPT's have been separated from the ME signal. The accompanying paper by LeFever *et al.* [19] describes a typical approach to executing the decomposition program. The accompanying paper also addresses the issue of reliability and accuracy of the decomposition procedure.

Due to the complexity of the myoelectric signal characteristics and the inherent variability of the MUAP waveform (shape) within a train from a single motor unit, it was not possible to devise a completely automatic decomposition procedure that would be reliable under all circumstances. Therefore, provisions were made for the decomposition program to request assistance from the operator in making decisions. However, when operator intervention is requested, the computer program can be directed to simplify the operator's decision by displaying only the waveforms in question, having removed previously identified waveforms. At this point the operator has available all previous statistics concerning the ME signal on which to base his decision.

Summary

The goal of the described system was to obtain the greatest level of accuracy in the detection of the firing times of as many concurrently active motor units as possible from the myoelectric signal detected by a single electrode. The described system consists of four main sections. First, a three-channel recording (from one needle electrode) is obtained. The signal is differentially amplified with a bandpass of 1-10 kHz. Second, the signal is digitized, compressed and stored on digital tape. The compression is performed to remove insignificant portions of the signal below a preset threshold level. Third, the stored signal is processed to minimize superposition of motor unit action potentials. This is accomplished by digitally filtering the signal with a Hamming windowed, finite impulse response filter having zero phase distortion. The shape of the digital filter is chosen by the operator to visually minimize superposition. Typically, the breakpoints and rolloffs of the filter are set at 2 kHz with 12 dB/octave and 7 kHz with 48 dB/octave. Fourth, an algorithm, developed and implemented on a PDP 11/34 digital computer, is employed to identify individual motor unit action potentials in the processed signal. The algorithm uses a continuously-updated template matching routine and firing statistics of the motor units to identify motor unit action potentials in the myoelectric signal. The templates of the motor unit action potentials are continuously updated to enable the algorithm to function even when the shape of a specific motor unit action potential undergoes variations.

Appendix
Alignment Errors Versus Sampling Rate

The sampling rate used in the digitizing of the ME signals is five to ten times the maximum frequency present in the EMG signal spectrum. Sampling at slower rates closer to twice the maximum frequency (Nyquist criterion) would produce poor results due to excessive alignment errors. The alignment errors occur because the sampled values of the ME signal waveforms are aligned with sampled values in MUAP templates. This means these two waveforms can be shifted with respect to each other only in integer increments of the sampling interval, thereby eliminating the possibility of perfect alignment. The error in alignment is, at worst, one half the sampling interval. The error to signal ratio (in the squared sense) can be computed from the following formula:

$$E/S = \frac{\int_{-\infty}^{\infty} (s(t) - s(t-T))^2 \, dt}{\int_{-\infty}^{\infty} (s(t))^2 \, dt}$$

where $s(t)$ is the signal (MUAP waveform) and T is the alignment offset. For example, when

$$s(t) = \begin{cases} \sin(2\pi \text{ ft}); & 0 < t < 1/f \\ 0; & \text{elsewhere} \end{cases}$$

(one cycle of a sine wave) a sampling rate equal to $4f$ would result in a maximal squared error of approximately 26 percent, yet under 5 percent for a sampling rate equal to $10f$. The greatest power density (spectrum mode) for this example waveform occurs at frequency f. Since this waveform has a shape somewhat similar to many MUAP waveforms, a sampling rate ten times the highest ME signal spectrum mode (up to 5 kHz has been observed in our data) was chosen.

Acknowledgment

We would like to express our gratitude to Prof. T. F. Weiss and Prof. W. M. Siebert for their continuous advice throughout this project. We are particularly grateful for the numerous contributions made by Dr. A. Xenakis.

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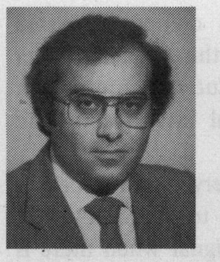

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