A TECHNIQUE FOR THE DETECTION, DECOMPOSITION AND ANALYSIS OF THE EMG SIGNAL

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The decomposition of the electromyographic (EMG) signal is the procedure by which the signal is separated into its constituent motor units action potential trains (MUAPTs). This concept is illustrated in Fig. 1. The development of a system to accomplish such a decomposition will be beneficial both to researchers interested in understanding motor unit properties and behavior, and to clinicians interested in assessing and monitoring the state of a muscle.

In the clinical environment, measurements of some characteristics of the motor unit action potential (MUAP) wave form (for example, shape, amplitude and time duration) are currently used to assess the severity of a neuromuscular disease or in some cases to assist in making a diagnosis. Thus,
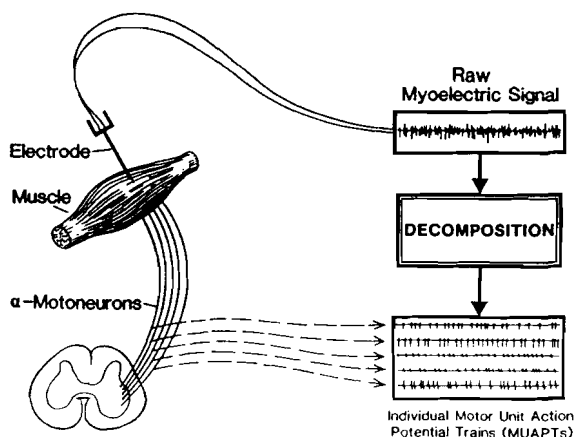

Fig. 1. A schematic representation of the decomposition of the EMG signal into its constituent motor unit action potential trains. (From De Luca et al. 1982; with permission of the authors.)

the decomposition of the EMG signal is useful in two ways. First, a partial decomposition must be implicitly performed by the clinical investigator to insure that what is actually observed is a MUAP and not a superposition of two or more MUAPs or some other ephemeral artifact. Second, averaging the MUAP wave forms present in the same train will produce a low noise representation of the MUAP and hence provide a more faithful representation of the events occurring within the muscle. Any decomposition scheme devised for such application (i.e., to extract only MUAP shape and amplitude) will have weak constraints on its performance. A useful technique should allow detection of some, but not necessarily all firing of a single unit in a particular record.

For physiological investigation, both the statistic of the inter-pulse intervals (IPI, time between two successive firings of the same motor unit) and the MUAP wave form characteristics are used to study motor unit properties and motor control mechanisms of muscles. In these conditions, much stronger constraints are imposed on the performance of a decomposition technique. It is desirable, in fact, to monitor the simultaneous activities of as many motor units as possible. Furthermore, all the firings of the observed motor units should be detected. Shiavi and Negin (1973) showed that an error of 1% in the detection of a motor unit firing prevented the observation of some relevant motor unit behavioral phenomena. Statistical analysis of IPI also implies acquisition and processing of relatively long EMG signal records (in the order of dozens of seconds) thus increasing the time required for the decomposition.

A decomposition technique satisfying the set of requirements for physiological investigations will also provide all the information currently used in clinical studies, as well as additional information on the temporal behavior of motor unit firing.

Due to the novel approach presented by this system, it is useful to clarify some points concerning the capabilities and applicability of this system:

(1) Not all the EMG signals acquired with this technique can be decomposed with a 100% accuracy. There are many factors which determine the suitability of any particular EMG signal record. Force level of the muscle contraction is not necessarily a major hindrance; EMG signals detected at near maximal force levels have been decomposed successfully. Far more important are the dissimilarity of the MUAP wave forms belonging to different motor units, the number of MUAPTs present, and the stability of the MUAP wave form during the record.

(2) The decomposition algorithm described in the following pages may be used in a variety of modes, ranging from fully automatic to highly human-operator interactive. The chosen mode of operation will determine the trade-off between the accuracy of the data and the amount of time required to perform a decomposition. For a record containing 6 MUAPTs, the time required to decompose the signal with 100% accuracy will range from 15 sec to 15 min for one-second of data, depending on the quality of the data. The same data may be decomposed in a fully automatic mode, requiring from 1 sec to 15 sec for one-second of data, but the accuracy of the decomposition would be approximately 65%. Additional 30 sec per one-second of data should be added to the above figures to take into account the pre-processing operations. These figures could be drastically reduced if the system were redesigned with emphasis on minimal processing time.

(3) As many as 12 MUAPTs from simultaneously active motor units have been decomposed accurately from an EMG signal. To date, the longest EMG signal record that has been decomposed accurately was 144 sec long and contained approximately 7000 discharges of 4 motor units.

(4) The signal conditioning which is performed

in various phases of the system modifies the wave form of the MUAPs. Therefore, standard measurements of the MUAP wave form such as amplitude, time duration and number of phases may not be compared to those of conventionally acquired and recorded EMG signals. However, it is important to note that such information may be easily made available by using the cannula of the needle or one of the wire surfaces for acquiring EMG signals in a conventional manner, and using the event timing from the decomposed MUAPTs to trigger average the conventionally obtained signal. This suggested procedure is similar to the 'macro' EMG signal technique described by Stålberg (1980) with the additional advantage of recovering the wave form of many MUAPs, rather than only one as in the case for Stålberg's technique.

(5) The purpose of this paper is to provide a simplified presentation of the decomposition system and of the signal detection and recording techniques utilized to prepare the EMG signal for subsequent decomposition. References for a more detailed and formal presentation of the decomposition algorithm will be provided. Some statistical techniques for analyzing the decomposed MUAPTs will be discussed.

Background

In the past, several investigators have devised techniques to identify MUAPs from each motor unit action potential train contained in the EMG signal. The different techniques that have been employed may be generally categorized as either visual identification by the investigators (Gurfinkel et al. 1964, 1970; Masland et al. 1969; Clamann 1970; Person and Kudina 1971; De Luca and Forrest 1972, 1973; Maton and Bouisset 1972; Hannerz 1974; Kranz and Baumgartner 1974; Desmedt and Godaux 1977; and others) or automatic identification by electronic apparatus (Gerstein and Clark 1964; Simon 1965; Glaser and Marks 1966; Keehn 1966; McCann and Ray 1966; Friedman 1968; Leifer 1969; Schmidt and Stromberg 1969; Mishelevich 1970; Schmidt 1971; Dill et al. 1972; Shiavi 1972; Andreassen 1977; and others). Procedures that consist exclusively of visual analy-

sis limit the scope and accuracy as well as requiring a tremendous amount of time for performing the MUAP identifications and firing time measurements. The criteria upon which automatic identifications are based may be categorized as either feature extraction (peak amplitude, rise time, area, or other characteristics of the MUAP wave form) 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 wave forms produced by superposition of two or more simultaneously occurring MUAPs. Most automatic detection schemes also cannot accommodate a slow change in a MUAP wave form's shape or amplitude throughout a contraction. This latter consideration is important because the relative position of the recording electrode and active muscle fibers is subject to variation during a muscle contraction.

The system described in this chapter overcomes some of the limitations in the previous approaches and satisfies the requirements for physiological investigation as specified above. The initial description of this concept dates back to LeFever and De Luca (1978). A detailed description of the precursor system may be found in LeFever and De Luca (1982) and LeFever et al. (1982). The subsequent modifications, some of which are described in this paper, have been executed by B. Mambrito and J. Creigh and may be found in Mambrito (1983).

The major features of the system are: (1) multiple channel recording of the EMG signal to increase discrimination power among MUAPs; (2) recording bandwidth of 1–10 kHz; (3) highly computer-assisted recording and decomposition techniques; (4) slow variations in the shape of the MUAP wave forms and IPI statistics are allowed; (5) MUAP superposition can be decomposed in most cases; (6) means for on-line checking of the EMG signal quality in terms of decomposition suitability; (7) means for verifying the validity of the results.

The major limitations are: (1) only records derived from attempted isometric contractions have been decomposed; (2) in its current form, the technique may require interaction with a highly trained operator.

Signal acquisition and pre-processing

The EMG signal acquisition and quality verification system is depicted in Fig. 2. The system requires the capability of recording multiple independent channels of EMG signal. A special electrode to accomplish this task has been constructed based on the design of an electrode reported in an earlier study (De Luca and Forrest 1972). A schematic of the new light-weight quadripolar electrode may be seen in Fig. 3. It consists of 25-gauge stainless steel tubing having an opening in the wall of the shaft approximately 2 mm from the proximal edge of the tip. In this opening are exposed the cross-sectional areas of four 75 μm diameter insulated wires (90% platinum-10% iridium), located at the corners of a square and spaced approximately 200 μm apart. This geometrical arrangement was chosen so that the activity from 4 or 5 motor units would be consistently detected in most muscles. Note that the detection surfaces are removed from the needle tip to allow MUAP detection from uninjured muscle fibers.

Fig. 3 presents one of several possible combinations providing 3 differential channels of EMG signal. The lines A, B, C, D, E are individually shielded and fed into 5 high-input-impedance front-end buffers (10^{12} Ω input resistance and 25 pA bias current) and are successively fed into a set of 4 differential amplifiers. For the purpose of decomposition, the differential amplifier outputs V1, V2, V3 of 3 channels are bandpass filtered using differential amplifiers with low and high frequency 3 dB points set at 1 and 10 kHz. The fourth channel, VC, may be differentially amplified with a bandwidth of 20 Hz to 10 kHz, providing a conventional EMG signal from which the conventional wave forms of the MUAP may be recovered by trigger-averaging from the decomposed MUAPTs.

The procedure of setting the lower 3 dB point at 1 kHz rather than at a lower frequency is consistently observed to reduce the amplitude of the slower rise-time MUAP wave forms produced by muscle fibers distant from the recording site. As indicated in Fig. 2, the outputs of this last stage of amplification and filtering (the block indicating the amplifiers and filters) are viewed on an oscillo-
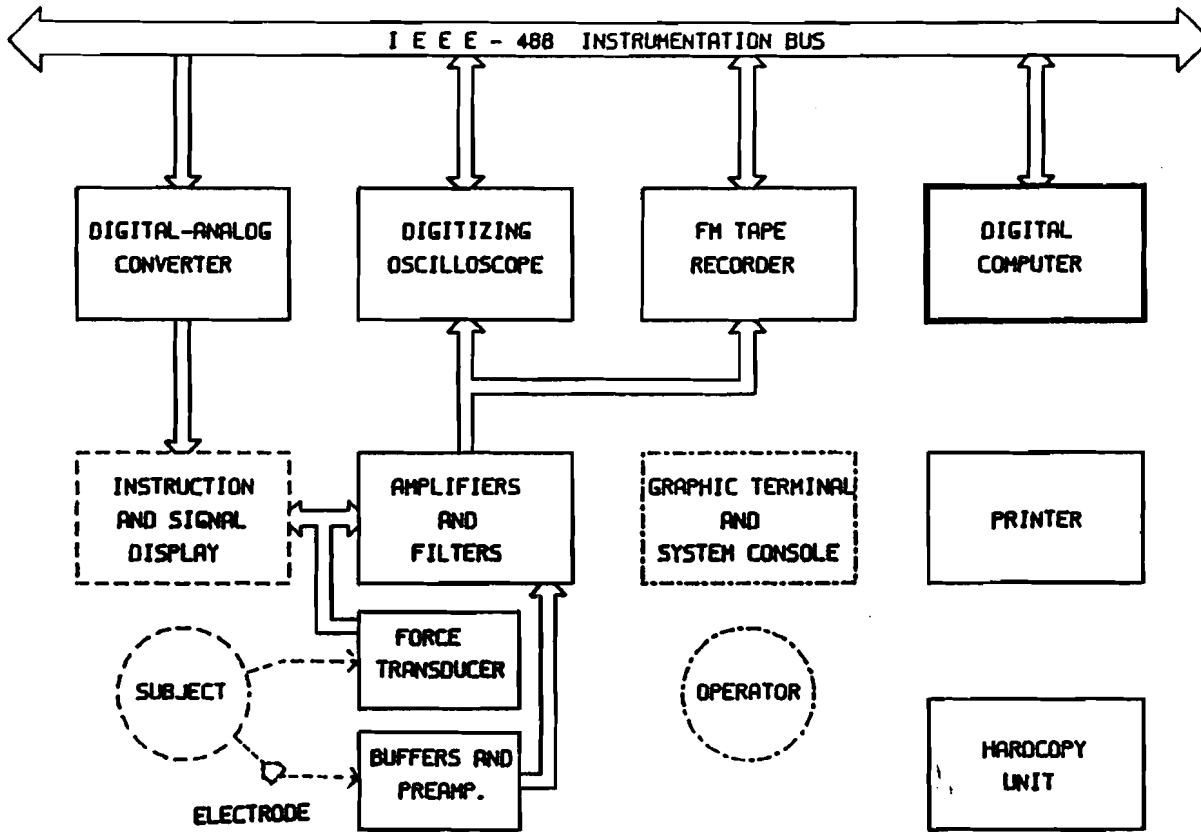
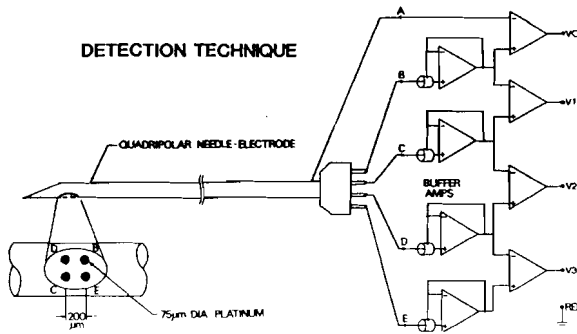Fig. 2. EMG signal acquisition, quality verification and decomposition system.

Fig. 3. A schematic representation of the light-weight quadripolar needle electrode configured to detect 3 independent channels of EMG signal V1, V2, V3 for the purpose of decomposition. A fourth channel VC is also displayed for the purpose of simultaneously recording one conventional EMG signal channel.
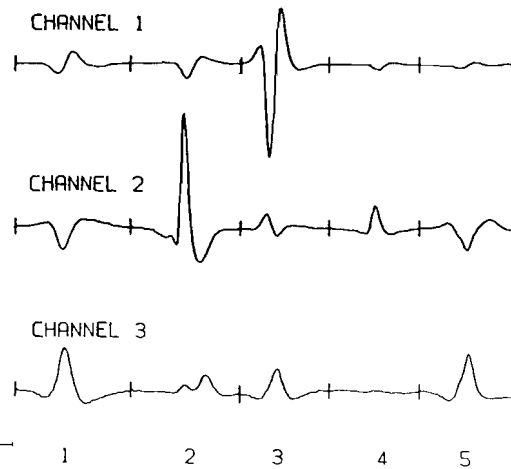

Fig. 4. Three-channel representation of action potentials from 5 different motor units. The 3 channels represent the same electrical event (MUAP) as seen from 3 different geometrical perspectives.

scope. When the oscilloscope is triggered by a MUAP arrival, 20 msec long segments of the signal are transmitted to the digital computer. These segments can then be plotted sequentially on the graphic terminal and decomposition attempts can be made. These operations enable the operator to assess the spatial discrimination among MUAP wave forms and the stability of the recording, i.e., to make a judgment on how convenient it is to decompose that particular EMG signal. If sufficiently high quality EMG signals are detected, the data collection may proceed, otherwise the electrode(s) should be repositioned. During an experiment, the outputs of the last stage of amplification and filtering are recorded on an FM tape recorder at a sufficient speed to provide a bandwidth up to 20 kHz. With this arrangement it is possible to obtain MUAP with peak-to-peak rise times as short as 100 μsec.

The main advantage of multiple channel recording is to increase the discrimination power among different MUAPs. This fact is *absolutely essential* for performing a correct decomposition. The necessity of this feature is dramatically illustrated in Fig. 4, which contains segments of 3 channels of simultaneously detected signals with MUAPs from 5 motor units. Note that in channel 1, MUAPs nos. 4 and 5 have similar wave forms; such is also the case for MUAPs nos. 1 and 2. On channel 2, MUAPs nos. 3 and 4 have similar representation whereas, MUAPs nos. 1 and 5 have similar wave shapes on channels 2 and 3. And finally, MUAPs nos. 1, 3 and 5 have similar representation on channel 3. It is apparent that any identification and decomposition technique attempting to make discrimination among several simultaneously active motor units using only one channel of information will not be accurate.

The analog signals are transferred off-line to digital storage. Due to the signal processing method to detect firings, a sampling rate higher than the Nyquist frequency (which is twice the maximal signal frequency, in this case 10 kHz because of the wideband recording technique) is recom-
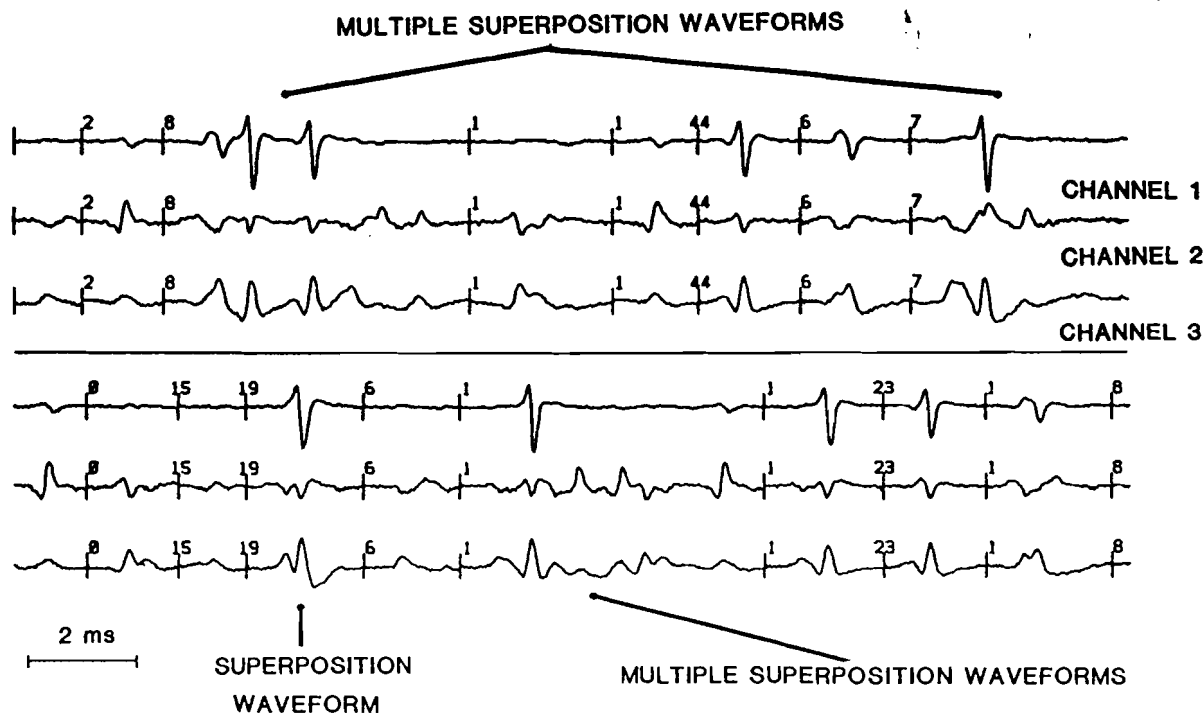

Fig. 5. An example of 3 channels of a real, filtered and time compressed EMG signal. The numbers above the vertical separating lines (skipped interval markers) represent the time in milliseconds which contained no useful information and was removed.

mended. A typical sampling rate value is 50 kHz, which may be conveniently achieved by playing back the EMG signal slower than it is recorded and sampling it at the appropriate rate (50 kHz divided by the speed reduction factor). The computer program that samples data stores only those segments of data containing positive or negative peaks above a preset threshold. This threshold is selected by the operator dependent upon the level of background noise in the data. The portions of data intervals between stored segments are stored only as a number of skipped samples. This method reduces the storage requirements from 5 to 20 times less than uncompressed storage. An example of compressed EMG signal is shown in Fig. 5 where the numbers near the vertical bars indicate the number of milliseconds skipped between sampled wave forms.

The analog high pass filtering at 1 kHz is effective in substantially reducing both amplitude and the time duration of slow rise-time MUAP wave forms recorded from fibers distant from the electrode. However, it is sometimes useful to further filter the record to reduce the degree of superposition among MUAPs by further shortening their time duration. In such cases, a symmetric Hamming window, finite impulse response digital filter is used. This type of filter has no phase distortion which could add undesirable extra-phases to the MUAP wave forms. The parameters of the filter (high and low cut-off frequency and roll-off) can be chosen specifically for each record using the power spectrum of specific MUAP wave forms in the record as a guide.

The decomposition algorithm

Whenever a wave form is encountered in the EMG signal, one of the following events may occur in the decomposition algorithm:

(1) The detected wave form may be the MUAP of a specific motor unit. In this case the decomposition algorithm attempts to match the wave form with a set of templates representing the MUAPs of all the detectable motor units. The motor unit whose template provides the best match (single-template matching) is assumed to have fired

at the time of occurrence of the analyzed wave form. The single-template matching criteria are based upon the *maximum a posteriori* probability receiver theory, which has found wide applications in the field of Communications (Van Trees 1968). However, the theoretical detection algorithm has been derived under a set of assumptions, none of which, in practice, is exactly appropriate for the EMG signal. Thus, extensive modifications have been introduced in the original algorithm to adapt the theoretical case to the practical one.

(2) The detected wave form may be caused by the superposition (summation) of two or more MUAP wave forms. In the case of superposition of two MUAPs only, a superposition matching algorithm may be utilized. The scheme employed by this algorithm is similar to that of the single-template match criteria; with the addition of a procedure that attempts to fit a second motor unit template to the wave form obtained by subtracting the first template from the EMG signal. Triple or multiple partial superposition of MUAP wave forms can sometimes be solved by repeated application of the decomposition algorithm in various modes.

The superposition algorithm is particularly useful in clinical applications, because it can determine if polyphasic action potentials are indeed representative of an individual motor unit.

(3) The detected wave form may be the MUAP of a newly recruited motor unit for which a template has not yet been established. In this case the operator may utilize the detected wave form to establish a new template for the motor unit.

(4) The detected wave form may be produced by the background noise or by the firing of a motor unit whose MUAP is so small that it cannot be detected with reliability. In this case the wave form is skipped.

Whenever an unknown wave form is encountered the decomposition algorithm selects one of the above options and, if necessary, attempts to make a template assignment. Decisions are made automatically by the algorithm if specific numerical conditions are verified. Otherwise the decisions are delegated to the operator who may select a different set of options for the decision-making process of the algorithm, or the operator may

directly make a decision. There are two *basic* features which distinguish our decomposition algorithm from other previous attempts. First, the template shapes are automatically updated at each detection so that the algorithm can function even if the MUAP wave form shapes display slow variations during a contraction. Second, statistical parameters concerning individual motor unit firing times (the mean time interval between two successive firings of the same motor unit and variance of this interval) are used in conjunction with template parameters matching (shape, amplitude and time duration) to make single-template and superposition matching decisions. Under the assumptions of the maximum a posteriori receiver theory this allows decisions to be made with a *minimal probability of error*. However, the statistical parameters may vary with time and force during a contraction, thus they are also recursively estimated and updated at each detection.

In addition to the existing basic features, the algorithm has been implemented so as to provide the investigator with numerous options facilitating his/her involvement with the complex decomposition process.

The reader interested in the details of the decision mechanism, their mathematical formulation and their implementation is referred to LeFever and De Luca (1982), LeFever et al. (1982) and Mambrito (1983).

Test for consistency and accuracy

It is essential to assess the accuracy of any EMG signal decomposition system to validate the results obtained using such a technique. Furthermore, the decomposition technique may be highly interactive and during decomposition many decisions may be made by the operator. Thus, it is also necessary to assess the consistency of the results produced by different operators.

The issue of the consistency is the simplest of the two, and it has been addressed by LeFever et al. (1982). Briefly, the following test was performed. Two highly trained operators (each with at least 400 h experience in decomposing EMG signals) and a third, less experienced, operator (16

h of EMG signal decomposition) were required to independently decompose the same EMG signal record which was considered 'difficult' (i.e., at the limit of the decomposition technique capabilities according to the two experienced operators). The EMG signal selected contained 5 MUAPTs which the skilled operators believed had been reliably detected. Both skilled operators were 100% in agreement for the detection of a total of 479 MUAPs from 5 motor units. The results of the untrained operator decomposition contained a total of 12 discrepancies with respect to the two trained operators. Since the original the consistency has been tested in a similar fashion on many other occasions. Complete agreement has always been obtained among operators having more than 300 h of experience with the technique.

The issue of the accuracy is much more complicated. It is impossible to measure the decomposition accuracy in an absolute sense, with real EMG signal, since occurrence times of all the MUAPs and precise definitions of all MUAP wave forms in the EMG signal are unknown *a priori*. So far, this limitation has been circumvented in two ways.

First, the accuracy was tested on synthetically generated EMG signal. For details on the procedure, to generate synthetic EMG signal and execution of the test, refer to LeFever et al. (1982). Briefly, the synthetic EMG was constructed by linearly superimposing 8 mathematically generated MUAPTs along with gaussian noise. The standard deviation of the zero mean gaussian noise was 40% of the peak amplitude of the smallest MUAP wave form. A segment of the synthetic EMG signal record used for the test is shown in Fig. 6. A skilled operator was able to decompose the record with an accuracy of 99.8%, incurring one error in a total of 435 classifications. This particular record is now used as a benchmark to identify the performance criterion of new operators.

Second, an indirect test of the accuracy of the decomposition technique on real EMG signal was obtained in the following way (Mambrito 1983). Two needle electrodes were inserted in the same muscle (tibialis anterior) about 1 cm apart. The two sets of EMG signals from the two electrodes were recorded simultaneously and decomposed.

Fig. 6. An example of mathematically synthesized and time compressed EMG signal used to test the accuracy of the decomposition system. As in the previous figure, the vertical lines are skipped interval markers and the numbers represent the milliseconds of time removed.

Some motor units presented motor unit action potential trains in both sets of signals. A comparison of the results from 3 different contractions with two 'common' MUAPTs per contraction showed 100% agreement for a total 1415 detections of the 'common' MUAPs. In this case, an undetected error in the results from the 'common' MUAP detections could occur only if a simultaneous error of the same kind (wrong classification of a MUAP or missed detection) is made in the decomposition of the two records. The chances of such an event are uncalculably small. Thus, the consistency of the decomposition data of the same units from two different electrodes provides an indirect measure of the accuracy in real data decomposition.

Implementation of the experiment control and decomposition system

The main experiment controller, as indicated in Fig. 2, is a PDP 11/34 digital computer with a floating-point processor and 64 kbytes of memory. A Tektronix 4012 with hardcopy unit is used as interactive graphic display and operator system

interface. A Tektronix 5223 digitizing oscilloscope is used to monitor the EMG signal and transfer segments of data to the, computer on-line. A Honeywell 5600 C FM tape recorder is used to record the EMG signal. The original decomposition program, developed on the PDP 11/34 under RT-11 operating system, is now implemented also on VAX 11/750 under VMS operating system, and new interactive features have been added to the program. Most of the programs for experiment control, data quality verifications, decomposition and data display are written in Fortran with some subroutines written in assembly language to reduce the processing time; and all the programs for data sampling are written in assembly language.

Time domain analysis of MUAP trains

(1) MUAP characteristics

In clinical environments, the wave form of the MUAP is used to provide what have become to be considered conventional parameters; these are: the amplitude, the time duration and the number of phases of the MUAP. These parameters are considered to carry information related to the state of

the muscle fibers. The decomposition technique described in this paper renders MUAP wave forms which are not comparable, in terms of amplitude, time duration and number of phases, to those which are acquired by conventional means. However, because a highly accurate representation of the timing events of the MUAPTs (decomposed from the EMG) is available, it is possible to obtain the conventional wave forms from the fourth channel (VC) presented in Fig. 3, which could be bandpass filtered in a conventional manner. The wave form recovery is realized in the following way. After decomposing the EMG signal from channels V1, V2 and V3 (see Fig. 3), the times at which the MUAP wave forms occurred may be used to mark the time periods at which the corresponding MUAP wave forms occurred in the sig-

nal from channel VC. The next step consists of removing from the noisy signals all the time periods which have been identified as containing the wave form. Then these time periods are averaged. The noise, being unrelated amongst the time periods will cancel out and the wave form contained in the time periods, being considerably similar, will be enhanced. If the noise in the averaged time periods is independent, then the improvement in the signal-to-noise ratio of the recovered wave form will be proportional to the square root of the number of time periods that are averaged.

The wave forms of a MUAP of one train obtained from the EMG signals that were bandpassed at 1–10 kHz are presented in a raster plot in Fig. 7. This figure is presented for the purpose of indicating that the wave form of the MUAP is not
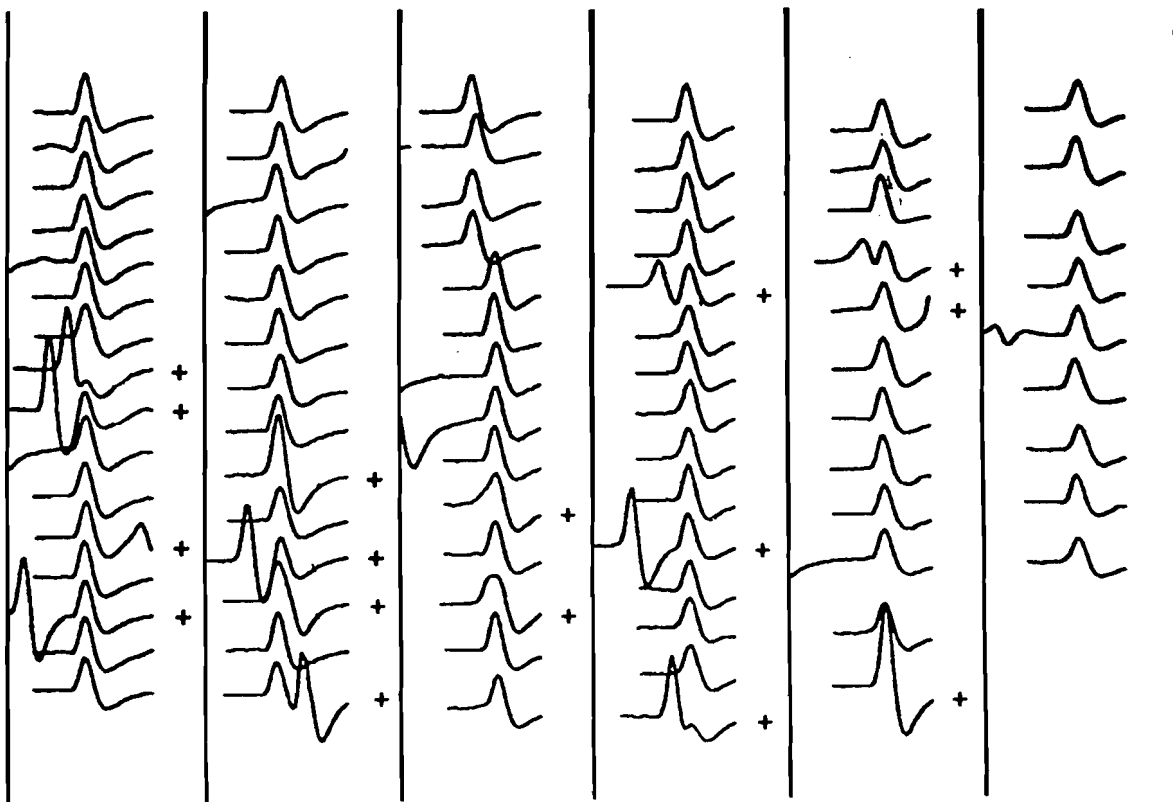

Fig. 7. An example of the MUAP raster plot. MUAPs (of the same motor unit) are shown as they are detected during the decomposition of the record. MUAPs are displayed sequentially in time from top to bottom and from left to right. MUAPs marked with a + sign represent superpositions of the displayed MUAP and of some other MUAP(s) present in the record and simultaneously firing with the detected MUAP.

stable during a contraction; even during an isometric constant-force contraction as was the case in this particular example. The plus sign represents situations when a superposition with MUAP of some other train occurred.

(2) MUAP arrival plots (IPI bar plot)

The arrival of MUAPs of the same motor unit is represented as an impulse on a horizontal line which expresses units of time since the beginning of the contraction. An example of such plot is presented in Fig. 8. Different horizontal strips correspond to different motor unit action potential trains. The continuous line represents the output force and it is scaled on the right vertical coordinate in percent of maximal voluntary contraction (MVC). This kind of plot is useful for event timing.

(3) Inter-pulse interval vs. time during the contraction plot (IPI dot plot)

The left vertical coordinate of each dot represents the time (in msec) since the last firing of the same motor unit. An example of such a plot is presented in Fig. 9 (top portion). Each horizontal division indicates the discharges of an individual
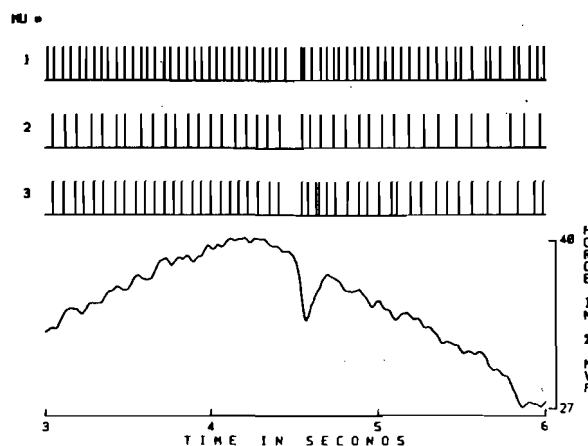

Fig. 8. Example of IPI bar plot. Each vertical bar represents the arrival of a MUAP at the time (since the beginning of the contraction) indicated on the horizontal line at the bottom of the graph. Each horizontal strip presents the activity of a different motor unit. The continuous line represents the output of the force transducer scaled on the right vertical coordinate in percent of maximal voluntary contraction (MVC).
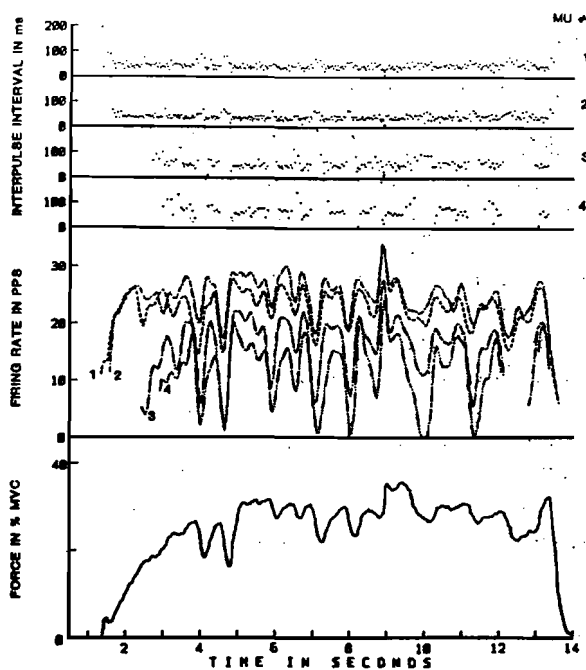

Fig. 9. Example of IPI dot plot (upper portion of the figure) and motor unit firing rate plot (middle portion of the figure). In the IPI dot plot, each dot represents a MUAP arrival at the time indicated on the horizontal coordinate. The left vertical coordinate is the time since the last firing of the same motor unit (in milliseconds). In the motor unit firing rate plot, the time varying mean firing rate of each detected unit is represented by different dot-dashed lines. The firing rate is measured in pulses per second on the left vertical coordinate. The continuous line in the lower portion of the figure represents the output of the force transducer scaled on the left vertical coordinate in percent of maximal voluntary contraction level (MVC). The mean firing rates were calculated from the IPI values ... the IPI dot plot.

motor unit; the horizontal coordinate of each dot represents the actual time of MUAP arrival. This kind of plot is very useful for identification of errors in the decomposition. In fact, isolated dots out of range (i.e., abnormally long or short IPI) are generally indicative of a missed detection or of a misclassification unless such an event is accompanied by an associated event in the force record.

(4) Mean firing rate plots

Having available the IPIs of a motor unit, it is possible to calculate the number of occurrences per unit time, that is the firing rate. This may be

obtained by passing the impulse train presented in the IPI bar plot (Fig. 8) through a non-causal Hanning filter with symmetric, unit area impulse response. Practical experience has indicated that a filter time length of 400–500 msec provides an acceptable and useful compromise between estimation bias and smoothness.

An example of the time-varying mean firing rate is presented in Fig. 9 (middle portion). For each motor unit the firing rate is represented by different dot-dashed lines. Values of the mean firing rate are scaled on the left vertical coordinate in pulses per second, and the horizontal coordinate represents the time since the beginning of the contraction. This kind of plot is useful for studying relationships among different motor units. In the example shown in Fig. 9 (lower portion of the figure), the continuous line represents the output force, scaled in percent maximal voluntary contraction on the vertical coordinate.

Investigations undertaken

Investigations undertaken in the past using the decomposition technique described in the present paper are fully reported in De Luca et al. (1982a,b); a brief summary is presented here.

The electrical activity of up to 8 concurrently active motor units has been recorded and decomposed from the human deltoid and first dorsal interosseous muscles. Concurrently active motor unit behavior has been examined during constant-force and triangular force-varying isometric contractions reaching 40 and 80% MVC. Experiments were performed on 4 normal subjects and 3 groups of highly trained performers (long-distance swimmers, powerlifters and pianists).

Results pertaining to the triangular force-varying isometric contractions revealed a highly ordered recruitment and decruitment scheme, based on motoneuron excitability, in both muscle and in all subject groups. Differences were observed between the initial (recruitment) and final (decruitment) firing rates in each muscle. These parameters were invariant with respect to the force rates studied, although some differences were observed among

subject groups. In general, firing rates of the first dorsal interosseous motor units increased steadily with increasing force (up to 80% MVC). The firing rates of deltoid motor units rose sharply just after the recruitment and then increased only slightly thereafter. The recruitment was found to be the major mechanism for generating extra force between 40 and 80% MVC in the deltoid, while rate coding played the major role in the first dorsal interosseus.

A computer cross-correlation analysis has been performed on motor unit firing rate and muscle-force output records obtained from both constant force and triangular force-varying isometric contractions. The temporal relationships between firing rate activity and force output have provided evidence that the deltoid of long-distance swimmers has a significantly higher percentage of slowly fatiguing fibers than that of normal subjects. Results showed that both muscles are uncapable of producing a purely isotonic contraction under isometric conditions. Small force variations at 1–2 Hz result from a common drive to all active motoneurons in a single muscle pool. Rapid force reversals during triangular, force-varying isometric contractions appear to be accomplished through a size-related motor unit control scheme. All firing rates decline prior to the force peak, but small motor units with slow-twitch responses tend to decrease their firing rates before large, fast-twitch motor units. This mechanism is not visually controlled and does not depend on force rate in non-ballistic contractions.

Another investigation which made full use of the entire system described in the present paper has recently been completed. This research documents an interplay between recruitment and rate coding of muscle output. The recruitment of a new motor unit has an inhibitory influence on the firing rates of previously activated motor units. This effect is likely to be mediated, at least partially, via the stretch reflex loop and possibly the recurrent inhibition mediated by the Renshaw cells.

Investigations recently completed (Mambrito 1983) involve simultaneous recording from two antagonist muscles to study relationship among simultaneous active units in different muscles.

Summary

In the present paper we have described a system for acquiring, processing and decomposing EMG signals for the purpose of extracting as many motor unit action potential trains as possible with the greatest level of accuracy. This system consists of 4 main sections.

The first section consists of methodologies for signal acquisition and quality verification. Three channels of EMG signals are acquired using a quadripolar needle electrode designed to enhance discrimination among different MUAPs. An automated experiment control system is devised to free the experimenter from the burden of experiment detailed surveillance and bookkeeping; and to allow on-line assessment of the EMG signal quality in terms of decomposition suitability.

The second section consists of methodologies for signal sampling and conditioning. The EMG signal is bandpass filtered (between 1 kHz and 10 kHz), sampled and compressed by eliminating parts of the signal under a preset threshold level.

The third section consists of a signal decomposition technique where motor unit action potential trains are extracted from the EMG signal using a highly computer assisted interactive algorithm. The algorithm uses a continuously updated template matching routine and firing statistics to identify MUAPs in the EMG signal. The templates of the MUAPs are continuously updated to enable the algorithm to function even when the shape of a specific MUAP undergoes slow variations.

The fourth section deals with ways in which to analyze and display the results. The more frequently used representation formats are: (1) display of MUAP wave shapes; (2) impulse trains representing motor unit firings; (3) IPI plots where time interval between successive firings of the same motor unit is plotted vs. time of the muscle contraction; (4) firing rate plots where the estimated time-varying mean firing rate of the detected motor units is plotted vs. time of the muscle contraction.

The performance of the system has been tested in terms of: (1) consistency among results obtained by different operators; (2) accuracy evaluated on synthetic EMG signal; (3) indirect measure of accuracy on real EMG signal by comparing results pertaining the same motor unit action potential trains derived by two EMG signals, independently and simultaneously recorded from two different electrodes.

Résumé

Technique pour la détection, la décomposition et l'analyse du signal EMG

Dans cet article nous avons décrit un système pour acquérir, traiter et décomposer les signaux EMG afin de dégager le plus grand nombre possible de trains de potentiels d'action d'unités motrices (MUAP) avec la plus grande précision possible. Ce système comporte 4 parties principales.

La première partie concerne les méthodologies de l'acquisition du signal et la vérification de sa qualité. Les signaux EMG sont acquis sur 3 canaux en utilisant une électrode aiguille quadripolaire conçue pour augmenter la discrimination des différentes MUAP. Un système de contrôle expérimental automatisé est conçu pour libérer l'expérimentateur de la tâche de surveillance détaillée de l'expérience et de la tenue du procès-verbal, et pour permettre un contrôle en direct de la qualité du signal EMG en termes de validité de sa décomposition.

La seconde partie concerne la méthodologie d'échantillonnage et de conditionnement. Le signal EMG est passé par un filtre passe-bande (de 1 kHz à 10 kHz) échantillonné et compressé en éliminant la partie du signal inférieure à un seuil prédéterminé.

La troisième partie porte sur la technique de décomposition du signal, avec extraction des trains de MUAP du signal EMG à l'aide d'un algorithme interactif étroitement assisté par ordinateur. L'algorithme utilise une routine d'appariements de formes ajustée en permanence et d'évaluation statistique des décharges pour identifier ces MUAP dans le signal EMG. Les formes des MUAP sont continuellement actualisées afin de permettre à l'algorithme de fonctionner même lorsque la forme

d'une MUAP particulière subit des variations lentes.

La quatrième partie comprend les moyens d'analyse et de présentation des résultats. Les représentations les plus fréquemment utilisées sont: (1) présentation de la forme des MUAP; (2) trains de potentiels représentant la décharge de l'unité motrice; (3) graphiques d'intervalles entre influx, avec l'intervalle entre décharges successives de la même unité motrice porté en fonction du temps de contraction du muscle; (4) graphiques de la fréquence de décharge où la moyenne estimée de la fréquence de décharge est représentée en fonction du temps de contraction du muscle.

Les performances du système ont été étudiées en termes de: (1) reproductibilité des résultats obtenus par différents expérimentateurs; (2) précision évaluée sur des signaux EMG simulés; (3) mesure indirecte de la précision sur des signaux EMG réels en comparant pour la même unité motrice des résultats obtenus sur deux signaux EMG enregistrés indépendamment et simultanément par deux électrodes différentes.

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