Decomposition and Analysis of Intramuscular Electromyographic Signals

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Introduction

The clinical community has long shown interest in the concept of extracting as many *motor unit action potentials* (MUAPs) as possible from an intramuscular *electromyographic* (EMG) signal. Adrian and Bronk (1929) developed the first concentric needle electrode to identify both shape and firing rate of the MUAPs. Subsequent manual approaches of graphically measuring and quantifying the EMG signal evolved into computer-based techniques directed at identifying individual action potentials and discharge times by shape discrimination. The Precision Decomposition technique described in this chapter recovers all the usable information available in the EMG signal. The information can be conveniently grouped into two categories: morphology and control properties. Morphology describes the parameters of the MUAP shape such as the peak-to-peak amplitude, the time duration, the number of phases, and the area. These parameters are provided by the recovered Concentric and Macro MUAP. The morphology of the MUAP describes features that are related to the anatomical and physiological properties of the muscle fibers. These are the parameters which the clinician is accustomed to evaluating during a standard clinical EMG examination. The control properties of the motor units dictate the firing characteristics of the motor units. Therefore, the firing characteristics provide a description of how the motor units are controlled by the central nervous system and to some extent the peripheral nervous system. Clinically, they quantify upper motoneuron diseases.

The technique of Precision Decomposition has been under development by our group since the late 1970s. The first public description of it was in the form of an abstract published in the Abstracts of the Society for Neuroscience (LeFever and De Luca, 1978). The signal processing concepts which underlie the approach appeared in the IEEE Transaction of Biomedical Engineering (LeFever et al. 1982a, b). A more pragmatic description of the algorithms and workings of the technique was provided by Mambrito and De Luca (1984). This paper also described a generic foolproof method of measuring the accuracy of any decomposition technique. Stashuk and De Luca (1989) have provided an update on useful modifications and applications of the technique while De Luca (1993) recently provided a comprehensive, hands-on account of the methodology.

Principle

The term decomposition has been commonly used to describe the process whereby individual MUAPs are identified and uniquely classified from a set of superimposed *motor*

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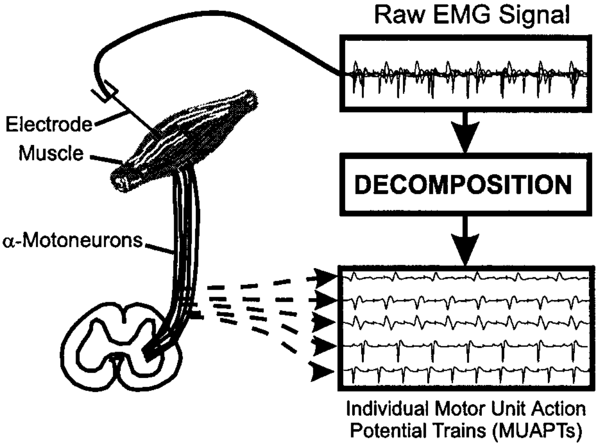
Fig. 1. Pictorial outline of the decomposition of the EMG signal into its constituent MUAPs (From De Luca et al. 1982a).



unit action potential trains (MUAPTs) belonging to concurrently active motor units. The concept of decomposition is depicted in Fig. 1. It involves the breaking down of the interference EMG signal that is recorded when more than one motor unit is active in the vicinity of the detection electrode. Identification refers to the categorization of the times of occurrences of the MUAP as well as the description of its morphological characteristics. From the above description it is apparent that the process of decomposing an EMG signal may range from a trivial task when only two MUAPTs with distinctly different MUAP shapes are present to a theoretical impossibility when many MUAPTs with nearly similar and unstable MUAP shapes are present.

A completely decomposed EMG signal provides all the information available in the signal. The timing information provides a complete description of the inter-firing interval (IFI), firing rate and synchronization characteristics; the availability of all the MUAPs which are discharged by a specific motor unit enables a more consistent expression of the shape by averaging the shape over a set of discharges.

Field of Application

The comprehensive, more accurate and more reliable information provided by decomposition finds applicability in both clinical and research environments. It is a new tool which enables us to explore the workings of the nervous system in normal and dysfunctional modalities. In the field of neurology, the ability to measure the behavior of firing rates and synchronization of motor unit discharges holds the promise of more analytically classifying dysfunctions of CNS origin. Consider the potential advantages of diagnosing a CNS abnormality by inserting a needle into a muscle with no direct assault to the CNS. The ability to obtain more reliable representations of MUAP shapes by averaging over several correctly identified MUAPs of an individual motor unit provides a more accurate basis for diagnostics based on morphological measurements. Furthermore, the capability of storing and measuring numerous MUAPs makes more convenient the laborious process of obtaining normative data. In fact, it enables individual laboratories to obtain their own normative data, thus allowing them to develop improvements in methodologies and approaches for measuring the characteristics of the MUAPs.

In the field of neurophysiology, the decomposition technique allows researchers to study the behavior of several concurrently active motor units and determine their characteristics beyond those relating to individual motor units and to discharge-to-discharge occurrences. It is now feasible to search for information transmission within the nervous system beyond individual neuron-to-neuron interaction. We can now explore more comprehensively and more effectively the orchestration of neuronal activation within and among muscles. It will be possible to execute these studies in the cooperative human performing voluntary contractions and without destroying the environment of the system under investigation. Furthermore, any enhancement of knowledge obtained from fundamental studies on the normal CNS can augment the clinical armament for performing diagnoses.

Scope

- Accuracy ranges from 85 to 100% depending on the complexity of the signal and the number of motor units.
- Able to decompose EMG signals detected up to 100% maximal contraction, nominally up to 80%; high threshold motor unit behavior may be studied.
- Resolves the occurrence of two or more superimposed MUAPs.
- Able to decompose up to 11 concurrently active motor units.
- Decomposition time = k(Accuracy)(Number of Motor Units)(Complexity of signal)

Unique Aspects of the Precision Decomposition

- Uses a special needle or wire electrode which has four detection surfaces, each 50 μm in diameter.
- The quadrifilar electrode detects Micro Signals. These are less selective than Single Fiber signals, but more selective than Concentric Signals.
- The Micro Signals are recorded with a bandwidth of 1 kHz–10 kHz.
- Use of quadrifilar wire electrodes allows for minor anisometric and long contractions
- May be operated in automatic or operator-assisted modes. Automatic mode is faster but less accurate.

Characteristics of the Precision Decomposition

- Morphological information of Concentric and Macro MUAPs when using needle electrode
- Control properties of individual motor units:
  - Dot Plot shows the duration of all IFIs of each motor unit. This plot may be used to study the behavior of the motor unit firings.
  - Bar Plot shows the location of all the MUAPs of each motor unit. This plot may be used to determine the recruitment and derecruitment threshold of a motor unit.
  - Firing Rate Plot shows the behavior of the firing rates of concurrent motor units.
- Groups of Motor Units:
  - Cross-correlation Plot shows the amount and relative latency of the cross-correlation (cf. Chapter 18) among the firing rates of concurrently active motor units.
  - Synchronization Plot shows the amount of synchronization between any pair of MUAPTs that have been decomposed.

Limitations

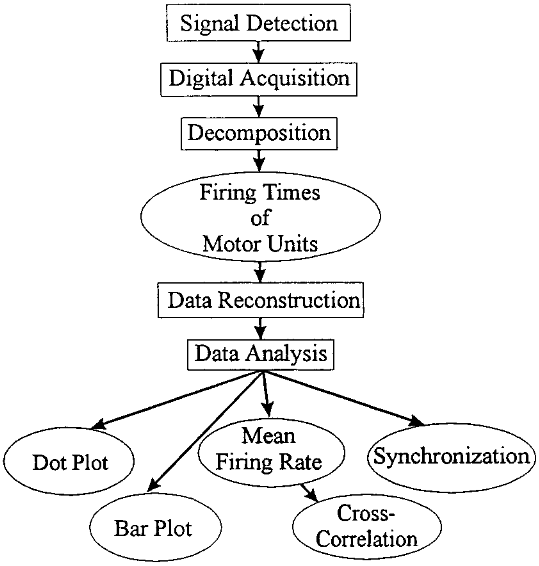
- With needle electrodes, use is generally limited to isometric contractions.
- With wire electrode, use includes slow dynamic contractions.
- Works only on EMG signals recorded during force rates less than 40% MVC/s.
- Can be challenging if the signal is complex and/or signal quality is low.

Outline

The decomposition procedure consists of the following components (See Fig. 2):

1. Signal detection
2. Needle positioning and needle movement
3. Signal acquisition and sampling
4. The decomposition algorithms
5. Data reconstruction
6. Data analysis and presentation.

Fig. 2. Flowchart of the decomposition process.



Materials

- Quadrifilar needle electrode or quadrifilar fine wire electrode
- Needle front end: Buffer amplifiers and differential amplifiers
- PC with high-speed data acquisition board
- Sampling and compression software
- Decomposition software
- Analysis software

Procedure

Signal Detection

An important feature of the signal detection segment of the Precision Decomposition consists of having a *special electrode* that simultaneously detects three channels of an EMG signal from the same proximity of muscle tissue. This is a fundamentally important aspect of our approach. The three channels of signals are necessary to reduce ambiguities in the decision making processes which are employed by the computer algorithms to distinguish among different MUAPTs in the EMG signal. This task is accomplished by a specially designed quadrifilar electrode. Two types of quadrifilar electrodes are used: one is a needle electrode and the other is a wire electrode.

Electrode Choice

The needle electrode has the following *advantages*:
- It may be used to obtain the morphological characteristics of the action potentials.
- It may be used for obtaining Macro EMG signals.
- It may be precisely located in the muscle.
- It may be manipulated to locate it in regions which provide high quality signals.
- It is useful for clinical studies.

It has the following *drawbacks*:
- It cannot be used for dynamic contractions.

- It is painful when recording from deeply located muscles.
- It cannot be left in the muscle for prolonged periods; typically 1 hour.

The wire electrode has the following *advantages*:
- It may be used with slow dynamic contractions.
- It is not painful.
- It may be kept in the muscles for prolonged periods (several hours).

It has the following *drawbacks*:
- It cannot be relocated, thus compromising the ability to explore locations which yield signals that are more decomposable.
- It may migrate during a contraction.

The Needle Electrode

See Fig. 3A for details of the needle electrode and means for connecting it to the amplifiers. The salient feature of this electrode is its four detection surfaces located in a side port of the needle cannula. The wires are either 50 µm or 75 µm in diameter (depending on the fiber density of the particular muscle being studied) and are correspondingly spaced either 150 µm or 200 µm apart on the corners of a square configuration. These configurations were determined by empirical tests which found these dimensions of the detection surfaces to yield the signal quality required by the decomposition algorithms. The detection surfaces are connected in bipolar configurations through differential amplifiers to provide three differential outputs, each carrying an EMG signal. We found that the electrode with the smaller detection surfaces is more selective and therefore better suited for use in muscles with higher muscle fiber density and for contractions at

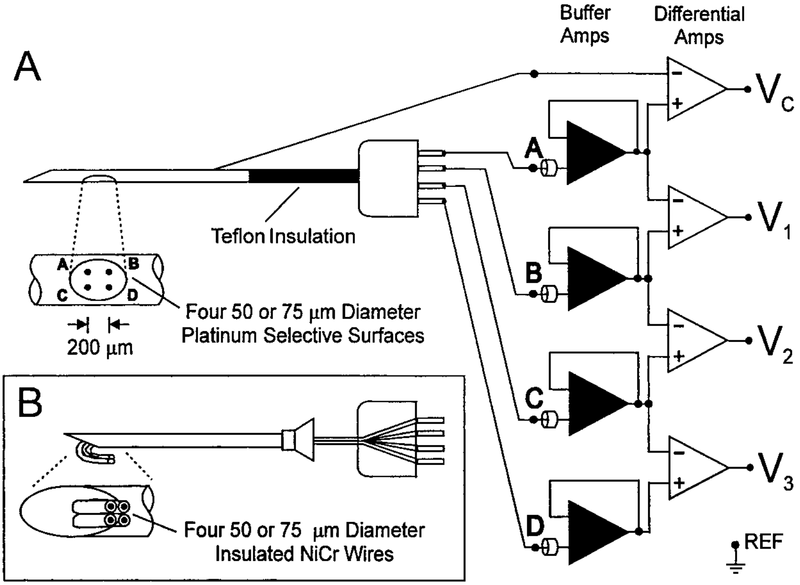


Fig. 3. A schematic representation of the electrode set-up for use in the Precision Decomposition technique. A) Quadrifilar needle electrode configured to detect 3 differential channels of EMG signals (V1 to V3) from the selective surfaces of the needle side port as well as an additional channel from the needle cannula (VC). Another needle configuration (not shown here) allows signals to be recorded from a concentric surface at the tip of the needle. B) Instead of the needle electrode, a quadrifilar wire electrode can be connected to the amplifiers. The wires are inserted into the muscle with a disposable hypodermic needle which is removed after the electrode is positioned. The distal end of the wires form a barb which helps to secure the electrode in the muscle. (Adapted from Mambrito and De Luca 1984)

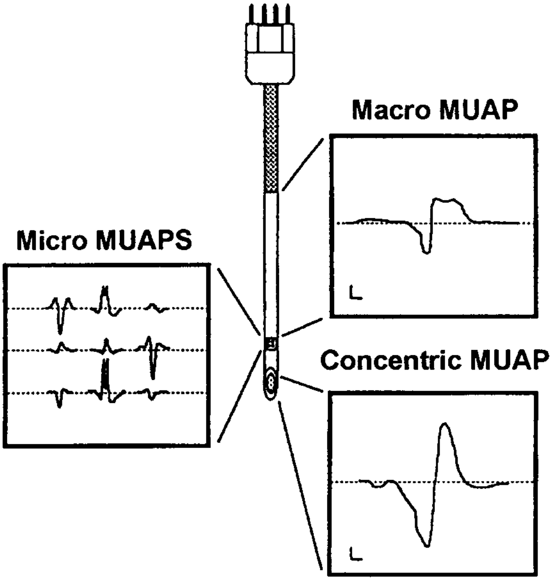


Fig. 4. Examples of the Micro, Macro and Concentric signals detected by the quadrifilar needle electrode. When using the quadrifilar wire electrode only the Micro signals are recorded. (From De Luca 1993)

higher force levels. The quadrifilar electrode is also able to detect either a concentric needle EMG signal, or via another configuration the Macro EMG signal. Examples of these arrangements are shown in Fig. 4. The concentric needle EMG is detected by a plug located at the tip of the needle. The detection surface of the plug has an area of 2.7 mm^2, the standard dimension used in concentric needles. Similarly, the Macro detection surface is standard size. Thus, depending on the configuration, a quadrifilar needle electrode detects three channels of EMG signals from the side port and either a concentric EMG signal or a Macro EMG signal for a total of four channels of EMG signals.

The Wire Electrode See Fig. 3B for details of the wire electrode and means for connecting it to the amplifiers. The electrode consists of four Nichrome or platinum wires coated with nylon. The diameter of the wire is 50 μm or 75 μm, depending on the required detection selectivity, the smaller wire configuration being more selective. The wire is cut in cross-section, exposing the minimal amount of area. The distal 1 mm of the wire bundle is curved forming a barb which assists in securing the electrode into the muscle.

Needle Positioning and Needle Movement

The highly selective nature of the quadrifilar needle electrode, which makes identification of several motor units possible, makes collecting stable EMG signals a challenging task. Small movements that may normally have little or no effect on signals detected with concentric or macro needle electrodes can have detrimental effects on the signals detected from the quadrifilar electrode. For this reason we have developed several techniques for inserting and positioning the quadrifilar electrode that minimize its movement and maximize signal quality.

Needle Insertion The most stable EMG signals are those that are obtained from a needle that is inserted oblique to the direction of the muscle fibers, typically at an angle of 30 degrees. If inserted more parallel to the muscle fibers, there tends to be more sliding of the fibers with respect to the electrode. At angles steeper than 30 degrees, there tends to be more needle movement due to shear forces on the cannula. To minimize needle movement, one has to find the angle where the shearing forces are just enough to act as an anchor on any fibers that may be moving. Our experience has shown this angle to be about 30 degrees. If possible, position the detection surfaces of the quadrifilar electrode so that they are near a motor point. In this region one finds MUAPs that propagate in opposite directions. When measured with the quadrifilar electrode, such MUAPs have opposite polarity. The difference in their MUAP shapes makes them easier to distinguish and decompose the signal.

Needle Rotation

Due to its unique design, the quadrifilar needle electrode requires a slightly different positioning technique than a standard concentric needle electrode. The detection surface on a concentric electrode is relatively large and located on the tip. Rotation of the electrode causes small changes in signal quality compared to inward and outward translations. This type of electrode is typically positioned by moving it inward and outward, making many needle tracks. The detection surfaces on the quadrifilar electrode are much smaller and located on a side port, rendering the electrode more sensitive to rotation. When positioning the quadrifilar electrode, it is helpful to rotate it back and forth as it is slowly inserted or withdrawn. This enables the experimenter to sample the maximum area, and minimizes the number of needle tracks.

Audio Feedback

Sound is a useful tool when searching for MUAPs. As the detection surfaces of the quadrifilar electrode are positioned closer to active muscle fibers, the signals tend to increase in amplitude and frequency. This is reflected by louder and sharper popping and crackling sounds when the signals are fed into an audio device. By using this audio feedback, the experimenter can concentrate on how he is positioning the electrode rather than constantly turning his head to look at a screen or oscilloscope. Consequently, better signals can be found faster.

Contraction Force

It may take several minutes to locate a position where the motor unit shapes are distinct. If the subject maintains a force level that is too high during positioning, the muscle will fatigue too quickly; if the force is too low, the needle will not give an accurate representation of how it will anchor itself in the muscle. When positioning the electrode, have the subject maintain approximately 10 % MVC and try to find two or three distinct motor unit shapes. Once a suitable position has been found, have the subject slowly increase the force level to the desired amount while monitoring the signal. Generally two or three more motor units will be observed. If the signal does not remain stable when the force is increased, try another position.

Stability

Perhaps the most difficult part of needle positioning is finding a signal that remains stable while the force level changes. Even during isometric contractions, there are slight movements of the muscle fibers relative to each other, the fascia, the skin, and the electrode. Unfortunately, these movements can cause signal instability. There are, however, several ways to deal with this. It is sometimes useful to watch how the needle moves and see how the signals change during a contraction. The needle can then be positioned such that the movement will improve signal quality. If this is not successful, hold the needle and keep it from moving. This tends to work better, but it can also create problems. Remember, one wants to keep the detection surfaces in a fixed position relative to the local muscle fibers. Thus, it is sometimes necessary for the needle to move with the rest of the muscle so that the detection surfaces can remain stable relative to the local fibers. Holding the needle may prevent this from occurring. In general, the most trouble-free signals are obtained from electrodes that are well secured in the muscle and are not held.

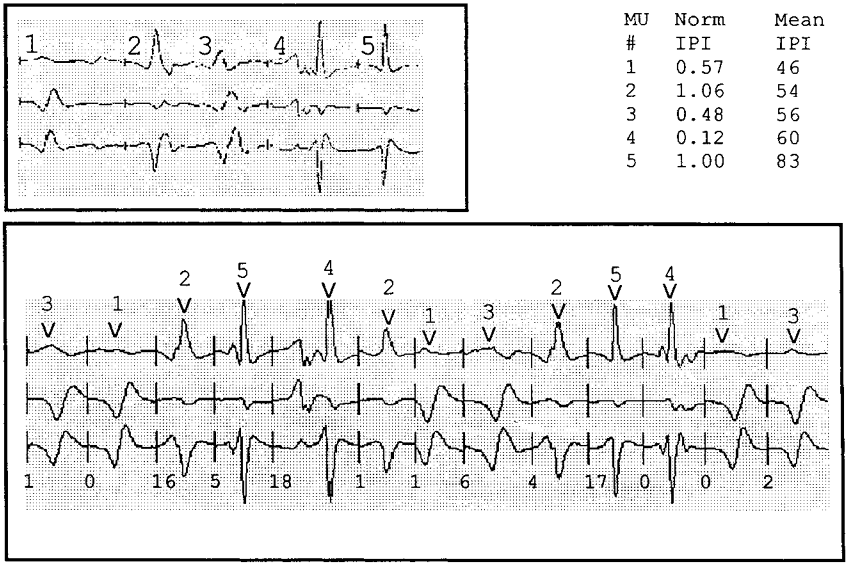
Signal Acquisition and Sampling

Amplification and Filtering

Any attempt to record an EMG signal should always amplify the signal as much as possible, without distorting the signal, prior to digitizing the signal. In doing so, the sampling resolution of the digitized signal is maximized because the full sampling range is used. The recommended procedure is to adjust the gains of the amplifiers to the value where the EMG signal is as large as possible without any clipping at its peaks. The signals detected from the fine wires at the tip of the needle or from the wire electrodes are band-limited to 1kHz to 10kHz. This is a unique feature of our decomposition procedure. It purposefully distorts the shapes of the action potentials, thus rendering them unfamiliar in appearance to the investigator, but particularly useful to the decomposition algorithms. The shapes become shorter and sharper in appearance; the tails of the MUAPs are considerably reduced in length, decreasing the chance of superposition among the different MUAPs. It is recommended that the concentric needle EMG signal be recorded with a bandwidth of 10Hz to 10kHz and the Macro EMG signal with a bandwidth of 10Hz to 1kHz.

Sampling Threshold

When the signal in any of the channels surpasses a preset threshold value, the signals are sampled and digitized. The threshold has a default value which has been found to be appropriate for a typical signal. By judiciously setting the threshold value, it is possible to improve the signal-to-noise ratio of the sampled signal that will be analyzed. This operation requires practice and is only recommended when the user has become familiar with the system. Efficiency in data storage is achieved by storing only those parts of the signal where there is activity above the threshold value. A complete time reference is provided by storing the amount of time between stored signal epochs represented by the number of skipped samples. Thus, no information pertinent to the decomposition process is lost. An example of the time-compressed data is presented in Fig. 5 (lower panel)



MU #	Norm IPI	Mean IPI
1	0.57	46
2	1.06	54
3	0.48	56
4	0.12	60
5	1.00	83

Fig. 5. TOP LEFT: Three-channel representation of motor unit (MU) templates from five different MUs. TOP RIGHT: Average IPI and normalized IPI for the MUs identified on the left. BOTTOM: Compressed three-channel EMG signal with assigned MU numbers. Vertical bars indicate skipped time intervals. Numbers below bars represent the skipped time in ms. Height of the bars represents the save threshold, i.e., minimum signal amplitude which is not skipped during the digitization process.

which presents a view of the screen during an operator-assisted decomposition. Note the vertical bars indicating the skipped time and the number of milliseconds skipped which appears directly below the skipped interval.

We have called the signals detected at the side port detection surfaces, Micro EMG signals. They are detected from a few (approximately 3 or 4) fibers per motor unit. Thus the Micro EMG signals are not as selective as those from a single fiber electrode, but are much more selective than those detected from a concentric electrode. The Micro EMG signals are sampled at a rate of 50 kHz. This sampling rate is well above the *Nyquist rate* (see Chapter 45). It is necessary to provide the required resolution of the MUAPs so that sufficiently accurate alignments can be made when comparing MUAPs in the decomposition algorithm. This is an important feature of the Precision Decomposition because the decision space is in the time domain. The concentric needle and macro EMG signals can be sampled at a lower rate, typically 2 kHz, because they have narrower frequency bandwidths.

The Decomposition Algorithms

The decomposition routines are complex rule-based algorithms which have evolved over a period of two decades and contain information know-how for dealing with the peculiarities encountered in real EMG data. These algorithms identify action potentials using *template matching* and *probability of firing statistics*, resolve superpositions, and allocate the action potentials to motor units. User-interactive editing algorithms are used to check the accuracy and make modifications according to well-established rules. For details see De Luca (1993).

Data Reconstruction

With the time record of the MUAP firings of each MUAPT in the EMG signal established by the decomposition of the Micro EMG signals, it is possible to extract the Concentric and Macro EMG MUAPs from the corresponding EMG signals. This is accomplished by *waveform averaging* or in physiological terminology, *spike-triggered averaging* (cf. Chapter 18). That is, each time a MUAP of a particular motor unit is present, select the corresponding time interval from the concentric or Macro EMG signal and save it. Then average the waves in all the time intervals. In this fashion, that part of the waveform (in the time intervals) which belongs to the MUAP will add across the time intervals and that part not associated with the MUAP will tend to cancel out because the positive and negative phases of the other action potentials in the time intervals will overlap considerably. This averaging procedure works best if the number of time intervals is large, the "noise" signals are small in number and low in amplitude, and there is little synchronization among the motor units.

The other necessary factor for the trigger-averaging to work is that the MUAP being recovered must be present in both the Micro signals and the Concentric or Macro signal being considered. The geometry of the quadrifilar electrode is organized with this requirement in mind. An example of recovered Concentric MUAP and Macro MUAP is presented in Fig. 4.

Data Analysis and Presentation

When an action potential has been identified as belonging to a specific motor unit, the algorithms seek the greatest value of the amplitude of the action potential and store the time of its occurrence. In so doing, a time series of all the discharges of each motor unit

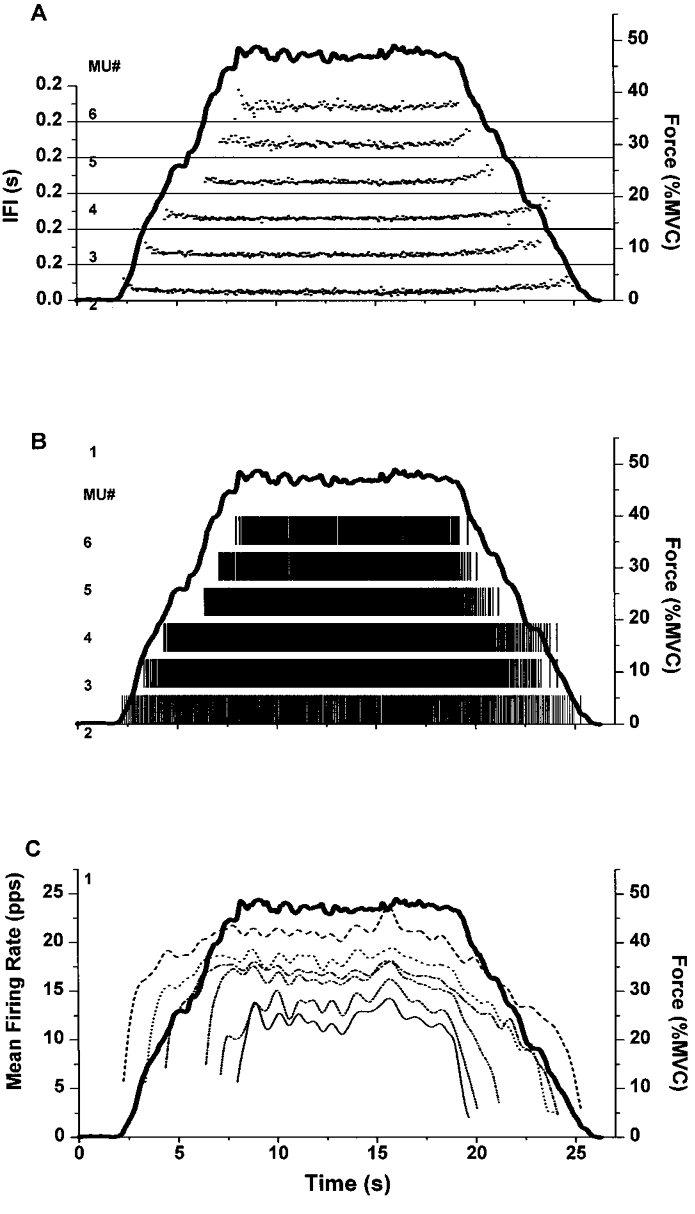


Fig. 6. Plots A to C are derived from the same decomposed EMG signal record. Contraction time is measured on the horizontal axis and contraction force (solid line), normalized to the maximum voluntary contraction (MVC), is measured on the right vertical axis. A) Dot Plot: Each inter-firing interval (IFI) of a MUAPT is plotted sequentially on the vertical scale. B) Bar Plot: A bar is placed in the location of each motor unit action potential (MUAP). C) Firing Rate Plot: The mean number of pulses per second of each motor unit is plotted as a function of time.

is obtained. The time intervals between discharges are plotted as a function of contraction time as shown in Fig. 6A. Such a Dot Plot is used in the user-interactive editing procedure to check for decomposition errors. To illustrate the recruitment order of motor units, the firing time data are plotted as Bar Plots, an example of which is provided in Fig. 6B. The individual discharges are useful for investigating motor unit characteristics such as synchronization and other discharge-to-discharge relationships such as reflex responses, but provide little useful information concerning the control aspects of the motor unit firings. For this purpose it is more useful to study the behavior of the firing rates of motor units that provide a more mechanically relevant relationship. The firing rates may be obtained in a variety of ways. We prefer to *low-pass filter* each motor unit's firing time impulse train with a *Hanning window* to produce a continuous-time, mean firing rate signal. For most applications we prefer a Hanning window width of 400 ms. However, the amount of smoothing will depend on the information to be extracted from the firing rates. Figure 6C shows the mean firing rate signals obtained from the motor unit discharges using a smoothing window of 400 ms.

Results

Applications for neuroscience focus on the behavior characteristics of the firings of concurrently active motor units. Consequently, we will describe results relevant to this issue. For clinically relevant provisions of the Precision Decomposition technique, please refer to De Luca (1993).

Firing Rate Decay

The first observation directly resulting from Precision Decomposition analysis was the firing rate decay (De Luca and Forrest, 1973; De Luca, 1985; De Luca et al., 1996). We reported that during isotonic and isometric contractions, the firing rate of the motor units decreased as a function of time (Fig. 7A). As the firing rate decreased, we never saw a new motor unit being recruited during the first 20 s of a contraction. We first suggested (De Luca, 1979) and later interpreted (De Luca et al., 1996) the firing rate decrease during sustained voluntary contractions to be a manifestation of two phenomena: a) The intrinsic property of the motoneuron to exhibit a firing rate decay over time when stimulated with a DC current which was first described in an animal preparation by Kernell (1965). b) A reduced need to fire a motor unit due to the increase in amplitude and duration of its force twitch upon repeated discharge, commonly referred to as twitch potentiation.

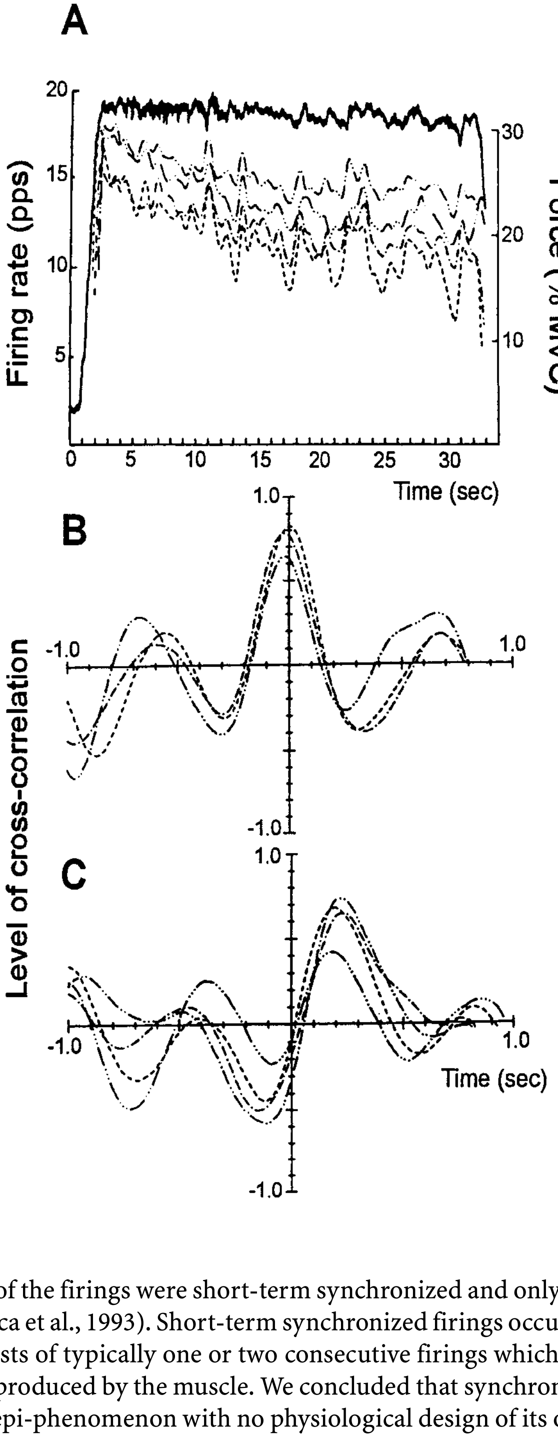
Common Drive

The second observation was the phenomenon of common drive (De Luca et al., 1982a, b). We found that the firing rates of motor units fluctuated in unison with essentially no time delay between them. This was seen by cross-correlating the firing rates of pairs of concurrently active motor units (Fig 7B). We saw this behavior in all muscles tested, ranging from small distal muscles to large proximal muscles. Even motor units belonging to different motoneuron pools exhibited common firing rate fluctuations when controlled as one functional unit; this we observed during antagonist muscle co-activation (De Luca and Mambrito, 1987). The existence of the common drive has been verified by independent investigators (Miles, 1987; Stashuk and de Bruin, 1988; Guiheneuc, 1992; Iyer et al., 1994; Semmler et al., 1997). It indicates that the CNS has evolved a relatively simple strategy for controlling motor units. Additionally we found that the irregular nature of the firing rates and the common drive phenomenon imply that muscles cannot produce smooth constant forces. We verified this fact by cross-correlating the firing rates and the force output of the muscle and found a significant correlation with a latency due to the mechanical delay in force buildup of the muscle fibers and force transmission through the muscle and tendon tissue (Fig. 7C).

Synchronization

The existence of a high degree of cross-correlation between the firing rates of motor units does not imply that the individual firings of the motor units are synchronized. By synchronization it is meant that motor units fire at a fixed time latency with respect to each other. Synchronization occurs in two modalities: short-term and long-term (Fig. 8). A study of motor unit pairs detected during isometric isotonic contractions in six muscles

Fig. 7. A) Firing rate records of four concurrently active motor units (dashed lines) are shown superimposed on the force output (solid line) recorded during an isometric constant-force contraction of the deltoid muscle. The force level is given as a percentage of MVC on the right. B) The cross-correlations of the mean firing rates of a motor unit with those of the other units. Note that the peaks occur at zero time. C) The cross-correlations of the firing rates of all four motor units with the force output of the muscle. Peaks occurring at positive time lags indicate that the firing rate leads the force as is expected due to the time required to build up the force in the muscle after the fibers have been activated. (From De Luca et al. 1982b)



revealed that an average of 8 % of the firings were short-term synchronized and only 1 % long-term synchronized (De Luca et al., 1993). Short-term synchronized firings occurred at sporadic intervals and in bursts of typically one or two consecutive firings which had no apparent effect on the force produced by the muscle. We concluded that synchronization of motor unit firings is an epi-phenomenon with no physiological design of its own.

Onion Skin

The third observation was the onion skin phenomenon. Along with Person and Kudina (1972) as well as Tanji and Kato (1973), we (De Luca and Forrest, 1973) were among the first to report that during isometric contractions lasting less than 20s, the earlier recruited motor units always fired at greater average rates than later recruited motor units. (When the firing rates are plotted as a function of time, the hierarchical values of the motor unit firing rates form overlapping layers resembling the structure of the skin

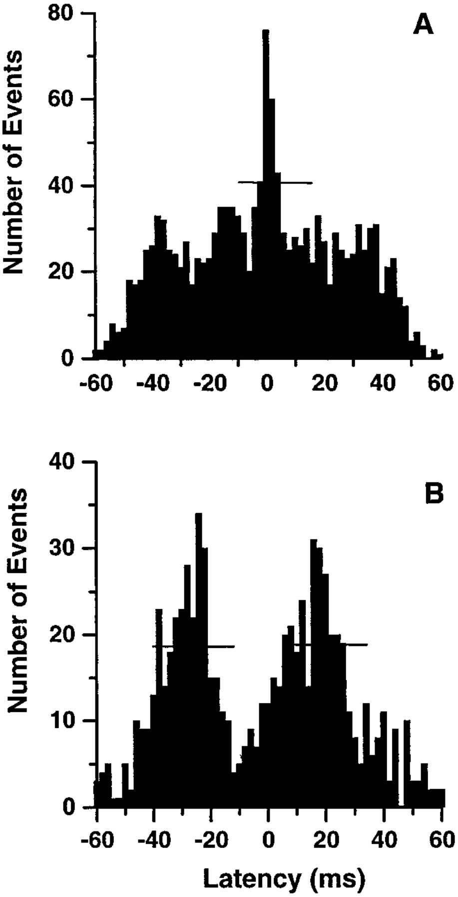


Fig. 8. Synchronization plots: The amount or synchronization between a pair of motor units is studied by calculating a cross-interval histogram. A cross-interval histogram accumulates the occurrences of the time interval between the firing of one motor unit and the first subsequent and previous firing that occur in the companion motor unit. A) Example of a cross-interval histogram which displayed short-term synchronization. B) Example of long-term synchronization.

of an onion. See Fig. 6C). Subsequently (De Luca et al., 1982a), we documented this phenomenon in detail. Independent verifications followed by Hoffer et al. (1987) and Stashuk and de Bruin (1988). Thus, the later recruited, more glycolytic, faster-twitch motor units which require a greater firing rate than the earlier recruited, more oxidative, slower-twitch motor units to fuse would be less likely to tetanize. Even during high level contractions in the neighborhood of 80 to 100 % MVC, the firing rates of the high threshold motor units are in the range of 20–30 pulses per second (pps), an amount likely to be insufficient for complete tetanization. This finding ran counter to the previously held belief that higher threshold motor units would be expected to fire faster so as to produce more force. The onion skin phenomenon begs the question as to why motor unit control developed so as to not maximize the force-generating capacity of a muscle. After all, if the purpose of a muscle was to generate force, it was reasonable to speculate that the motor unit control would be organized to make the most of available mechanical capacity within the muscle. Why should muscles evolve to have an apparent Reserve Capacity not commonly accessible during voluntary contractions? This an intriguing question. One possible explanation is that the higher threshold motor units, which are faster fatiguing, would become exhausted quickly if they fired fast. A control system so organized would not provide sustained contractions at high force levels which would be necessary to cope with life-threatening situations and ensure the survival of the species. It appears that the motor unit control developed to maximize a combination of contraction force and contraction time rather than only the contraction force. The available reserve capacity for generating force over brief periods of time may explain the occurrence of exceptional feats of strength that are reported to occur during life-threatening situations.

Two corollary observations were also made for the behavior of the firing rates: a) The later recruited motor units had greater initial firing rates as previously indicated by Clamann (1970). b) The firing rates of all units converged to a near common value during maximal contractions (De Luca and Erim, 1994; Erim et al., 1996).

All the above findings indicate that the control signals (net excitation) act on the motoneuron pool as a unit. As proposed by Henneman and colleagues (Henneman et al., 1965a,b) the individual properties of the motoneurons determine the recruitment hierarchy in response to the net excitation. To that enlightening observation we now add that the firing rate of the individual motor units responds to the net excitation communally and simultaneously, and that the average value of the firing rates is also hierarchically organized with an inverse relationship to the recruitment threshold.

Diversification

The fourth observation was the diversification of the control properties (De Luca et al., 1982a). The motor units of smaller, distal muscles such as the first dorsal interosseous tend to be recruited in the force range up to 50 % MVC and have mean firing rates that reach relatively high values (approx. 40 pps) at 80 % MVC. Whereas those from larger, proximal muscles such as the deltoid and the trapezius recruit their motor units in a force range up to 80 % MVC and have firing rates that reach relatively lower values (approx. 30 pps). A similar observation in the adductor pollicis and biceps brachii muscles was reported independently by Kukulka and Clamann (1981). The reduced dynamic range of the larger more proximal muscles may be due to the increased recurrent inhibition of the Renshaw system which is more prominent in these muscles as shown by Rossi and Mazzachio (1991). These diverse control properties are useful in at least two ways. First, they allow for a smoother force. Smaller muscles have less motor units, therefore, force gradation due to recruitment would be coarser throughout the full range than in larger muscles which have many more (an order of magnitude or more) motor units. Second, the larger more proximal muscles tend to be more postural and are required to produce sustained contractions more often. The lower firing rates in these muscles delay the progression of fatigue.

Exercise

We found that long-term exercise appears to induce modifications in the motor unit control properties (Adam et al., 1988). Comparing the motor unit control parameters of the first dorsal interosseous muscles of the dominant and non-dominant hands performing isometric, isotonic contractions at the same MVC level, we found that motor units of the dominant side had lower firing rates for the same level of contraction, and a larger number of motor units were recruited at lower force levels. This finding is consistent with the previously known fact that the dominant hand has slower twitch muscle fibers, probably due to the life-long preferential use. The twitches of slower fibers fuse at lower firing rates allowing for a reduced excitation and decreased firing rates in the dominant hand without a reduction in force output.

Aging

We have recently reported that aging causes alterations in the motor unit control properties (Erim et al., in press). In our study in the first dorsal interosseous muscle of elderly subjects above 65 years of age, we found that the firing rate and the recruitment threshold of motor units became modified in the same manner as that induced by exercise. This observation was not surprising because it is well known that aged muscles contain a greater percentage of slow twitch Type I fibers, as is the case in exercised muscles, although the cause for the increased percentage of Type I fibers appears to be different. When we studied the common drive in the elderly, we saw that in approximately one-half of them the cross-correlation between pairs of motor units was severely re-

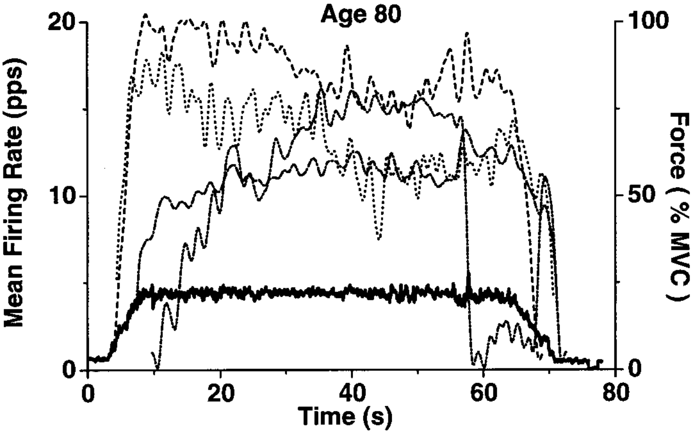


Fig. 9. Example of cross-over of motor unit firing rates in an elderly subject. See legend to Figure 6C for details of plot. (From Erim et al., in press)

duced and in some cases apparently nonexistent. Also, in the elderly, the onion skin phenomenon was disrupted (Fig. 9). When plotted as a function of contraction time, the firing rates of numerous motor units crossed over those of earlier recruited ones and the behavior of the firing rates was not orderly in a hierarchical sense; some decreased while others increased during an isometric, isotonic contraction. We surmise that this dissociation among the firing rates of motor units leads to an inefficient force generation scheme.

Motor Unit Substitution

All the above observations were made on relatively short-duration (less than 20 s) isometric, isotonic contractions. They may not fully describe the behavior of the control properties during sustained contractions of limb muscles or postural muscles which are commonly required to contract for prolonged periods of time. Recently, we have seen cases where the onion skin property is disturbed during short-term (20 s or less) contractions of normal healthy trapezius muscle and during long-duration (150 s or more) contractions in normal healthy first dorsal interosseous muscles. We suspect that the cross-over of the firing rates is due to at least two factors which cause the firing rates of earlier recruited motor units to decrease below the value of the newly recruited motor units: a) The Renshaw recurrent inhibition of earlier recruited motor units which is more dominant in proximal muscles such as the trapezius, hence the disturbed onion skin during short-duration contractions. b) The motoneuron adaptation process reported by Kernell (1965) which decreases the firing rates of motor units during sustained activation, causing the discharge rates of earlier recruited motor units to decrease below that of later recruited motor units.

While studying long-duration contractions in the range of 5 min to 60 min with our colleague Westgaard, we observed definite examples of motor unit substitution (Westgaard and De Luca, 1999). These are cases where a motor unit stopped firing during a sustained contraction when the activity level decreased slightly, and in response to a subsequent slight increase in the force output, a new motor unit was recruited in place of the one that was derecruited (Fig. 10). We believe this phenomenon is the result of adaptation of the recruitment threshold of active motoneurons. The recruitment threshold of a motor unit which had been active for some time would have become greater than the recruitment threshold of the next one in the hierarchy. In this fashion the next motor unit becomes recruited in response to an increase in the net excitation to the motoneuron pool.

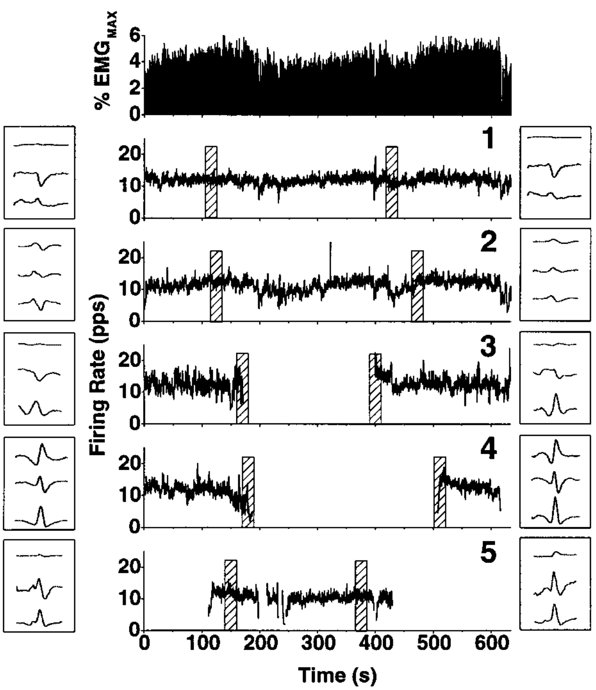


Fig. 10. Motor unit substitution during sustained contraction of the trapezius muscle. The top panel shows the root-mean-square (RMS) amplitude of the surface EMG signal normalized to the value measured at the MVC. The plots below represent the firing rates of five motor units identified by Precision Decomposition from intramuscular EMG signals obtained with a quadrifilar wire electrode. Motor units #1 and #2 fire continuously, while motor unit #3 ceases firing as the surface EMG signal decreases (t = 170 s) and becomes active again as the amplitude of the EMG signal increases (t = 400 s). Motor unit #4 behaves in a similar fashion. The novel observation is the fact that motor unit #5, the highest threshold unit in this group, fires when the lower threshold motor units are silent (200 s < t < 400 s). We refer to this phenomenon as motor unit substitution. Boxes to the left and right of the firing rate plots contain the characteristic Micro EMG shapes for each of the MUAPTs. Motor unit action potential shapes are averages obtained at time intervals indicated by shaded bars in each of the firing rate plots. (Modified from Westgaard and De Luca 1999)

Troubleshoot

Difficult Superpositions

During an automatic or operator-assisted decomposition, superpositions of several MUAPs almost always create problems. In the operator-assisted mode the program stops and asks the operator for help; in the automatic mode it tends to skip the superimposed waves. In either case, the superpositions need to be resolved by the operator if 100% accuracy is desired. The following steps may be helpful when trying to resolve the more difficult superpositions.

Normalized IFI

When subtracting templates from a superposition, remove the most obvious components first. As each template is removed, components of other templates may become easier to recognize. Use the normalized IFI information to determine which motor units have the greatest probability of firing. Look ahead in the signal to determine which waves, other than those that may be contained in the superposition, fulfill this criterion. This tactic may give hints as to which waveforms are hidden in the superposition. Keep in mind that rapid force changes can cause peculiar firing patterns; thus IFI information may not always be useful.

Sometimes templates may not be cleanly subtracted, leaving a residual that clutters the rest of the superposition. This can be due to peak misalignments which are caused by the overlapping of several shapes. Try subtracting the template from a peak on a different channel or try subtracting templates in a different order. This approach may simplify the resolution of the superposition. If all else fails, skip the superposition and go back to it later. When more information is known about the signal, it may be easier to resolve.

Error Detection

The Dot plot, a plot of the IFIs as a function of contraction time for every motor unit, is useful to detect incorrect motor unit allocation. An example of this plot for a decomposed signal record containing errors is presented in Figure 11A. If the firing of a motor unit has been missed, the amplitude of the IFI will be twice as great as that of the average firing interval. An example of this case may be seen in motor unit #2, where at approximately 11 s an abnormally great IFI occurs. The missed detection of a firing is likely accompanied by an incorrect allocation to another motor unit. Therefore, in the time vicinity of the skipped firing of one motor unit there will be one or two short IFIs in another unit. This occurrence is noted in motor unit #4 at roughly the same time. Using an

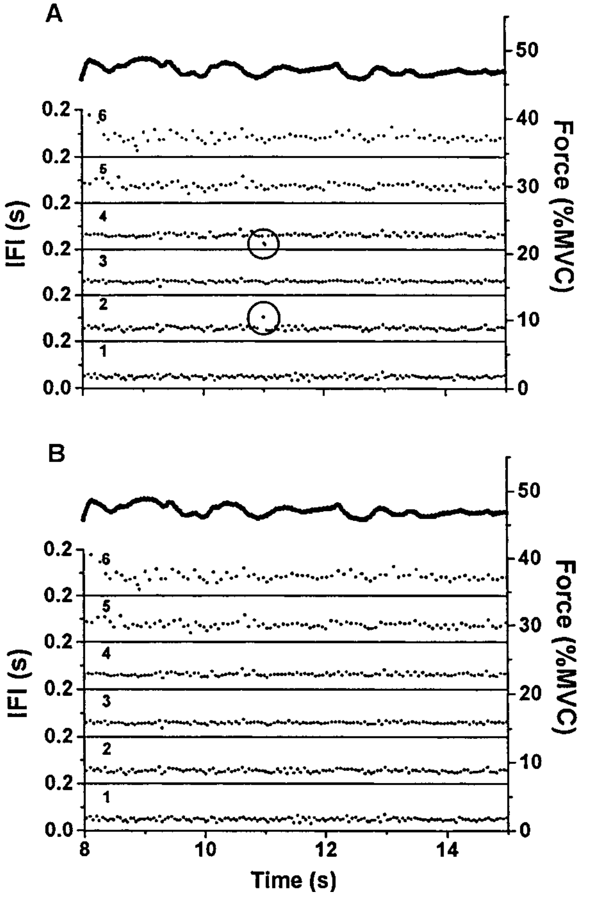


Fig. 11. A) An example of the decomposed IFIs of six concurrently active motor units containing two classification errors. Circles indicate the occurrence of one large and two small IFIs, which are due to the misqualification of motor unit #4 for motor unit #2. The use of the Dot Plot in identifying discordant motor unit firings becomes apparent. B) The same record of data after the editing procedure.

editor program which displays the original EMG record as well as the assigned motor unit templates and IFI statistics, the classification of motor units is adjusted. The new Dot Plot (Fig. 11B) shows the error removed from the IFI plots.

Comments

Validation of Decomposition Technique

A basic fundamental question arises when decomposing a signal that has an unobservable source, such as the EMG signal, into its constituent units (MUAPs). That is – how does one know that the decomposed sequence of motor unit discharges represents the true and unique solution? Therefore, it is essential to assess the accuracy of any EMG signal decomposition system and 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.

Testing for Consistency

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

Testing for Accuracy

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 waveforms in the EMG signal are unknown a priori or a posteriori. 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 a synthetic EMG signal and execution of the test, refer to LeFever et al. (1982 a, b). 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 waveform. 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.

Secondly, a direct test of the accuracy of the decomposition technique on real EMG signal was obtained in the following way (Mambrito and De Luca 1984). 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. Some motor units contributed MUAPTs 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 incalculably 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. This test has been repeated numerous times with similar results.

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Abbreviations

EMG	Electromyographic
IFI	Inter-Firing Interval
MVC	Maximum Voluntary Contraction
MUAP	Motor Unit Action Potential
MUAPT	Motor Unit Action Potential Train