te that this plot has linear scales, because in our opinion such a resentation provides a more direct expression of the power distribu- n. A logarithmic scale, which is the scale of preference in other ciplines such as acoustics, would compress the spectrum and unnec- arily distort the distribution.

Three parameters of the power density spectrum may be conveniently d to provide useful measures of the spectrum. They are: the median quency, the mean frequency, and the bandwidth of the spectrum. her parameters such as the mode frequency and ratios of segments of power density spectrum have been used by some investigators but not considered reliable measures, given the inevitably noisy nature the spectrum (refer to Fig. 3.12). The bandwidth measure has been cussed in the previous chapter. Note that because the amplitude scale n V/Hz, the 3 dB points or the corner frequencies are defined by a rease of a factor of 0.5. The median frequency and the mean quency are defined by the following equations:

$$\int_{o}^{f_{med}} S_m(f)\,df = \int_{f_{med}}^{\infty} S_m(f)\,df$$

$$f_{mean} = \frac{\int_{o}^{f} f\,S_m(f)\,df}{\int_{o}^{f} S_m(f)\,df}$$

re $S_m(f)$ is the power density spectrum of the EMG signal. Stulen De Luca (1981) performed a mathematical analysis to investigate restrictions in estimating various parameters of the power density trum. The median and mean frequency parameters were found to he most reliable, and of these two, the median frequency was found e less sensitive to noise. This quality is particularly useful when the al is obtained during low level contractions when the signal to noise may be less than 6.

CHAPTER 4

Decomposition of the EMG Signal and Analysis of the Motor Unit Action Potential Trains

Decomposition of the EMG signal is the procedure by which the EMG signal is separated into its constituent motor unit action potential trains. This concept is illustrated in Figure 4.1. 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) waveform (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, the decomposition of the EMG signal is useful in two ways. First, a partial decomposition must be implicitly performed by the clinical investigator to ensure 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 waveforms 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, firings of a single unit in a particular record.

For physiological investigation, both the statistic of the interpulse intervals (IPI, time between two successive firings of the same motor unit) and the MUAP waveform 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.

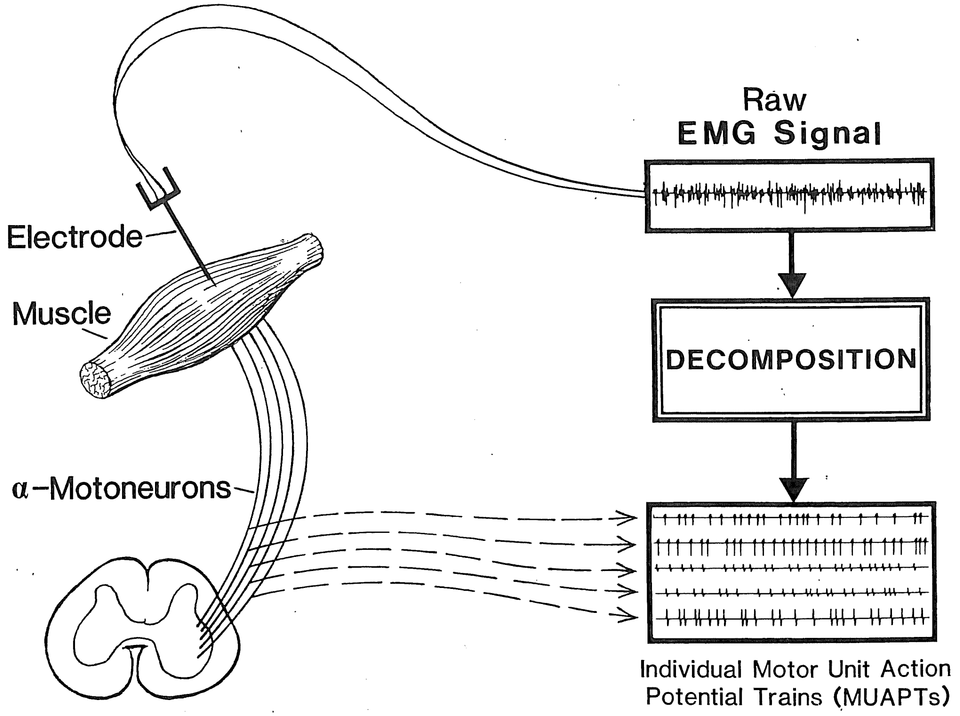

Figure 4.1. A schematic representation of the decomposition of the EMG signal into its constituent motor unit action potential trains (From C.J. De Luca et al, © 1982, *Journal of Physiology*.)

It is apparent that a decomposition technique satisfying the requirements for physiological investigations will also provide all the information currently used in clinical studies. The additional information on the temporal behavior of motor unit firing may also provide useful information which clinicians may exploit in the future.

Given the above requirements and constraints, any design approach to EMG signal decomposition must address two major issues: convenience of use and accuracy. The first point implies that any suitable technique should work on EMG signals that are routinely and repetitively acquired by a specific and convenient method. The second issue is more important since it validates the results. Therefore, it is essential that any method used for decomposing the EMG signal should be able to provide a measure of its accuracy.

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 waveforms belonging to different motor units, the number of MUAPTs present, and the stability of the MUAP waveform during the record.
2. The decomposition algorithm of the system 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 tradeoff between the accuracy of the data and the amount of time required to perform a decomposition. For a record containing six MUAPTs, the time required to decompose the signal with 100% accuracy will range from 15 s to 15 min for 1 s of data, depending on the quality of the data. The same data may be decomposed in a fully automatic mode, requiring from 1 to 15 s for 1 s of data, but the accuracy of the decomposition would be approximately 65%.
3. As many as 11 MUAPTs have been decomposed accurately from an EMG signal. To date, the longest EMG signal record that has been decomposed accurately was 144 s long and contained approximately 7000 discharges of four motor units.
4. The signal conditioning which is performed in various phases of the system modifies the waveform of the MUAPs. Therefore, standard measurements of the MUAP waveform such as amplitude, time duration, and number of phases, may not be compared to those of conventionally acquired and recorded 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 waveform of many MUAPs, other than only one, as in the case for Stålberg's technique.
5. This chapter will focus on the decomposition aspects.

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 (Clamann, 1970; De Luca and Forrest, 1972, 1973; Desmedt and Godaux, 1977; Gurfinkel' et al, 1970; Gurfinkel' et al., 1964; Hannerz, 1974; Kranz and Baumgartner, 1974; Masland et al, 1969; Maton and Bouisset, 1972; Person and Kudina, 1971; and others) or automatic identification by electronic apparatus (Andreassen, 1977; Dill et al, 1972; Friedman, 1968; Gerstein and Clark, 1964; Glaser and Marks, 1966; Keehn, 1966; Leifer, 1969; McCann and Ray, 1966; Mishelevich, 1970; Schmidt, 1971; Schmidt and Stromberg, 1969; Shiavi, 1972; Simon, 1965; and others). Procedures that consist exclusively of visual analysis 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 some other characteristic of the MUAP waveform) or signal space representation (usually referred to as correlation, matched filter, template, or square-error separation techniques). One of the major problems with most automatic detection schemes is the inability to resolve waveforms produced by superposition of two or more simultaneously occurring MUAPs. Most automatic detection schemes also cannot accommodate a slow change in a MUAP waveform'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 (1980), with a shortened description being given by LeFever and De Luca (1982) and LeFever et al. (1982). The subsequent modifications, some of which are described in this chapter may be found in their entirety 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 waveforms 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. To date, a number of 9 MUAPTs simultaneously present in the EMG signal have been found to constitute a practical limit in the number of decomposable units from one record.
3. The technique requires interaction with a highly trained operator.

SIGNAL ACQUISITION

The EMG signal acquisition and quality verification system is depicted in Figure 4.2. 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 lightweight quadripolar electrode may be seen in Figure 4.3. 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 four or five motor units would be consistently detected in most muscles. The four wires (pick up areas) terminate on four male pin connectors mounted on an insulated base that is epoxied to the shaft. The shaft itself makes electrical contact with another pin. The five pins on the electrode may be connected to form a variety of differential recording arrangements, each providing a channel of EMG signal.

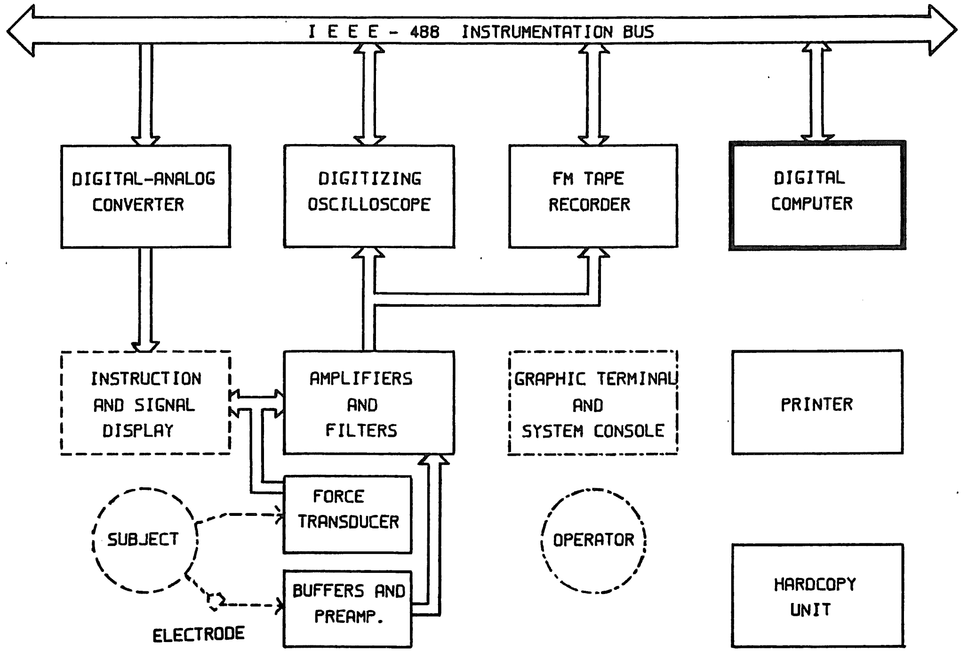

Figure 4.2. EMG signal acquisition, quality verification, and decomposition system.

Figure 4.3 presents one of several possible combinations providing three differential channels of EMG signal. The lines A, B, C, D, and E are individually shielded and fed into five high input-impedance front end buffers (10^{12} ohms input resistance and 25 pA bias current) and are

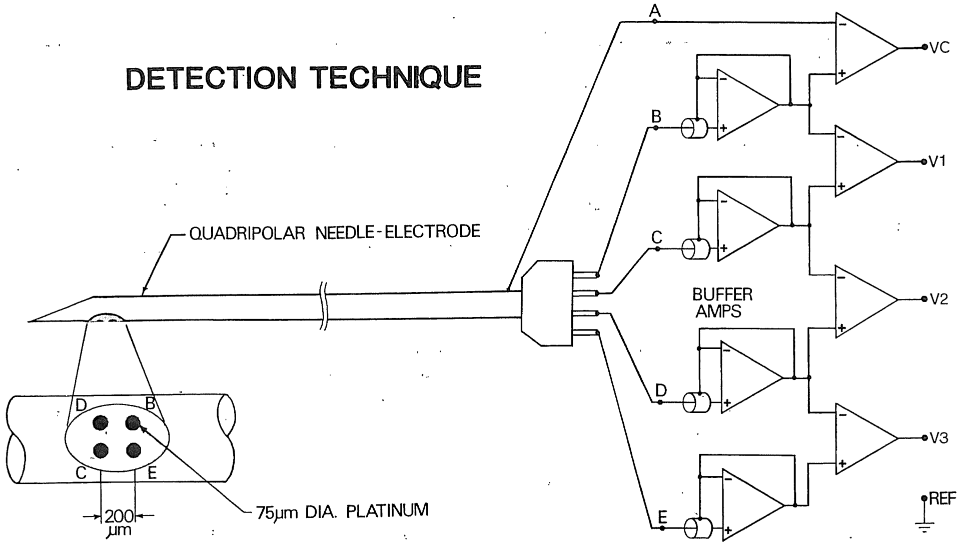

Figure 4.3. A schematic representation of the lightweight quadripolar needle electrode configured to detect three independent channels of EMG signal (V1, V2, V3) for the purpose of decomposition. A fourth channel VC is also displayed for the purpose of simultaneously recording one conventional EMG signal channel.

successively fed into a set of four differential amplifiers. For the purpose of decomposition, the differential amplifier outputs V1, V2, and V3 of three channels are band-pass 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 waveforms 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 waveforms produced by muscle fibers distant from the recording site. As indicated in Figure 4.2, the outputs of this last stage of amplification and filtering (the block indicating the amplifiers and filters) are viewed on an oscilloscope. When the oscilloscope is triggered by a MUAP arrival, 20-ms 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 waveforms 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 output of the last stage of amplification and filtering is 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 μs.

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 Figure 4.4, which contains segments of three channels of simultaneously detected signals with MUAPs from five motor units. Note that in channel 1, MUAPs 4 and 5 have similar waveforms; such is the case for MUAPs 1 and 2. On channel 2, MUAPs 3 and 4 have similar representation whereas, MUAPs 1 and 5 have similar waveshapes on channels 2 and 3. Finally, MUAPs 1, 3, and 5

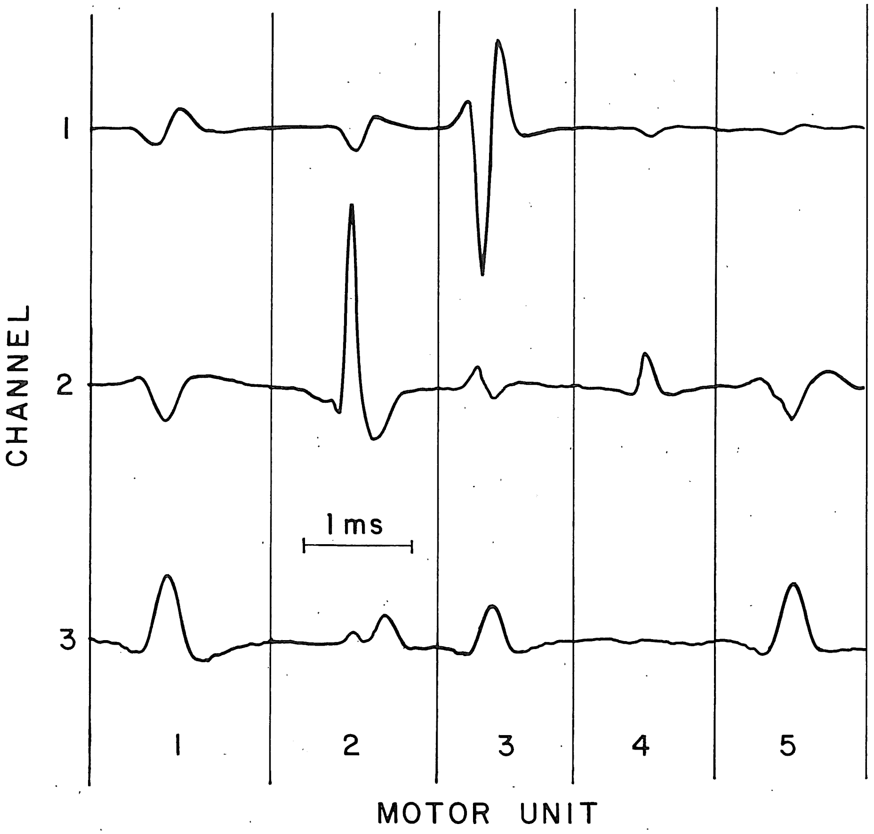

Figure 4.4. Three-channel representation of action potentials from five different motor units. The three channels represent the same electrical event (MUAP) as seen from three different geometrical perspectives.

have similar representation on channel 3. It is apparent that any identification and decomposition technique attempting to discriminate among several simultaneously active motor units using only one channel of information will not be accurate.

DATA SAMPLING AND COMPRESSION

The analog signals are transferred off-line to digital storage. As will be clarified later, due to the signal processing method recommended to detect firings, a sampling rate several times higher than the Nyquist frequency (which is twice the maximal signal frequency in this case) must be used.

A sampling rate of 50 kHz is recommended since some of the MUAP waveforms obtained using the wideband recording technique described before have frequency spectra that range up to 10 kHz. The high sampling rate may be conveniently achieved by playing back the EMG signal 32 times slower than it is recorded and sampling at a rate of 1.5625 kHz. 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 Figure 4.5, where the numbers near the *vertical bars* indicate number of milliseconds skipped between sampled waveforms.

SIGNAL CONDITIONING

The analog high pass filtering at 1 kHz is effective in substantially reducing both amplitude and the time duration of slow rise-time MUAP waveforms recorded from fibers distant from the electrode. However, it is sometimes useful to filter the record further 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 extraphases to the MUAP waveforms. The parameters of the filter (high- and low-cutoff frequency and rolloff) can be chosen specifically for each record using the power spectrum of specific MUAP waveforms in the record as a guide.

THE DECOMPOSITION ALGORITHM

The detection of the occurrence of a particular motor unit firing is based upon the *maximum a posteriori* probability receiver theory, which has found wide applications in the field of communications (Van Trees, 1968). The theoretical computations have been derived under a set of assumptions, none of which in practice is exactly appropriate for the EMG signal. The *maximum a posteriori* probability receiver theory assumptions and EMG signal characteristics differ in the following manner:

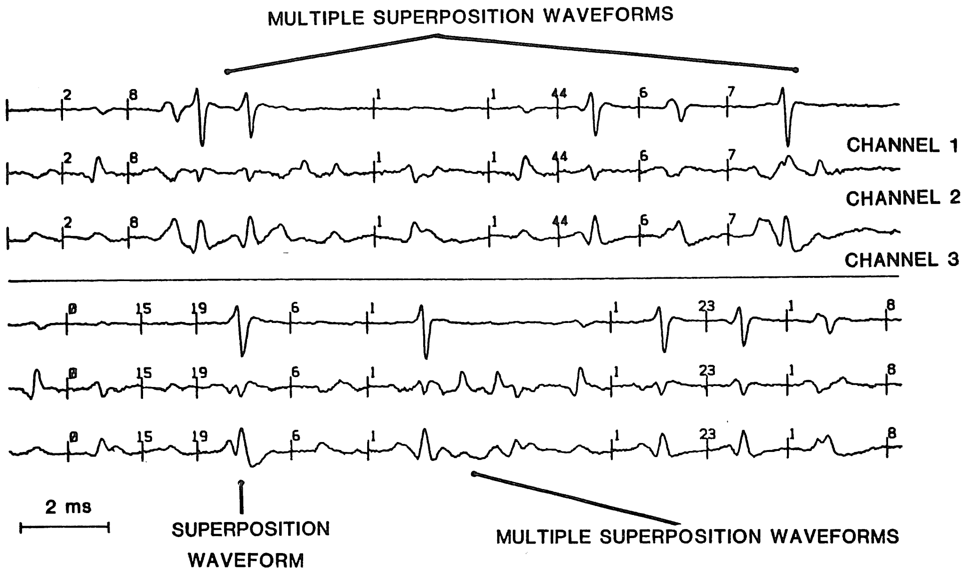

Figure 4.5. An example of three channels of a real, filtered, and time-compressed EMG signal. The *numbers* above the *vertical separating lines* (skipped interval markers) represent the time in milliseconds which contained no useful information and was removed.

1. One, and only one, of a set of M signals is present from time t to time $t+T$. The number of M signals present in the set, and the time t of possible occurrence of any one signal in the set are known. (What is unknown is which one of the M signals will actually occur.) In the case of the EMG signal, more than one MUAP may be present in the same time interval t to $t+T$. The time t of possible occurrence, and the number M of motor units firing at a certain time are unknown.
2. The exact waveform or template of each signal (or the waveform in absence of perturbing noise) is known, and all the templates have the same time duration T. In the case of the EMG signal, different MUAPs have different durations; the exact template of each MUAP is unknown; and the waveform shape of the same MUAP may change in time during a contraction.
3. The *a priori* probability of occurrence of any of the M signals in any interval t to $t+T$ is known. Obviously, this is not the case for the EMG signal.
4. The signal is perturbed only by additive, zero mean, Gaussian distributed, white noise with known variance. In the case of the EMG signal, the perturbing noise consists mainly of low amplitude MUAPs which cannot be detected with reliability, thus, the perturbing noise is not white and its variance is unknown.

Theoretical Computations in the Maximum A Posteriori Probability Receiver Algorithm. The *maximum a posteriori* probability receiver algorithm uses the following decision criteria when an unknown waveform occurs. The most likely template is chosen, given the characteristics of the particular occurrence (i.e., the template with the *maximum a posteriori* probability is chosen as the one corresponding to the unknown waveform). It can be shown that this is equivalent to making the decision with the minimum probability of error.

In order to perform this task, the following computations must be made. Upon occurrence of an unknown waveform, the difference signals between unknown waveform and M templates are computed. Then the energies in the difference signals are also computed. These energy values, or squared errors, are modified using a weighting factor derived from the probability values described above in no. 4, and the variance of the perturbing noise. In particular, squared errors resulting from matching less likely templates are increased while squared errors resulting from matching more likely templates are decreased. The template which gives lowest final value of modified squared error is chosen as the one corresponding to the unknown waveform. The variance of the perturbing noise controls the degree to which the probability weighting factors effect the decision. For low variance values, the decision is more affected by the energy term (i.e., by the similarity between "unknown" waveform and template), while for high variance values, the probability weighting factor (i.e., the probability of occurrence of each template) dominates the decision. If the signal has multiple channel representations (as in the case of the EMG signal), all the energy computations are performed for each channel; the total squared error (before the modification with the probability weighting factor) is obtained by summing the squared errors for each channel.

The original *maximum a posteriori* probability receiver decision technique has been extensively modified to take into account the wide difference between the theoretical *maximum a posteriori* probability receiver case and practical EMG signal case. In the following parts of this section we will describe the modification to the *maximum a posteriori* probability receiver algorithm and its implementation.

The Motor Unit Templates. The first problem is how to obtain the set of templates. Each motor unit template is an estimate of the MUAP waveform (amplitude and shape on all three channels). Prior to the analysis of an EMG signal record, both the number of different motor units (whose firing can be detected) and their corresponding MUAP waveforms are unknown. Therefore, all templates must be created during the decomposition. When the operator has decided that a waveform in the EMG signal is produced by an action potential of a "new motor unit," a new template is created using the waveform itself. This template may also be updated at each successive detection of the motor unit firing by averaging the template with the detected waveform in the EMG signal. This operation will improve the estimate of the MUAP waveform by reducing the amount of perturbing noise in the template and will also compensate for slow variations in template shape. (The term new motor unit is used nonrigorously.) The new MUAP waveform may be from an already firing, although previously undetected, motor unit which has increased in amplitude (due to electrode movement) so that it now exceeds the sampling threshold. If the amplitude of this MUAP waveform is significantly greater than the sampling threshold, a newly recruited motor unit has probably been detected. If not, subsequent analysis of the firing pattern will permit the distinction between a newly recruited and an already firing motor unit to be made.

The A Priori Probabilities of Firing. The second problem is how to obtain the *a priori* probability of occurrence of all the MUAPs whose templates are available in any interval t to $t{+}T$ of the record. This may be accomplished by measuring the interpulse interval (IPI) between adjacent firings of a motor unit. The mean and the variance of the IPIs of the detected motor unit can be recursively obtained by using expressions that have been reported by LeFever and De Luca (1982). The use of a running recursive expression during the decomposition allows slow time variations in the IPI mean and variance. If the time sequence of firing of each motor unit is modeled as a renewal process with Gaussian distributed IPIs, the relative probability of occurrence of a MUAP for each motor unit can be approximated from IPI mean and variance. Such probability is continually updated at each firing detection.

Detection of a Motor Unit Firing. At this point, it would be possible to compute the squared error as described in the theoretical *maximum a posteriori* probability receiver computations. However, it has been found that the absolute change in a MUAP waveform from one firing to the next is roughly proportional to the waveform amplitude. Hence, the ratio between squared error and template energy should be used as the decision criterion instead of simply the squared error.

Because a motor unit firing can occur at any unknown instant of time, the problem arises as to how to align the templates with the "unknown" detected waveform to compute the squared error. To achieve this, the peak (greatest absolute value) of each motor unit template is aligned with the peak of the unknown waveform and shifted back and forth to achieve the minimal squared error. During this operation, an alignment error may occur which, at most, is equal to one half the sampling period. It is this alignment error that poses the requirement for the high sampling rate reported in the data sampling and compression section. For expressions on the alignment error, see LeFever and De Luca (1982).

Perturbing Noise. The last dissimilarity between theoretical and practical conditions relates to the nature of the perturbing noise and its variance, which is used to modify the squared error value. In the decomposition algorithm, the noise is still considered white; rather than estimating the value of the variance from the EMG signal, the value is set by the operator to control the degree to which the probability weighting factor affects the decision.

While the theoretical *maximum a posteriori* probability receiver algorithm always automatically leads to a choice of one among the M available templates, this cannot be allowed for the EMG signal. In fact, the random superposition of two or more differing MUAP waveforms may produce a complex waveform quite similar to some other previously identified MUAP not actually present. The peak that has been detected may also have arisen from only the background noise. Alternatively, the MUAP detected may actually be produced by a newly recruited motor unit for which no template has been established. For these reasons a detection is confirmed only if the detected waveform is "close" enough to the most likely template. A measure of how close two waveforms are is obtained using signal space representation techniques as described by LeFever and De Luca (1982). For the purpose of the present description, it is sufficient to note that the confirmation of a detection will be automatic only if preset numerical constraints on the value of the squared error are satisfied.

When a detection cannot be confirmed, the decision is transferred to the superposition algorithm described in the next section.

The Superposition Algorithm. The purpose of the superposition algorithm is to resolve an EMG signal waveform, formed by the summation of multiple MUAP waveforms. Only combinations of two waveforms (two templates) are considered, since the computation time is prohibitive for more. Triple or multiple partial superposition of MUAP waveforms can sometimes be solved by repeated application of the decomposition algorithm in various modes. The scheme employed by the superposition decomposition algorithm is similar to the single match criteria. Added to these criteria is a procedure that attempts to fit a second motor unit template to the waveform obtained by subtracting the first template from the EMG signal.

The above approach is implemented as follows. Each template is aligned with the detected highest peaks (in the channel where such a peak occurs) in the "unknown" EMG signal waveform and is subtracted from the signal. (The operation is similar to that performed for a single match.) Then an attempt is made to resolve the remaining waveform by aligning each of the remaining templates with the remainder and subtracting. The template providing the smallest squared error is chosen as the second template. The energy in the remainder after subtraction of the two templates is the squared error used to make the decision. This squared error value is modified using the probability weighting factor corresponding to the first subtracted template.

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

TEST FOR CONSISTENCY AND ACCURACY

As stated in the introduction of this chapter, it is essential to assess the accuracy of any EMG signal decomposition system to validate the results obtained using such a technique. This point cannot be overemphasized. Furthermore, this technique is 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 extensively addressed by LeFever et al (1982). Briefly, the following test was performed. Two highly trained operators (each with at least 400 hours of experience in decomposing EMG signals) and a third, less experienced operator (16 hours of EMG signal decomposition) were required to decompose the same EMG signal record independently, 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 five 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 five 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 test reported by LeFever et al and De Luca (1982), 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 hours 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 waveforms 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 signals. For details on the procedure to generate synthetic EMG signals and execution of the test refer to LeFever et al (1982). Briefly, the synthetic EMG was constructed by linearly superimposing eight mathematically generated MUAPs along with Gaussian noise. Prior to the simulation, a real force record was obtained from a muscle contraction, and force thresholds for recruitment were randomly chosen for each "synthetic" motor unit. At any point in time throughout the simulated contraction, the mean firing rate of each motor unit was proportional to the difference between force input to a stochastic event generator and the recruitment threshold. The stochastic event generator used a renewal process to create each firing time. The standard deviation of the zero mean Gaussian noise was 40% of the peak amplitude of the smallest MUAP waveform. A segment of the synthetic EMG signal record used for the test is shown in Figure 4.6. A skilled operator was able to decompose the record with an accuracy of 99.8%, incurring one error in a total of 435 classifications. (The particular error was quite inconsequential in that it occurred as an incorrect classification among two MUAPs which belonged to different motor units but had similar shapes and fired less than 1 ms apart.) This error was immediately obvious when the IPI data were plotted. The location of the error was identified, and that segment of the record was subjected to more rigorous decision criteria which rendered the correct identification. In fact, the IPI plots are routinely used to quickly scan for any obvious errors. 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 a real EMG signal was obtained in the following way. Two quadripolar 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 presented motor unit action potential trains in both sets of signals. A comparison of the results from three different contractions with two "common" MUAPTs per contraction showed 100% agreement for a total of 1415 detections of the "common" MUAPs. In this case, an undetected error in the results from the "common" MUAPs detections could occur only if a simultaneous error of the same kind (wrong classification of a MUAP or missed detection) was 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.

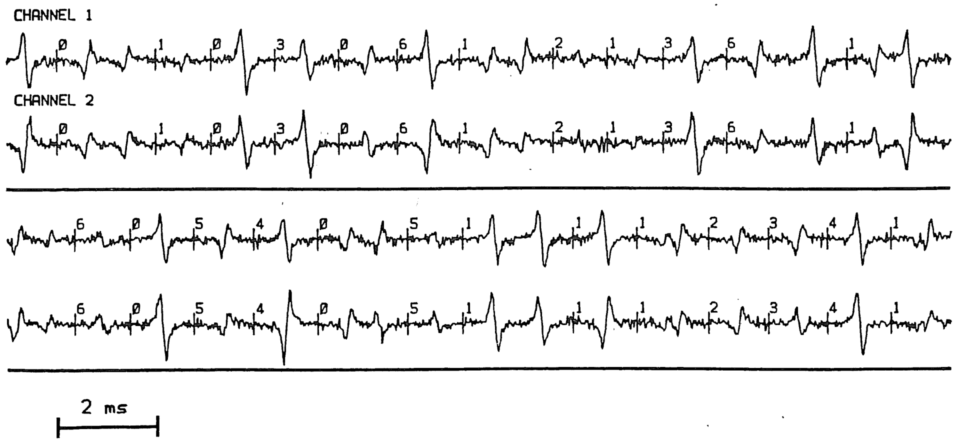

Figure 4.6. An example of a mathematically synthesized and time-compressed EMG signal used to test the accuracy of the decomposition system. As in the previous figure, the *short vertical lines* are skipped interval markers, and the *numbers* represent the milliseconds of time removed.

TIME DOMAIN ANALYSIS OF MOTOR UNIT ACTION POTENTIAL TRAINS

Having described a system which will provide detailed and accurate measures of the characteristics of MUAPTs, it now remains to describe approaches for processing the data. The data reduction techniques that follow may of course be used for any MUAPT data, regardless of how it is obtained. However, the reader is reminded that erroneous data yields erroneous results when analyzed.

Motor Unit Action Potential Characteristics

In clinical environments, the waveform of the MUAP is used to provide what have come 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 chapter renders MUAP waveforms 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 waveforms from the fourth channel presented in Figure 4.3, which is bondpassed in a conventional manner. The waveform recovery is realized by trigger averaging the conventional EMG signal with the timing of the motor unit discharges available from the decomposed MUAPTs. Refer to the next section for an explanation of trigger averaging.

The waveforms of a MUAP of one train obtained from the EMG signals that were bandpassed at 1 to 10 kHz are presented in a raster plot in Figure 4.7. This figure is presented for the purpose of indicating that the waveform of the MUAP is not stable during a contraction, even 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.

Trigger Averaging

The process of trigger averaging is employed to extract a continuously recurring waveform that is enveloped by considerable noise, rendering the quality of the waveform unacceptable at any occurrence. However, if the time at which the waveform occurs is known (as is the case for the decomposed MUAPTs), it may be used to mark the time period in the

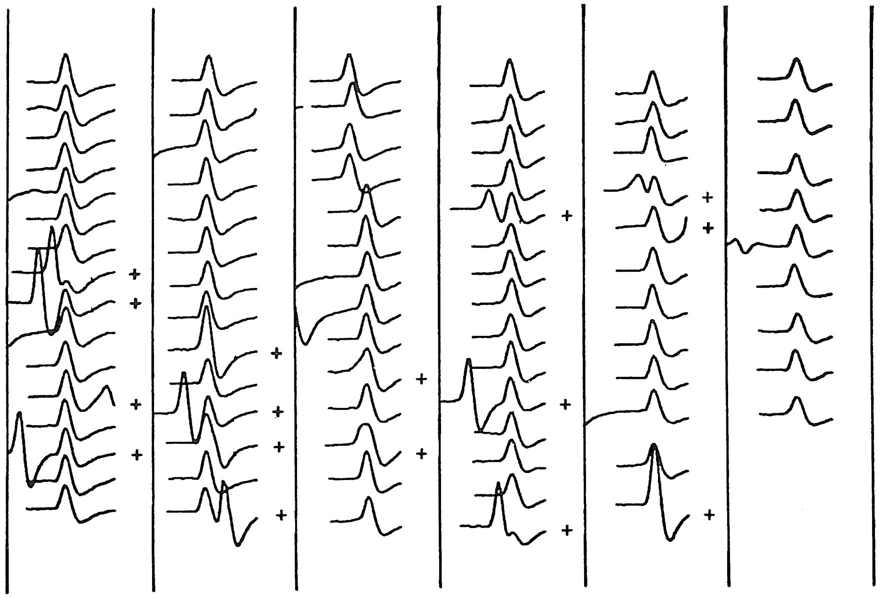

Figure 4.7. An example of the MUAP raster plot. MUAPs (of the same motor unit) are shown as they are detected during the decomposition of the record. MUAPs are displayed sequentially in time from *top* to *bottom* and from *left* to *right*. MUAPs marked with a + sign represent superpositions of the displayed MUAP and of some other MUAP(s) present in the record and simultaneously firing with the detected MUAP.

noisy signal which contains the waveform of interest. This may be done every time the waveform is present in subsequent parts of the signal. The next step consists of removing from the noisy signals all the time periods which have been identified as containing the waveform. Then these time periods are averaged. The noise, being unrelated among the time periods, will cancel out, and the waveform contained in the time periods, being considerably similar, will be enhanced. It is apparent that the greater the number of accurate identifications of the discharge of a motor unit, the more accurate will be the waveform of the recovered MUAP. If the noise in the averaged time periods is independent, then the improvement in the signal-to-noise ratio of the recovered waveform will be proportional to the square root of the number of time periods that are averaged.

The decomposition approach described in this chapter provides the high accuracy required and at the same time provides the means of extracting the waveform of several MUAPs from the same EMG signal.

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 a plot is presented in Figure 4.8. 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.

Interpulse Interval vs. Time during the Contraction Plot (IPI DOT Plot)

The left vertical coordinate of each *dot* represents the time (in ms) since the last firing of the same motor unit. An example of such a plot is presented in Figure 4.9 (*top*). Each *horizontal division* indicates the discharges of an individual 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

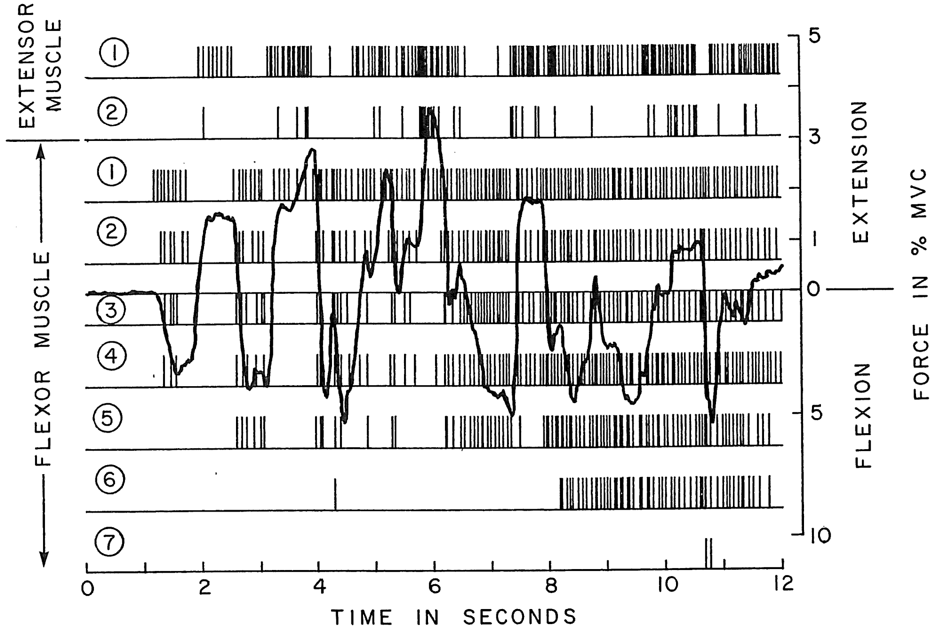

Figure 4.8. Example of IPI BAR plot. Each *vertical bar* represents the arrival of a MUAP at the time (since the beginning of the contraction) indicated on the *horizontal line* at the *bottom* of the *graph*. Each *horizontal strip* presents the activity of a different motor unit. The *continuous line* represents the output of the force transducer scaled on the *right vertical coordinate* in percent of maximal voluntary contraction (MVC). This particular example contains motor unit action potential trains from two antagonist muscles (flexor pollicis longus and extensor pollicis longus) detected during random isometric flexion-extension of the interphalangeal joint of the thumb.

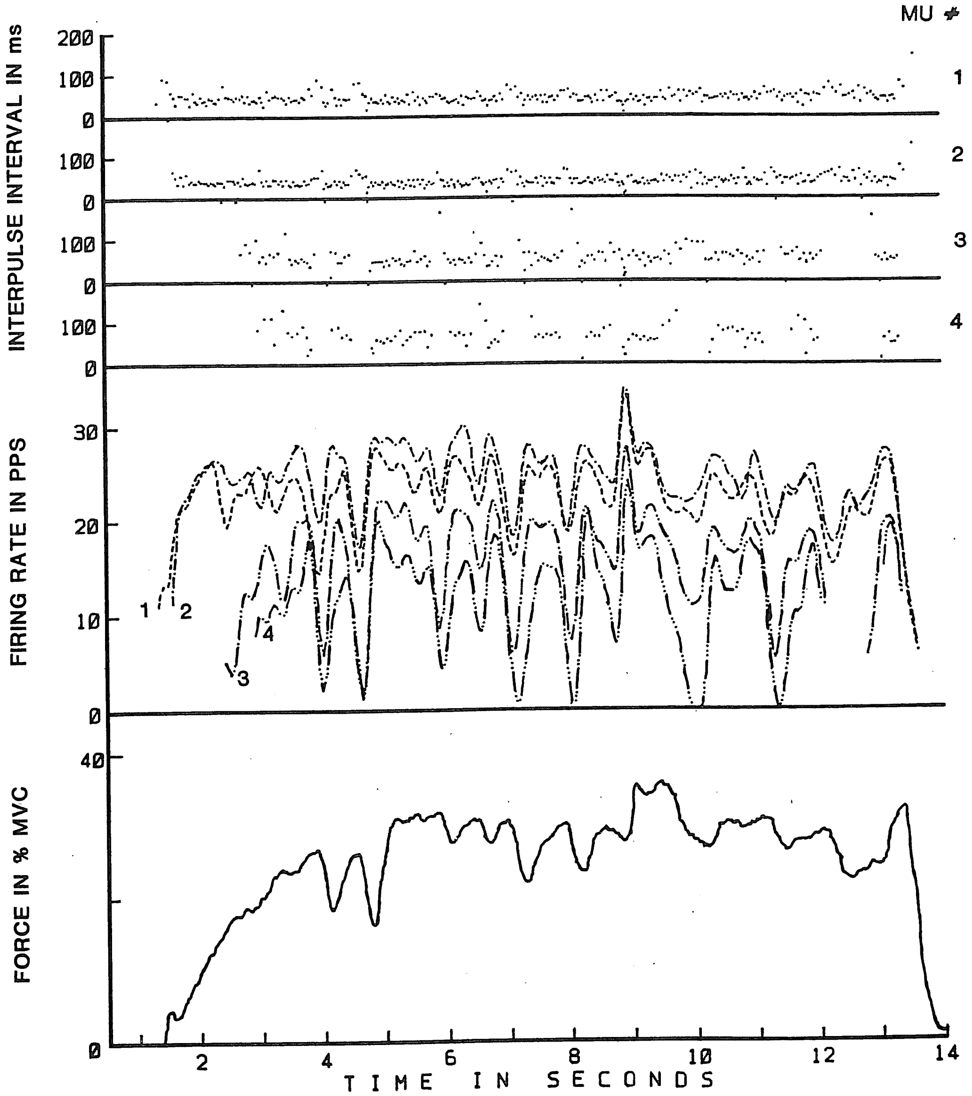

Figure 4.9. Example of IPI DOT plot (*top*) and motor unit firing rate plot (*middle*). In the IPI DOT plot, each dot represents a MUAP arrival at the time indicated on the *horizontal coordinate*. The *left vertical coordinate* is the time since the last firing of the same motor unit (in milliseconds). 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* (*bottom*) 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 presented in the IPI DOT plot.

indicative of a missed detection or of a misclassification unless such an event is accompanied by a consistent event in the force record.

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. It is customary to express this measure as pulses per second. Note that the term *firing rate* is used, rather than firing frequency, which is often found in the literature. The term frequency implies periodicity among the discharges of a motor unit. Such is not the case. The IPIs are semirandom in nature, hence, the concept of *rate* must be used to describe the behavior of the discharge properly. The firing rate value may be obtained by inverting the value of the IPI interval(s). If only one IPI is used, the instantaneous firing rate is obtained. This value will be semirandom in nature. It contains exactly the same information as the IPI value.

A more useful measure of the behavior of the firing rate of a motor unit during a contraction may be obtained by calculating the time varying mean firing rate. This is obtained by averaging the value of the instantaneous firing rate over several consecutive values. Referring back to the descriptions of the averaging process in Chapter 2, the reader is reminded that the average value may be obtained in various ways, each requiring a tradeoff between smoothness and bias of the results. This issue is particularly important in calculating the mean firing rate because it is always preferable to be able to associate the behavior of the mean firing rate of a motor unit at any time with the physiological behavior at that time and with minimal bias on previous behavior. This requirement may be accomplished by estimating the time-varying mean firing rate by convoluting the impulse train presented in the IPI BAR plot (Fig. 4.8) with a noncausal Hanning filter having a symmetric, unit area impulse response. The mathematical expression of this operation may be expressed as follows:

$$h(t) = \frac{1 - \cos(2\pi t/T)}{2};\ 0 \le t \le T$$

$$h(t) = 0 \text{ elsewhere}$$

where T determines the width of the time window over which the "filtering" is performed. This filter is recommended because it achieves a very sharp attenuation, thus rendering a smooth time-varying mean firing rate with minimal bias. Practical experience has indicated that a T value of 400 to 500 ms provides an acceptable and useful compromise between estimation bias and smoothness. The above operation is equivalent to multiplying each IPI by the filter function and shifting the filter function along the time scale.

An example of the time-varying mean firing rate is presented in Figure 4.9 (*middle*). 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 Figure 4.9 (lower portion), the continuous line represents the output force, scaled in percent maximal voluntary contraction on the *vertical coordinate.*

Correlation of the Mean Firing Rates

This operation should not be attempted unless the mean firing rate is calculated from IPIs which are identified with at least 99% accuracy, relating to false classification (Shiavi and Negin, 1973). The decomposition system described in this chapter can ensure such occurrence under specific conditions and, hence, makes this analysis procedure possible.

The concept of cross-correlation of two signals, $x(t)$ and $y(t)$, is defined by the mathematical expression:

$$R_{xy}(\tau) = \frac{1}{T}\int_0^T x(t)\, y(t+\tau)\, \mathrm{dt}$$

In words, the cross-correlation function is estimated by the following operations:

1. Delay (or shift) the signal $x(t)$ relative to the signal $y(t)$ by a time displacement equal to τ seconds.
2. Multiply the value of $y(t)$ at any instant by the value of $x(t)$ that had occurred τ period of time before.
3. Average the instantaneous value product over the sampling time, T.
4. Repeat the above steps for another value of τ.

This operation provides a measure of the amount of common behavior among the time-varying firing rates of two motor units. In a sense, it is the indication of the common input that drives the motor unit to fire.

Figure 4.10 presents examples of the cross-correlation of motor unit firing rates obtained during constant force contractions. Figure 4.10*A* represents the time-varying mean firing rates of four motor units and the attempted isometric constant-force produced by the muscle. Figure 4.10*B* presents the cross-correlation among the firing rates, and Figure 4.10*C* the cross-correlation of the firing rates and the force output.

Conditional Intensity Functions

This particular operation is useful for measuring the tendency for two motor units to fire at, or nearly at, the same time, i.e., synchronization.

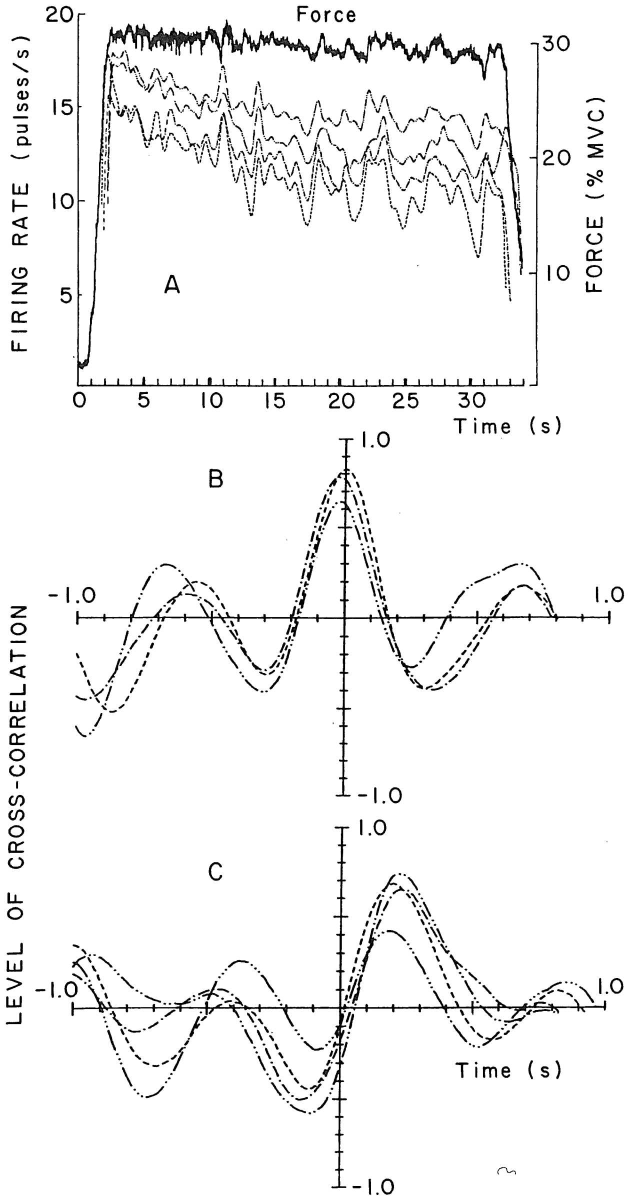

Figure 4.10. (*A*) Firing rate records of four concurrently active motor units (*dashed lines*) are shown superimposed on the force output (*solid line*) recorded during a constant force isometric abduction of the deltoid. The force level is given in percent of maximal voluntary contraction (MVC) at right. (*B*) Functions obtained by cross-correlating between firing rates. (C) Cross-correlation between firing rates and force output. Positive shift of peaks in C indicates that firing rate activity leads force output.

Unlike the cross-correlation function, which is used to measure the common behavior of the mean firing rate (obtained over several motor unit discharges), the intensity function measures the common time occurrence of individual discharges. An alternative approach to interpreting the common time occurrence of two motor units is to consider whether the occurrence of the discharge of one motor unit "conditions" the other motor unit to discharge.

The conditional intensity function may be calculated according to the following steps. Consider two motor units, A and B. For each firing of motor unit A (the conditioning motor unit), measure the time difference to the firing of motor unit B (the conditioned motor unit) in both the forward and backward time direction up to a predetermined scanning interval. Accumulate the time values in a histogram. Bin widths of 0.5 ms and scanning intervals of 100 ms are suggested. Divide the total number of discharges of motor unit A within the scanning interval. The units of the histogram are now expressed in pulses per second, similar to the units of the firing rate. The histogram now provides an expression of the *intensity* of firing of the conditioned motor unit B when the conditioning motor unit A fires. This kind of representation has often been referred to in the literature as poststimulus histogram or cross-correlograms, where the conditioning "stimulus" can be the occurrence of any particular event such as tendon tap or the application of electrical stimulus. In this particular case the "stimulus" is the occurrence of a motor unit firing.

A bin width of 0.5 ms may be too small to collect any significant number of firings in a single bin. One possible solution in this case is to group 0.5-ms bins in larger bins. Another approach is to smooth the original conditional intensity plot with a filter having an appropriate impulse response.

The example in Figure 4.11 shows conditional intensity functions of one motor unit with respect to another conditioning unit. The histogram was smoothed with a 4-ms window triangular filter. The two MUAPTs required for this operation were obtained from the flexor pollicis longus muscle during an isometric contraction of the interphalangeal joint of the thumb. The *horizontal axis* represents the time (in milliseconds) since the firing of the conditioning units, and the *vertical axis* represents the conditional intensity in pulses per second. The example may be interpreted in the following way. The conditioned and conditioning motor unit have a tendency to fire together (synchronize) which is manifested by the high conditional intensity values at time zero. The peaks every 75 ms are a result of the periodic nature of the conditioning unit over the computation time interval. If the conditioning motor unit has a mean firing rate of 1/0.075 pulses per second, on the average every 75 ms after (before) the zero time, the conditioning motor unit will fire (fired)

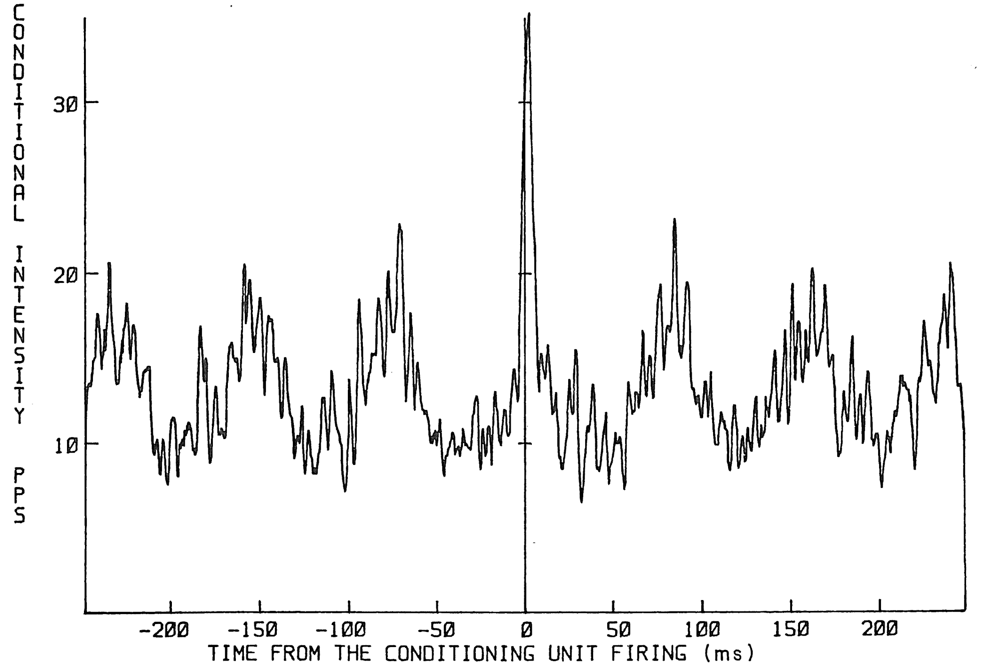

Figure 4.11. Example of a motor unit conditional intensity function. The *horizontal axis* represents the time (in milliseconds) since the firing of the conditioning unit, and the *vertical axis* represents the conditional intensity (in pulses per second). The large peak at time zero indicates that the conditioned and the conditioning motor unit tend to fire simultaneously.

again, and the same tendency to synchronize will produce the periodic peaks in the plots.

SUMMARY

In this chapter, we have described a system for acquiring, processing, and decomposing EMG signals for the purpose of extracting as many MUAPTs as possible with the greatest level of accuracy. This system consists of four 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 of displaying the results. The more frequently used representation formats are:

1. Display of MUAP waveshapes
2. Impulse trains representing motor unit firings
3. IPI plots, where time intervals between successive firings of the same motor unit are 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
5. Cross-correlation of firing rates which indicate the amount of common drive in the motor units
6. Conditional intensity functions which provide an indication of the amount of synchronization among motor unit discharges

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. Accuracy on real EMG signal by comparing results pertaining to the same MUAPT contained in two EMG signals which were independently and simultaneously detected from two different electrodes