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VIII. Properties of Muscle

A. General

Cross-Talk Between Myoelectric Signals of Adjacent Muscles

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Progress—Electrical stimulation techniques have enabled us to quantify the cross-talk or interface between adjacent muscles. The presence of cross-talk is a problem for myoelectric controls such as those used in prostheses and for analyzing the functional performance of antagonist and synergist muscle coactivation. Because voluntary control is goal-oriented, any effort to move a joint results in the activation of a number of synergistic and antagonistic muscles. The surface myoelectric signal recorded from one muscle may be affected by the electrical activity of its neighbor. This issue has never been investigated in quantitative detail.

Electrical stimulation of a nerve branch produces more selective control of an individual muscle than that achieved by a voluntary contraction. Therefore, electrical stimulation provides a suitable method of investigating the cross-talk between individual muscles. Surface myoelectric signal readings were taken from directly stimulated and adjacent muscles. The four-bar electrode developed for conduction velocity measurements (described in our 1984 Activities Report) allows us to verify that the myoelectric signal does not result from adjacent muscles.

Preliminary Results—Preliminary results demonstrate that the myoelectric signal generated by the electrical activation of the tibialis anterior muscle is present on the peroneus brevis muscle (5-15 percent) and on the soleus muscle (3-8 percent). These findings clearly reinforce the need to develop appropriate techniques when selectivity is an important experimental requirement.

Topical Anesthesia and Muscle Hypertonicity

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Progress—Some form of muscle rigidity (spasticity) affects at least 6 million people in the United States. The estimated annual cost to our society for health care and the reduction of manpower in the work environment exceeds $20 billion.

We have been experimenting with a noninvasive technique for rehabilitating patients who have suffered from strokes or head injuries. This technique entails the application of a topical anesthetic to selected skin areas on the affected limbs. We have observed that these applications are associated with notable decreases in muscle rigidity and often with increased limb mobility. The short-term effects (within 1 hour after application of the topical anesthetic) have been studied in 80 patients; the long-term effects are currently under investigation. To
date, we have collected various data concerning kinematic parameters, reflexes, and expressions of functional capabilities on 12 patients with stroke and head injury.

One of the electrophysiological tests made on the patients consisted of measuring the muscle response induced by an electrical stimulus to the nerve supplying the gastrocnemius and soleus muscles in the leg. These measurements were taken at various intervals during a 1-month segment in which the patients had the topical anesthetic applied to their legs 3 days per week and were requested to perform an exercise program while the muscle rigidity decreased. This test was intended to measure the sensitivity of specific neuronal connections in the spinal cord and to observe whether they were modified as a function of the therapy program. The data analyzed to date suggest that the topical anesthetic has an effect on the muscle response that is similar to that previously observed in healthy subjects. It now remains for us to study the time progression of the effect as a function of the exercise program.

External interest in this project continues to be high. We continue to receive many requests for information about our work from patients and clinicians.

Surface Electrode Design

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Progress—Clear and accurate detection of myoelectric activity from the surface of a muscle is a basic prerequisite for the detailed evaluation of muscle behavior. Most of our laboratory and clinical evaluations require some type of surface electrode to observe muscle signal properties such as amplitude, spectral shift, conduction velocity, and location of motor points. These parameters are useful in evaluating the status of an actively contracting muscle.

During the past few years, we have developed several configurations of active surface electrodes that do not require the use of conductive paste or gels. Each electrode configuration is based around an electronic circuit containing a high-impedance, low-noise, differential preamplifier housed in small, rugged, epoxy packages. (A detailed description of the active surface electrode concept appears in the NMRC 1983 Activities Report.) We have found that these surface electrodes have the mechanical and electrical stability necessary for reliable and consistent low-noise myoelectric recordings. We now use these “standard” electrodes in a vast majority of our laboratory experiments, such as those concerning muscle fatigue.

Currently, the circuitry and mechanical configuration of our active surface electrode designs are being reviewed. Fabrication using hybrid or monolithic circuit techniques is being considered for further standardizing our electrode designs. Designing our surface electrodes for production procedures using current standard manufacturing technology would enable other laboratories to use our surface electrodes.

Multi-Channel Surface Electrode Array

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Progress—Recently, two Boston University students working under the guidance of the NeuroMuscular Research Center and the Liberty Mutual Research Center in Hopkinton, MA, have designed and constructed a prototype electrode array for detecting myoelectric signals.
Properties of Muscle

The array consists of 16 button electrodes arranged in a 4 x 4 grid, covering an area of 60 mm². Signals from the electrode contacts can be combined in a variety of patterns, making this configuration suitable for many recording applications. The array may prove useful for measuring conduction velocity and muscle fatigue parameters, for locating innervation zones, and for studying cross-talk among different muscle groups. Research work focusing on these potential applications is continuing at our laboratory.

B. Muscle Contraction

The Myoelectric Signal Decomposition Technique

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Progress—During the past several years, a procedure for studying the individual behavior and interaction of populations of concurrently active motor units has been developed and refined. Information is obtained by analyzing, in detail, the electrical signal that is generated in a muscle when it contracts. This signal is called the myoelectric signal. In our technique, myoelectric signals are detected by a specialized needle electrode. The procedure has primarily three components: signal acquisition, decomposition, and the analysis of individual motor-unit information.

Work has continued on further development and refinement of the motor unit analysis procedure. These efforts have been concentrated on increasing the speed and ease with which the analysis can be performed. Improvements of this nature will further advance the clinical practicality of the technique and will facilitate physiologically based research. To this end, the use of alternate needle electrodes and signal decomposition techniques has been preliminarily studied. Program revisions and user manuals have been written to make the analysis system more readily accessible to investigators at the NeuroMuscular Research Center.

Using the motor-unit analysis technique, investigations into a number of interesting motor control questions are currently in progress. The study of the phenomenon of synchronization of motor-unit activity has been refined and extended. The effect of specific movement disorders on motor control schemes is being examined. Changes in motor-unit excitability due to the loss of skin sensory input are analyzed. Also of interest is the accuracy with which different muscles can follow a prescribed force trajectory and the implications of this to motor control.

The details of the technique were presented in June at the Second International Symposium of Computer EMG Applications in Monte Carlo, Monaco.

Control of Antagonist Muscles

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Progress—We are attempting to clarify the control mechanism of antagonist (opposing) muscles during the initiation and continued production of force associated with voluntary
contractions. Our study focuses on the flexor pollicis longus and extensor pollicis, the two sole activators of the distal thumb joint.

During isometric contractions, the firing rates of motor units within a muscle were greatly cross-correlated with essentially zero time-shift with respect to each other. This behavior has been termed the common drive. Common drive was also found to be present among the motor units of the agonist and antagonist muscles during voluntary coactivation to stiffen the interphalangeal joint. This observation suggests two interesting facts: 1) the common drive mechanism has a component of central origin; and 2) the brain may control the motor units of two (and possibly more) muscles as if they are one when the muscles are performing the same task.

We have suggested a control scheme to explain the behavior of the motor units in both muscles during varied contraction modalities. It consists of reciprocally organized flexion and extension commands originating from the brain along with a common coactivation command to both muscles. Both interact with the inhibitory and excitatory influence of sensory information that is supplied by specialized sensors within the muscle.

Articles describing our work in this area were published in *Brain Research* and the *Journal of Experimental Biology.*

**Motor Control in Movement Disorders**

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**Progress**—The myoelectric signal of normal subjects has been decomposed into its constituent motor units, and their behavior has been analyzed. The known statistical behavior of motor units from normal subjects can be used as the basis for comparing the motor-unit activity observed in subjects with different movement disorders. It is hoped that useful information can be gained from studying motor-unit behavior in impaired subjects.

Samples of the myoelectric signal from the first dorsal interosseous muscle of the hand in several patients with different movement disorders have been collected. The presence of the common drive is of considerable importance in this study. Also of importance is the relationship between motor-unit firing rates as a function of force output and as a function of recruitment threshold. Because there is considerable time and effort involved in the complete analysis of a patient’s data, efforts were focused on a patient with syringomyelia or liquid-filled cavity in the spinal cord.

It has been observed that common drive is preserved in the syringomyelia patient with clinical confirmation of deafferentation. Also, the firing rate of a motor unit, as a function of the force of recruitment, appears to be compressed when compared to similar contractions of a normal subject. A preliminary evaluation of the data obtained from the ulnar neuropathy and cerebellar atrophy patient suggests the presence of common drive.

**Synchronization of Motor Unit Discharges**

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**Purpose**—Synchronization is defined as the tendency for two or more motor units to fire with a preferred latency more often than would be expected if motor units functioned independ-
ently. In order to make accurate statements regarding the interactions of active motor units, decomposition and statistically robust analysis techniques must be employed. The goal of this work is to present irrefutable evidence indicating that synchronization is indeed a property of concurrently active motor units.

**Progress**—A computer algorithm was created that calculates the synchronization ratio—that is, a numerical estimate proportional to the amount of synchronous behavior among pairs of concurrently active motor units. During the past year we have revised this algorithm to determine the statistical significance of the results. Histograms of the relative latency between firings of two different motor-unit action potential trains are constructed. If it is assumed that the two trains act independently, the number of firings in each bin can be modeled as a Poisson distributed random variable. Consequently, we can determine the number of firings required in a bin to state at a prescribed level of confidence that the motor units are not contracting independently and that synchronization has occurred. Synchronization ratio measurements based on significant bins, defined with a 95-percent level of confidence, are used to quantify synchronous behavior.

The results indicate that synchronization exists in all 14 different muscles we have examined. We have also begun to examine the frequency and extent of synchronous behavior during recruitment of new motor units, between different-sized motor units, and across antagonist and synergist muscles.

It is hoped that these new results can be applied toward devising a clinical technique for use in the evaluation of neuromuscular dysfunction.

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**Force Output of Muscles During Voluntary Isometric Contraction**

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**Sponsor:** Liberty Mutual Insurance Company

**Progress**—Through this study we have investigated how smoothly different muscles produce a prescribed force. Different muscles use different control schemes to produce force. For example, recruitment is the major mechanism for generating force between 40 and 80 percent of maximal force in the deltoid, whereas rate coding of firing rates plays the major role in the first dorsal interosseous muscle of the hand. We have begun to investigate how these different control schemes affect the smoothness of the force output produced.

Muscles are incapable of producing a purely isotonic constant force contraction even under isometric conditions. In our previous work we have shown that the firing rates of motor units have a common fluctuation that oscillates at 1-2 Hz. These firing-rate fluctuations are causally related to similar fluctuations in the force output of the muscle.

Through analysis of the power spectrum of the force output we have begun to investigate the frequency and amplitude of modulation of the firing rates and the force output. The smoothness of the force output will be described through linear regression analysis and normalized errors. Comparisons between different muscles at different force levels and with various types of isometric contractions will be made using the standard T-test.

Results of this study will provide an indication of how efficiently the neuromuscular system produces isotonic force output.
Sensorimotor Interaction in Motor Unit Control

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Progress—For several years we have been investigating a procedure whereby we apply a topical anesthetic to the skin and observe dramatic modifications in the response of the underlying muscles. Our work has shown that this procedure is particularly beneficial to stroke and head-injury patients who have muscle rigidity and a limited range of movement in their joints. In order to more fully understand the underlying physiological modifications, we have undertaken a study to investigate the effect on the individual motor units in the involved muscles. Our current work is limited to studying the changes that occur at the threshold of recruitment of motor units when the nearby skin is desensitized.

Myoelectric signals are detected from a hand muscle, the first dorsal interosseous, in healthy men during an increasing and decreasing force output, while a specialized needle electrode is inserted into the muscle. Motor-unit recruitment patterns are determined by the signal decomposition previously described. The effect of skin desensitization is examined by comparing the motor-unit recruitment threshold before and after the application of the topical anesthetic.

Preliminary Results—Preliminary indications are that the recruitment thresholds of larger motor units decrease and the recruitment thresholds of smaller ones increase. This modification suggests that inputs to the larger motoneurons and those to the smaller ones are not qualitatively similar in man. This preliminary result also explains the increase in the force output observed in stroke patients.

Automatic Decomposition of the Electromyogram

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Purpose—The electromyographic (EMG) examination plays an important role in the diagnostic evaluation of many neuromuscular disorders. It involves recording an electrical signal from a contracting muscle using a needle electrode. In current practice, most neurologists assess EMG signals in a way that is qualitative and subjective—by listening to their sound and by watching their pattern as they flash across an oscilloscope screen in real time.

There is a widely felt need for a quantitative method for analyzing EMG signals that would be more objective, more reproducible, and more diagnostically sensitive than the subjective methods in current use.

Two major approaches to quantitative EMG analysis have been taken. The first has been to decompose the signal into its component motor-unit action potentials (MUAPs). This has proved diagnostically sensitive but is limited to weak contractions because of the difficulty of decomposing high-force EMG signals, commonly called "interference patterns" because of their resemblance to random noise. The second approach has been to try to characterize high-force interference patterns statistically—for example, by their power spectral density. This has proved insensitive and unreliable. Thus, no method of quantitative EMG analysis has gained wide acceptance.

Progress—We hypothesized that advanced signal-processing techniques could be employed to efficiently and accurately decompose moderately complex EMG interference patterns into their component MUAPs.
We wrote a computer program (ADEMG—Automatic Decomposition Electromyography) for extracting MUAPs from EMG signals recorded during conventional EMG examinations. The program achieves greater speed and accuracy than existing EMG analysis methods through the use of four innovative signal-processing techniques: 1) a fast digital filter for transforming MUAPs into sharp spikes that can be easily detected and accurately identified; 2) an efficient algorithm for aligning and comparing spikes that achieves high temporal resolution at a low sampling rate; 3) a method for verifying or rejecting tentatively identified MUAP trains based on the regularity of their interspike intervals; and 4) a new noise-reducing algorithm for back-averaging the MUAP waveforms from the raw signal using their identified spikes as triggers. The program can analyze a 10-second EMG signal in 90 seconds of computation time and is able to decompose signals containing as many as 15 MUAP trains.

**Preliminary Results**—We used ADEMG as implemented on a PDP-11/34 minicomputer to collect normative MUAP properties for the biceps muscle and are continuing to collect a database of properties from other muscles and from patients with known neuromuscular disorders. Tests of the ADEMG method's accuracy and diagnostic sensitivity involving computer simulations and a comparative study with other quantitative EMG techniques on groups of patients with selected neuromuscular disorders are under way. ADEMG is also being implemented on a commercial electromyograph to make it more widely available to neuromuscular electrodiagnosticians.

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**Quantitative Analysis of the Surface Electromyogram**

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**Purpose**—Diagnostic electromyography (EMG) is an important tool in the evaluation of patients with known or suspected neuromuscular injuries or diseases. Most clinical applications of diagnostic EMG require that data be collected using intramuscular needle electrodes, which is usually a painful procedure.

If the EMG activity from superficial muscles can be quantitatively analyzed in a diagnostically meaningful way using surface (skin) electrodes, the discomfort of the procedure will be reduced. Serial EMG monitorings (e.g., of response to therapy for neuromuscular disability) would become more feasible, particularly for individuals with low pain tolerance as well as for children.

Previous studies of surface EMG have demonstrated that it does contain some diagnostically relevant information, but clinical application has been limited by distortion of the myoelectric signal from volume conduction through the interposed tissues.

**Progress**—We hypothesized that the surface EMG could be decomposed into its constituent motor-unit action potentials (MUAPs) using new, computer-based analysis techniques and that these surface MUAPs could be shown to contain information relevant to neuromuscular diagnosis and evaluation.

We developed a new computer technique, Automatic Decomposition EMG (ADEMG), which decomposes the EMG signal into its elemental MUAPs. This method is currently undergoing validation and clinical testing on conventional, needle-recorded EMG data. We are applying ADEMG also to the analysis of surface EMG data derived from normal individuals as well as from patients with selected neuromuscular disorders.

**Preliminary Results**—The Rehabilitation Research and Development's laboratory of neuromuscular electrophysiology has been equipped and configured for the collection and processing of human EMG data. This laboratory will func-
A Smart Trigger for Real-Time Neuroelectric Spike Classification

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Purpose—Neuroelectric signals recorded from muscle, nerve, and brain often contain action potentials or "spikes" arising from more than one cell. In order to examine the behavior of the individual cells, it is necessary to sort out the spikes. Some applications demand that this sorting be done with high accuracy in real time.

Important applications for a high-performance real-time spike classifier include basic electrophysiology, single-fiber electromyography (SFEMG), and functional electrical stimulation (FES). In basic electrophysiology, such a device would make studies of cellular behavior easier and more accurate. In SFEMG—a technique for diagnosing neuromuscular disorders in which a sensitive needle electrode is used to observe the discharges of individual muscle fibers—such a device would make the SFEMG examination less technically difficult and more practical for widespread use. In FES, such a device could be used to derive control signals for a prosthesis or paralyzed muscle from the discharges of individual motor units in an intact muscle. Presumably, these control signals would reflect the user's intentions more sensitively than signals derived from gross surface EMG.

At present, spikes can be sorted in real time by an electronic device called a window discriminator, or they can be sorted off-line by computer. Window discriminators are fairly simple, and hence somewhat intractable and simple-minded; they require careful hand tuning, have difficulty distinguishing similarly shaped spikes, are sensitive to changes in spike shape, and give unsatisfactory results if more than two or three spike trains are present. Computer analysis, on the other hand, can achieve excellent sorting performance by bringing sophisticated signal-processing algorithms to bear. Up to now, however, computer analysis has been too slow for real-time use.

Progress—We hypothesized that powerful signal-processing algorithms for spike detection and discrimination could be implemented on today's fast microprocessors to build an inexpensive high-performance real-time trigger. We expected that this device would be a useful instrument in basic electrophysiology and that it would simplify SFEMG examinations, thus making SFEMG diagnosis more common and more reliable.

We designed a device, which we call the Smart Trigger, that is able to automatically discriminate up to eight different spike waveforms on a single input channel and can deliver trigger pulses on eight separate output lines. It can be set to trigger on the input signal itself or on its first or second derivative. (Differentiation often improves triggering performance by flattening the signal baseline and sharpening the spikes.) The Smart Trigger uses the template-matching method—which takes into account the spike's full waveform rather than just a few features—to sort the spikes. The waveform of each spike that crosses a detection threshold is characterized by a 16-word "signature," and a template is stored for each different signature encountered. When the same signature is detected four times, it is assigned to an output line, and thereafter a trigger pulse is generated on the line each time a spike with that signature is detected. The templates are constantly updated to track slow changes in spike shape.

Preliminary Results—A prototype of the Smart Trigger is nearing completion. It employs three microprocessors operating in parallel. The input signal is sampled by an analog-to-digital reconversion in parallel with the Stanford EMG lab for ADEMG processing of depth and surface EMG recordings to continue our work in quantitative analysis.
The system is controlled by an M68000 microprocessor that also manages the front-panel switches and displays. To compensate for the delay through the system, the M68000 also buffers the input signal (on an auxiliary channel) to provide, via a digital-to-analog converter, a delayed version synchronized with the trigger pulses.

The EMG-Force Relationships of Skeletal Muscles Depends on Their Firing Rate and Recruitment Control Strategies

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**Purpose**—The linearity/nonlinearity of the EMG-force relationships of various skeletal muscles has been a topic of much interest and controversy. Important clinical applications of such basic knowledge await in gait, kinesiology evaluation, neurological diagnosis, and utilization of EMG in FES systems as a force feedback.

**Progress**—An adaptive stimulation system was designed and used in animal studies. The system can induce simultaneous control of firing rate and recruitment of motor units according to their size. Capabilities also allow recruitment of all the motor units to be completed when the firing rate is still increasing at various proportions.

**Preliminary Results**—Findings show that the EMG-force relationships are linear if recruitment is accounted to generate the initial 50 percent of the maximal force and firing rate the final 50 percent. As the recruitment range increases above 60 percent, the relationships become progressively nonlinear. The major conclusion on the results obtained so far from the m. gastrocnemius muscle clearly indicates dependence of the EMG-force relationship on the muscle control strategy.

Current studies explore the response of the soleus—a slow-twitch muscle to similar control strategies.

C. Muscle Fatigue

Muscle Fatigue and the Myoelectric Signal

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**Purpose**—The use of the myoelectric signal to objectively measure the rate at which a muscle fatigues has numerous rewarding prospects. The approach is based on the proven fact that the frequency spectrum of the myoelectric signal detected with surface electrodes changes in a systematic fashion during sustained contractions. High-frequency components decrease in amplitude, whereas low-frequency components increase.
Various studies during the past two decades have searched for the cause of this frequency shift and have specifically attempted to determine whether the change originates from the physical properties of muscle fibers such as their conduction velocity, or originates from control properties such as firing statistics. Although the origin of the change is not clearly understood, the effect on the frequency spectrum is consistent and is related to the progression of a sustained muscle contraction. For this reason it provides a useful mechanism for assessing the involvement of the physiological component in the fatigue characteristics displayed by individuals performing a task.

The objective measurement of physiological fatigue is essential to offset the seriously erroneous subjective evaluations that occur when psychological components are not isolated. Consequently, it is a vital tool in both industrial and health-care environments where the evaluation of fatigue-producing tasks is important.

Progress—To achieve these goals we have developed a device called the Muscle Fatigue Monitor (MFM), which automatically, on-line and in real-time, calculates and plots a single-parameter measure of the frequency shift.

A review article documenting the known facts describing the possible cause of the frequency shift, as well as evolving applications of the technique, was published in *CRC Critical Reviews in Bioengineering*. Another article was published in the *Journal of Applied Physiology*.

Muscle Fatigue and Back Pain

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Purpose—As many as 75 million Americans now suffer from severe lower back pain, and each year 7 million more people develop this problem. Despite the many millions of dollars spent on innumerable treatments for the back, the majority of patients have chronic, remitting symptoms. Improved methods for assessing back disorders could help to diminish the problem and the financial burden of this disabling condition.

Progress—We have begun to develop and implement a technique to provide the clinician with an objective index with which to measure treatment-outcome for lower back musculature. This technique estimates the fatigue rate of contracting muscles by measuring the shift occurring in the frequency spectrum of the surface-detected myoelectric signal. The dynamic interaction of synergistic back muscles during fatiguing contractions can be represented by “fatigue patterns” created by the different frequency shifts occurring in different muscles. Differences in these patterns associated with lower back disorders may represent functional disturbances in back muscles.

In preparation for implementing this technique, we have designed and constructed a restraining device to reliably stabilize the trunk in selective positions from sitting to standing. The device is equipped with strain-gauge load cells to monitor flexion, extension, or rotation torques of the trunk. A force meter placed in front of the subject provides visual feedback. In addition, preliminary modifications of another device will permit the analysis of multiple channels of myoelectric signals and will track the median frequency of the signal.

Data from 6 patients with chronic lower back pain and 16 normal controls are presently being analyzed. Preliminary results indicate substantial differences in the fatigue curves for these two groups. Additional tests to augment the sample size are under way.
Fatigue Properties of Motor Units During Voluntary and Electrically Induced Contractions

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Purpose—A major difficulty in the clinical application of functional electrical stimulation techniques is the high rate of fatigue observed in stimulated contractions. This problem is of concern when attempting to ambulate paraplegic patients or to define optimal patterns of electrical stimulation for scoliosis correction. A research project to investigate the problem was undertaken. We hope to develop optimized strategies for electrical stimulation that will improve clinical applications in rehabilitation.

During voluntary contractions, motor units fire at different rates. Each firing rate is affected by a number of deterministic and stochastic factors. The resulting signal is known as the interference myoelectric pattern. In comparison, electrically stimulated contractions result in synchronously firing motor units. Each stimulation pulse generates a sequence of responses called M-waves. This technique removes most of the stochastic components from the myoelectric signal. It is therefore possible to identify the effect of the firing-rate statistics on the surface myoelectric signal.

Progress—Mean and median frequency as well as conduction velocity of the M-wave were measured in the tibialis anterior muscle. Results were compared to those obtained during voluntary contractions. Preliminary results showed that the median or mean frequency was not directly proportional to the muscle-fiber conduction velocity. Furthermore, firing-rate statistics may not explain this lack of direct proportionality.

An article describing the technique used in this project was published in IEEE Transactions on Biomedical Engineering.

Muscle Fatigue Monitor

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Progress—The Muscle Fatigue Monitor (MFM) is an instrument that allows us to objectively measure muscle fatigue in subjects in both laboratory and field environments. The device has evolved through a series of stages, culminating in the present form. It calculates the median frequency of the myoelectric signal that occurs during a sustained contraction, using electrodes placed on the skin above the subject's muscle. Changes in the median frequency during a sustained muscle contraction are associated with the muscle fatigue process. A detailed description appears in our paper, “Muscle Fatigue Monitor (MFM): Second Generation,” published in IEEE Transactions on Biomedical Engineering, January 1985. The portable MFM device has proved useful for studying the underlying processes of muscle fatigue. We believe that such a powerful tool should be accessible to other laboratories and organizations collaborating with our muscle-fatigue research projects.

In an effort to make the MFM concept available to other researchers, we are now developing a more generalized MFM instrument.
based on the IBM PC computer. Although not as portable as the present generation MFM, the PC-based system will offer the advantage of more powerful color graphics, data manipulation, and commercial software well suited to the laboratory environment. The electronic circuitry used to measure muscle fatigue will be designed to be compatible with the standard card slots of the IBM PC series computers. Because many laboratories already possess an IBM PC-based system, the MFM circuit boards and floppy-disk MFM software are the only items necessary to complete a powerful fatigue measurement workstation.

A prototype version of this PC-based MFM system has been developed in our laboratory and was demonstrated at the International Rehabilitation Exhibition in New York in April 1986. An article describing the second generation MFM was published in *IEEE Transactions on Biomedical Engineering*. 