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XI. Muscles, Ligaments, and Tendons

A. General Properties of Muscle

Decomposition Analysis of the Surface Electromyogram

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Sponsor: *VA Rehabilitation Research and Development Service*

Purpose—Diagnostic clinical electromyography (EMG) involves analysis of myoelectric signals recorded using intramuscular needle electrodes. The use of surface electrodes rather than needles would be less painful and more easily accepted by many patients, especially children. However, surface recordings are generally considered unsuitable for electrodiagnosis because of the attenuation and distortion imposed on the myoelectric signals by the subcutaneous tissues and skin.

Recently, it has been shown that an array of small surface electrodes configured as a spatial filter is capable of overcoming some of this distortion. We are interested in developing methods to analyze surface-recorded signals, and in particular to decompose them into their constituent motor-unit action potentials (MUAPs), whose configurational properties, firing rates, and conduction velocities can then be estimated.

Progress—In some superficial muscles, such as abductor pollicis brevis, signals suitable for decomposition can be recorded differentially from a pair of small, closely spaced electrodes. In other muscles, such as brachial biceps, better selectivity can be obtained by forming a linear combination of the signals from an array of electrodes (spatial filter). An array of electrodes can also provide multiple channels of data.

We have experimented with two types of electrode: sharp pins that protrude from a plastic holder just enough (1 mm) to pierce the outer keratin layer of the skin, and flat metallic pads 2 mm square used on dry skin without electrode paste. The pin electrodes have low impedance (200 kilohms) and good selectivity, resulting in less noise, quieter baselines, better common-mode rejection, and signals twice as large and with sharper rise times than those recorded by pads. The pad electrodes exhibit high impedance (> 2 megohms) and high noise (10 μV rms), but are completely noninvasive. Signals from either pads or pins can be amplified using a conventional electromyograph.

The surface EMG can be analyzed using a method, called automatic decomposition electromyography (ADEMG), that we previously developed to analyze needle EMGs. Surface EMGs suffer from the loss of high-frequency detail, which makes MUAPs less distinctive from one another and hence more difficult to identify. This can be compensated to some extent by the additional information in a second channel. Two channels also allow estimation of the MUAP conduction velocity, based on the latency between MUAP arrival times at the two pickup points.

Preliminary Results—Our preliminary studies point to the feasibility of using surface recordings for diagnostic EMG. We have been able to decompose EMGs from abductor pollicis brevis and brachial biceps, yielding MUAPs with shapes and firing rates not unlike those seen with needle electrodes, and with conduction velocities similar to those reported in the literature.

Future Plans/Implications—Future work will involve refining the electrode design and tailoring the ADEMG algorithm for the special characteristics of the sur-

face signal. This approach to noninvasive quantitative EMG may have important application in the electrodiagnosis of neuromuscular disorders.

Publications Resulting from This Research

Decomposition Analysis of the Surface Electromyogram. McGill KC, Dorfman LJ, Howard JE, Valainis E, *Proc. 9th Ann Conf IEEE Eng Med Biol Soc*, 1987.

Automatic Decomposition of the Electromyogram

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Purpose—Automatic decomposition electromyography (ADEMG) is a computerized method for decomposing electromyographic (EMG) interference patterns into their constituent motor-unit action potentials (MUAPs) so that the configurational and behavioral properties of the MUAPs can be quantitated. ADEMG offers three advantages over traditional analysis of single MUAPs recorded during weak muscular contractions: the ability to process large numbers of MUAPs efficiently, the ability to analyze later-recruited as well as first-recruited MUAPs, and the ability to measure firing-related as well as shape-related MUAP properties.

Progress—We have measured the configurational and firing properties of 16,000 MUAPs from the brachial biceps, triceps, and anterior tibial muscles in 35 normal individuals in three age groups (20-40, 40-60, and 60-80 years old). Recordings were made during stable isometric contractions at threshold, 10 percent and 30 percent of maximum voluntary contraction, using standard concentric and monopolar needle electrodes. The MUAP properties were analyzed to determine the effects of contractile force, muscle, age, gender, and electrode type.

Results—In all muscles, increased contractile force was associated with significantly increased mean MUAP amplitude, rise rate, number of turns, and firing rate; and with significantly decreased mean MUAP duration, due to noise-dependency of the duration measurement. These results demonstrate that contractile force is a major determinant of MUAP shape and behavior properties and so must be measured or controlled in clinical EMG studies. These findings also lend support to the size principle of motorneuron activation.

Most mean MUAP properties differed significantly between muscles, pointing up the need for separate normative databases for each muscle. Mean MUAP amplitude, duration, and numbers of turns increased linearly with age, suggesting an ongoing process of progressive denervation and compensatory reinnervation. Mean MUAP firing rates decreased with age. In a subgroup of 12 age-matched gender pairs, men had larger mean MUAP amplitudes, rise rates, and numbers of turns, probably reflecting larger muscle-fiber diameters.

Mean MUAP amplitudes, rise rates, and numbers of turns were significantly greater when recorded with monopolar electrodes, while mean MUAP duration and firing rate did not differ significantly. These findings indicate that it may be acceptable to generalize normative data on MUAP duration from one electrode type to another, but that MUAP amplitudes and complexities require independent normative databases (or valid transformations).

Because ADEMG can analyze EMGs too complex to be decomposed by hand or by other computer programs, we have also investigated ADEMG's performance using computer simulations. We simulated EMGs of various complexities and noise levels using MUAPs from normal subjects. The results indicate that ADEMG typically identifies more than 50 percent of the MUAPs in a train with few misidentifications. Estimates of MUAP amplitude, rise rate, number of turns, and firing rate had standard errors of less than 2 percent while estimates of duration had standard errors of up to 20 percent. These findings validate ADEMG's identification and estimation algorithms and point out the difficulties inherent in estimating properties of MUAPs from forceful contractions.

The Myoelectric Signal Decomposition Technique

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Sponsor: *Liberty Mutual Insurance Company*

Purpose—The myoelectric signal decomposition procedure was developed by C.J. De Luca in the 1970s to study the individual behavior and interactions of populations of concurrently active motor units. The procedure consists of three parts: signal detection, acquisition, and decomposition. Individual motor unit information is obtained by a detailed analysis of the myoelectric signals detected by highly selective indwelling electrodes during muscle contraction.

Progress—Further refinement of this technique has continued since its initial development, and most recently has concentrated on increasing the speed and ease with which the analysis can be performed. Improvements of this nature have included an alternate electrode configuration better suited for the detection of myoelectric signals of suitable complexity, signal quality monitoring during signal acquisition to ensure stable myoelectric signals for high-yield decomposition, and modification of the decomposition algorithm to reduce and improve operator interaction and to maintain decomposition accuracy. Techniques for the combination of temporal information with the more classical morphological information used clinically are currently under development. Further improvements to the procedure involving initial template recognition and real time data acquisition are in the planning stages.

Results—Work in this area, however, has not been limited to refinement of the decomposition procedure; it has also included investigation of a number of motor-unit control questions. For example, using the motor unit analysis technique, a study of the phenomenon of synchronization of motor unit activity has been conducted. The effects of specific movement disorders on motor control schemes are also being examined. Changes in motor unit behavior due to the loss of skin sensory input are being investigated, as is the role of muscle function and co-contraction in the existence of common drive for motor unit pools of separate muscles. Myoelectric signals concurrently detected using several different myoelectric signal detection techniques from a common muscle volume are being combined with the decomposition technique to improve our understanding of myoelectric activity and signal composition at different levels of force and throughout prolonged, sustained contractions.

Surface Electrode Design

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Purpose—Clear and accurate detection of myoelectric activity of a muscle from the surface is a basic prerequisite for the comprehensive 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.

Progress—Over 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 me-

chanical 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. During the past year, thirty additional electrode units were produced in the Electronics Laboratory.

Results—To facilitate surface electrode attachment to large muscle groups which can be particularly difficult to secure reliably, we are investigating specialized conductive adhesives to hold the electrodes in place. These adhesives play the dual role of firmly securing the electrode to the skin and acting as an electrical contact surface used to detect the myoelectric activity. These additional features will enable the research to position quickly and reliably an array of electrodes on larger muscles such as those of the lower back.

Myoelectric Signal Quality Analyzer

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Purpose—To enhance the clinical applicability of the current myoelectric signal decomposition technique, several steps have been taken to improve the process of signal acquisition. During the past year, refinements in the design of the multichannel needle electrodes, coupled with construction of a new signal-quality analyzer, allowed the investigator to select the optimal electrode location necessary for accurate signal decomposition.

The signal-quality analyzer continually monitors the slope and amplitude of the myoelectric signals detected by the needle electrode during the experiment. The signal's slope and amplitude were chosen to categorize its waveshape and to determine if the waveshape falls within acceptable limits required for accurate decomposition.

The bar graph displays located on the front panel of the instrument indicate the instantaneous slope and amplitude of detected signals together with their adjustable setpoint limits. The device is designed to be rack mounted or the displays may be separated from the main unit and positioned close to the experiment. In this way, the instrument provides the necessary visual and audio feedback to the investigator to select the optimal position of the needle electrode. All outputs from the instrument are designed to be compatible with the existing acquisition hardware of the decomposition system's computer. The signal-quality analyzer will facilitate the usefulness of our decomposition techniques in both clinical and laboratory investigations.

The Frequency Response of Skeletal Muscles: Dependence on Control Strategies and Fiber Types

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Purpose—The correct frequency response model of a single skeletal muscle has been a longstanding problem. Only unphysiological control inputs (firing rate) could be used or alternate analogue models that preassumed the interaction mode of firing rate and recruitment (which were unknown until recently) could be used.

Progress—We tested the soleus (slow twitch) and m. gastrocnemius (fast twitch) under several physiological control strategies with the aid of our newly-developed stimulation system.

It was shown that the frequency response model consists of a second order system with double poles at 1.8 Hz. This was independent of the control

strategy used, the predominant muscle fiber type, or the force perturbation level. A pure time delay differentiated the models for fast and slow twitch muscles, being 11 msec and 16 msec, respectively.

Preliminary Results—Firing rate control input was reaffirmed to result in a nonlinear model as previously described in the literature.

Skeletal Muscle Reaction to Immobilization

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Sponsor: *None Listed*

Purpose—The purpose of this study was the prediction of reaction of human skeletal muscle to immobilization in various conditions regarding length, duration of immobilization period, and position of the limbs.

Progress—A muscle model, relating architecture of the skeletal muscle to its functional capacity, was formulated and experimentally determined on rat calf muscle and various others.

Application on human calf muscle, using morphological data of human cadavers has been done. The model was also applied in a description of muscular growth. Now it is used in analyzing the effects of various periods of immobilization in different positions, leading to differing muscle lengths.

The work is part of a program on "form, function and coordination of skeletal muscles," in which it is tried to relate experimental analysis of animal muscular function to real life human movements in vertical jumping and running.

Preliminary Results—Reaction of muscles to immobilization is very complex and not only varies with muscular position between stretch and shortening, but also varies within the muscle belly, altering architecture, functional capacity, and properties of the contractile tissue.

Future Plans/Implications—During the next year, varying modes of immobilization and their effects on muscular fibers (length, number of sarcomeres, type) and their position in the muscle belly will be studied. Next, interaction of these processes and growth (hypertrophy) will be induced and analyzed.

B. Muscle Contraction

Decomposition of Surface-Detected Myoelectric Signals

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Purpose—A procedure for the partial decomposition of surface-detected myoelectric signals has been developed. Myoelectric signals are simultaneously measured by selective surfaces of a needle electrode, the cannula, and a nearby surface electrode. A data collection-compression routine digitizes and acquires epochs of the selective needle signals containing motor unit action potentials (MAUPS), while the cannula and surface signals are continuously digitized and stored. The selective needle signals are decomposed into their component motor unit action potential trains (MUAPTs). The extracted MUAPTs are used to ensemble-average the cannula and surface-detected signals resulting in estimates of some of their constituent MUAPs. The MUAP estimates, and their respective MUAPT, are used

to decompose partially the cannula and surface myoelectric signals.

Results—The results of the data analysis reveal the potential for using the technique to investigate specific myoelectric phenomena. The size of the cannula and surface macro potentials are dependent on the size of the contributing motor unit and its proximity to the detection surfaces. Information on cannula and surface signals allows the study of size and distance effects. Although the amount of data analyzed is limited and the proportion of cannula and surface signals accounted for is small, the technique has been demonstrated to work and yield information that, upon further analysis, should augment our understanding of myoelectric activity and signal phenomena.

Muscle Force Output During Voluntary Contractions

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Purpose—This research effort focused on the study of fluctuations in the force output of the first dorsal interosseous, bicep, tricep, deltoid, tibialis anterior, soleus, and gastrocnemius/soleus muscles in healthy humans.

Progress—Subjects generated constant-force contractions at 20, 30, 60, and 80 percent of maximal voluntary effort. The signals analyzed were the deviations of the force signals from their means. Spectral and temporal analyses and quantification techniques were performed on the force-fluctuation signals. The signals were quantified by calculating the mean square value of the force fluctuations. Statistical analyses were performed on the results. The quantified fluctuations were then analyzed to examine their relationship to the function, fiber typing, and size of the different muscles.

Results—This study demonstrated that as the magnitude of the mean force increased, so did the magnitude of the force fluctuations. Spectral analysis revealed that the majority of the energy of the force fluctuations was below 5.0 Hz. The force fluctuation was separated into two components: extrinsic and intrinsic. The two components correspond respectively to the 0.1–0.8 and 0.8–13.0 Hz frequency bands. The extrinsic component is thought to be due to intentional effort by the subject to correct the force output. The extrinsic component is not a function of fiber type, function, or size of the muscle. The intrinsic component was found to be independent of muscle function. Fiber typing alone was not related, but when discussed in unison with the recruitment properties of the muscles, it does explain changes in the behavior of the force fluctuations. There exists a relationship between the size of the muscle and the intrinsic component. When the number of motor units increased, the intrinsic normalized deviation decreased in an exponential fashion.

Cross-Talk Between Myoelectric Signals of Adjacent Muscles

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Sponsor: *Liberty Mutual Insurance Company*

Progress—Surface myoelectric signals were detected from the skin surface above the tibialis anterior muscle, the peroneus brevis muscle, the soleus muscle, and the tibial bone during selective maximal electrical stimulation of the tibialis anterior muscle in 12 normal subjects. The double-differential technique developed by Broman, Bilotto, and De Luca (1985) was used to determine that the detected

signal was due to volume conduction from the tibialis anterior fibers. The ratios between peak-to-peak values (PP), average rectified values (ARV), and root mean square values (RMS) of the detected M-waves were used as cross-talk indices. The values ranged from 4.8 to 33.0 percent (PP), 4.7 to 36.0 percent (ARV), and 7.7 to 37.4 percent (RMS) for the tibial bone area; from 4.0 to 20.0 percent (PP), 3.5 to 10.0 percent (ARV), and 3.0 to 8.0 percent (PP), 3.4 to 9.1 percent (ARV), and 2.0 to 9.8 percent (RMS) for the soleus muscle area. Neither peak-to-peak values, average rectified values, nor root mean square values appeared to be correlated with leg size.

Results—It is concluded that a surface myoelectric signal detected on the skin above a muscle and having an amplitude of up to 17 percent of a signal detected above a neighboring muscle may be due to cross-talk rather than to activation of the muscle below the electrode.

A manuscript describing this work is in preparation.

Synchronization of Motor Unit Discharges

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Purpose—Synchronization of motor unit discharges is the tendency for pairs of motor units to contract with preferred latencies relative to each other, more often than would be expected if the motor units were functioning independently. A study of the interdependence of concurrently active motor units was performed.

Progress—Myoelectric signals were detected from healthy subjects during voluntary isometric contractions using a selective indwelling electrode configuration. The signals were decomposed into their constituent motor unit action potential trains (MUAPTs). Pairs of MUAPTs were then analyzed to determine if any interdependence existed. Histograms were created of the time intervals between the firing of a triggering or conditioning motor unit to the subsequent firing of the alternate or conditioned motor unit of a pair. Assuming the motor unit pairs are operating as independent Gaussian point processes, the histograms should be flat with an approximate expected value dependent on the histogram bin width and the mean firing rate of the conditioned motor unit. Bins containing 1.96 standard deviations more than the expected number of occurrences indicated a 95 percent confidence level statistically significant interdependence or synchronization.

Results—Synchronization measurements of motor units studied in the human first dorsal interosseous (FDI), deltoid, and tibialis anterior (TA) muscles during a variety of force protocols indicate that more than 60 percent of the motor unit pairs examined exhibited synchronization. The latency of the maximi was most often within ± 5 ms and had an average width of approximately 4 ms. The deltoid had lower amounts of synchronization than the FDI and TA muscles, which had similar levels. Synchronization was not found to be a function of contraction level in the deltoid or FDI. The analysis of motor units in synergist and antagonist muscle pairs revealed interdependence within but not across the muscles.

The results of this study were presented in September 1986, at the 33rd Annual Meeting of the American Association of Electromyography and Electrodiagnosis in Boston, and in November 1986, at the 16th Annual Meeting of the Society for Neuroscience in Washington, D.C.

The Common-Drive Principle of Motor Unit Control

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Purpose—The NeuroMuscular Research Center has previously described a principle of motor unit behavior called *common drive*, which states that the nervous system controls the firing rates of homonymous motornuerons in a tightly coupled manner. Slight increases or decreases in firing rate of one motor unit are accompanied by like changes in other motor units.

Progress—In an experiment conducted in the Motor Unit Laboratory, subjects performed submaximal isometric contractions of the first dorsal interosseous (FDI) and tibialis anterior (TA) muscles while motor unit activity was recorded by a specially designed quadrifilar needle electrode, amplified, and then stored on FM tape.

Results—Off-line decomposition of the signal into constituent motor unit action potentials revealed a high degree of cross-correlation of the motor units in the TA and in the FDI. There was a tendency toward higher cross-correlation between the motor units of the FDI and those of the TA. In previous research, it has been demonstrated that common drive exists in muscles that are coactivated and functionally related. These new data suggest that coactivation is not a sufficient condition for the existence of common drive. Rather, a common functional relationship between active muscles also appears to be necessary.

Exercise-Induced Adaptations of Skeletal Muscle Grafts

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Purpose—Many characteristics of skeletal muscle grafts, including mass, functional cross-sectional area, maximum tension development, and oxidative capacity, remain below control muscle values. These deficits potentially limit the usefulness of the graft to the host organism in tasks requiring strength or endurance. In addition to transplantation, the degeneration of skeletal muscle fibers occurs following a variety of diseases, trauma, and excessive physical exercise (especially if lengthening contractions occur). Regardless of the insult inducing degeneration, regeneration of muscle fibers appears to follow a common pathway.

The objective is to determine the effects of the intensity and duration of chronic exercise on the structure and function of free and of vascularized skeletal muscle grafts. In free grafts, the muscle will spontaneously revascularize and muscle fibers will degenerate and new fibers will regenerate. In vascularized grafts, the fibers survive. In both grafts, the fibers show a large functional deficit compared to control muscle. Hindlimb muscles will be grafted orthotopically in rats. Chronic physical activity patterns will be changed by daily running on a motor driven treadmill and by ablation of muscles synergistic to the graft. It has been well documented in normal muscle, and there are limited data on grafts, that chronic exercise of the appropriate intensity and duration can increase variables which show a deficit in grafts relative to control values. The change of activity will start at 28 days postgrafting and grafts will be studied through 112 days. The capability of different chronic activity patterns to alter growth in grafts that differ as to fiber type and anatomical site will be investigated.

Outcomes will be evaluated by morphological (gross dimensions, histochemistry), biochemical (protein concentrations, protein turnover, metabolic marker), and physiological (contractile properties) techniques. Physical exercise is a complex stimulus to skeletal muscle in terms of the type of contraction, the tension development during contraction, and the

frequency, intensity, and duration of exercise sessions. Resolution of these complexities will provide the scientific basis for establishing postgrafting procedures to improve the structure and function of grafts in humans and in the rehabilitation of muscles in which some fibers have regenerated due to disease, trauma, or excessive exercise.

Motor Control in Subjects with Clinical Disorders

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Sponsor: *VA Outpatient Clinic, Boston, MA; Liberty Mutual Insurance Company*

Purpose—This study has focused on using the known statistical behavior of motor units in muscles of normal subjects as a basis for comparison with motor unit activity observed in subjects with different clinical disorders, as a means for developing new clinical diagnosis procedures.

Progress—Myoelectric signals were acquired from the first dorsal interosseous muscle of several patients with different clinical disorders. The myoelectric signals were then decomposed, and the resulting motor unit behavior information analyzed. The existence of common drive and the relationships between motor unit firing rates and recruitment levels as functions of percent maximal voluntary contraction were specifically addressed and compared to normal subject population results.

Results—Progress has been steady but slow. To date, subjects with cerebellar atropy, ulnar nerve neuropathy, and syringomyelia or liquid-filled spinal cavity have been studied. It has been observed that for the most part the common drive of motor units in these subjects has been preserved. The patient afflicted with syringomyelia appears to have a compressed range of motor unit firing rates when compared to a normal subject performing similar contractions. Further study of the data collected from these subjects and others is ongoing.

C. Muscle Fatigue

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 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 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 similar, portable device was also developed for testing patients in a clinical setting. In addition, preliminary modifications of another device will permit the analysis of multiple channels of myoelectric signals and track the median frequency of the signal.

Results—Data from numerous chronic lower-back pain patients and normal controls have been collected and are being analyzed for several areas of investigation. First, we have documented the repeatability of the myoelectric signal parameters that comprise a fatigue pattern. In this same series of investigations, we have also established the sensitivity of these measures to the level of accuracy with which a surface electrode is relocated from one day to another or for different times in the same day. This information will be vital in establishing future protocols and interpreting our data.

Secondly, we have investigated the recovery process of median frequency measurements of lower back muscles following sustained fatiguing contractions. Recovery following rest periods of 1, 5, and 15 minutes were compared for control subjects. Similar tests are planned for lower-back pain patients.

Finally, we are targeting the first in a series of specific subcategories of lower-back patients to be tested by our assessment technique. We are testing patients with at least a 6 month history of chronic back pain without radiographic evidence of spinal abnormalities. This group is being tested according to the same protocols for previous tests on control subjects. Future tests are planned for other categories of lower-back pain.

This material was presented in November 1986 at the Eighth Annual Conference of the IEEE Engineering in Medicine and Biology Society in Fort Worth, Texas, and during the same month at the 16th Annual Meeting of the Society for Neuroscience in Washington, D.C.

Muscle Fatigue and Respiratory Failure

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Sponsor: *Boston University*

Purpose—Over the last year, the Pulmonary Center and the NeuroMuscular Research Center have developed a close liaison in an attempt to study the electrophysiologic phenomena that take place in the respiratory muscles. The studies were performed on volunteer subjects and patients with emphysema and chronic bronchitis. The studies are directed at evaluating the way in which respiratory muscles are coordinated and genesis of respiratory failure. Further understanding of these phenomena may lead to the development of strategies directed at improving the function of the muscles in those patients whose lung disease is such that there is little ventilatory reserve.

Progress—Data were obtained at University Hospital and Boston City Hospital on patients with lung disease and in normal subjects. Data analysis was performed in a joint form at the physiology laboratory and at the NeuroMuscular Research Center. Myoelectric signals from different muscles, including the diaphragm and other accessory muscles of respiration, were obtained while the subjects and patients performed different activities, such as arm and leg exercises, resistive breathing, and voluntary hyperventilation, that stressed the respiratory muscles. The data were analyzed and correlated with the observed changes. Patients were then placed in either a rehabilitation program or a respiratory muscle resting plan, and the studies were repeated in 2 to 3 weeks to evaluate progress.

This joint research promises to enlarge our knowledge in the field of pulmonary physiology and introduces a new dimension in our capacity to plan better therapy.

Muscle Fatigue and Myoelectric Signal

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Sponsor: *Liberty Mutual Insurance Company*

Purpose—The use of the myoelectric signal to measure objectively 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, while low-frequency components increase. Various studies during the past two decades have searched for the cause of this frequency shift and have 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 a task performed by individuals.

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 healthcare 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.

Muscle Fatigue Monitor

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Sponsor: *Liberty Mutual Insurance Company*

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 which calculates the median frequency of the myoelectric signals that occur 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. A portable device, the MFM has proven to be a powerful tool for studying the underlying processes of muscle fatigue.

In an effort to make the MFM concept available to other researchers, we have developed a more generalized MFM instrument based on the popular IBM PC computer. This system offers the advantages of powerful color graphics, data manipulation, and commercial software well-suited to the laboratory environment. In April 1986, a prototype version of the IBM PC-based MFM system was demonstrated at the Internationai Rehabilitation Exhibition in New York City.

The final hardware design of a dual-channel signal processing card is complete. It incorporates circuit modifications that enhance the dynamic performance of the device. These modifications allow measurement of the fatigue process in muscles performing cyclic activities such as walking or repetitive manual handling tasks in the workplace. The present device is now undergoing extensive evaluation coupled with the development of a modularized software package

necessary to complete the fatigue measurement system. Plans are underway to incorporate our IBM PC-based MFM into a portable trunk analysis system to investigate the fatigue process in the muscles of the lower back.

Motor Unit Properties Investigated by Voluntary and Electrically Elicited Contractions

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Purpose—The clinical application of functional electrical stimulation techniques on muscles is limited by several factors and in particular by the high rate of fatigue observed during electrically elicited contractions. But the application of these techniques within a laboratory setting does provide a means of externally controlling the firing rate of motor units, thereby enabling researchers to conduct a quantitative study of the effect of the firing rate on the resulting myoelectric signal spectral properties and on muscle fatigue.

Progress—This study was begun in 1985 to develop optimized strategies for electrical stimulation. The results of these experiments showed that during voluntary contractions, motor units of the human tibialis anterior are recruited with ascending order of conduction velocity, reflecting an ascending order of fiber size. These results are consistent with other results found in the literature, and support the general notion of *size principle*. During stimulated contractions with surface electrodes, motor units were recruited in a progression which was not necessarily related to the magnitude of their conduction velocity. Both during voluntary and electrically elicited contractions, mean and median frequencies were not found to be proportional to the mean muscle fiber conduction velocity.

The present experimental protocol focuses on obtaining more data about motor unit behavior and evaluating the repeatability of results obtained from certain subjects on different days. In this protocol, electrical stimulation of muscles is performed at different frequencies in order to evaluate the effect of firing rate on fatigue and spectral parameters.

Results—Preliminary results show that the behavior of a subject is reasonably repeatable on different days and confirms that median and mean frequencies are not always proportional to the mean muscle fiber conduction velocity. This work was presented (abstract) in November 1986 at the Eighth Annual Conference of the IEEE Engineering in Medicine and Biology Society, in Fort Worth, Texas.

D. Ligaments and Tendons

Structural and Functional Properties of Normal and Healing Ligaments

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Purpose—The focus of the Orthopaedic Bioengineering Laboratory is the mechanics of soft tissues such as ligaments, tendons, and cartilage. Of primary interest are the structural and mechanical properties of normal and healing tissues and the development of the specialized techniques necessary to study them.

Since the inception of this project, our laboratory has devoted significant effort in developing new and improved methodology which accurately character-

izes the quasi-static and nonlinear viscoelastic properties of parallel-fibered soft connective tissues, i.e., tendons and ligaments, and the correlative biochemical changes. Using the video dimensional analyzer system, we are able to study the biomechanical properties along the bone-ligament complex. As a result, we have evaluated the healing of the medial collateral ligament (MCL) in a rabbit model whereby the mechanical properties of the MCL substance (stress-strain curves) were evaluated together with the structural properties (load and energy absorbed at failure, mode of failure, etc.) of the MCL-bone complex. A plateau of improvement was found for these parameters which suggested that ruptured rabbit MCL without treatment is not capable of fully achieving normal ligament properties.

Preliminary Results—We have found that in rabbits, the total collagen mass of surgically transected MCL increased with healing time. Furthermore, Type I collagen was partially replaced by Type III as a result of increased scar formation. The same trend was noticed in the healing canine MCL. Biomechanical studies performed describe the effects of age, a variety of surgical techniques and treatment regimens, storage by freezing, and test environments. As a result, new techniques have been established that allow for a more accurate assessment of healing ligaments. For example, a new five-degrees-of-freedom knee laxity device is now available for analyzing the varus-valgus function of the knee, secondary to ligament repair. Using this device, it was discovered that under normal knee motion, the healing MCL was protected from valgus stresses by other joint structures, particularly the anterior cruciate ligament (ACL). This finding was further confirmed by an *in vivo* pilot study. In this study, the data showed that at the early healing periods, the properties of MCL with either full or partial laceration of the ACL were not as complete as in the case of intact ACL. At six weeks, knee joints with a partially lacerated ACL were more lax (exp./control = 1.8 ± 0.2) than those with normal ACL (1.6 ± 0.5), but those with no ACL were extremely lax (2.7 ± 0.2). Additional biomechanical and biochemical tests plus longer-term experimental animals are ongoing to determine the effect of laxity on the healing MCL.

Future Plans/Implications—We plan to evaluate the ligament repair process in a model synovial joint system. Specifically, we plan to study the functional role of the healing MCL and how its injury would change the kinematics of the knee joint. A variety of treatment and activity conditions will be used in order to determine which set of conditions will maximize the ligament healing, function and strength.

Publications Resulting from This Research

Treatment of Medial Collateral Ligament Injury: I. The Importance of Anterior Cruciate Ligament on the Varus-Valgus Knee Laxity. Inoue M, McGurk-Burleson E, Hollis JM, Woo SL-Y, Award Paper. *American Journal of Sports Medicine* 15(1):15-21, 1987.

Treatment of Medial Collateral Ligament Injury: II. Structure and Function of Canine Knees in Response to Differing Treatment Regimens. Woo SL-Y, Inoue M, McGurk-Burleson E, Gomez MA, Award Paper. *American Journal of Sports Medicine* 15(1):22-29, 1987.

Temperature-Dependent Behavior of Isolated Canine Medial Collateral Ligament. Woo SL-Y, Lee TQ, Gomez MA, Sato S, Field FP, *Journal of Biomechanical Engineering* 109:68-71, 1987.

Tensile Properties of the Medial Collateral Ligament as a Function of Age. Woo SL-Y, Orlando CA, Gomez MA, Frank CB, Akeson WH, *Journal of Orthopaedic Research* 4:133-141, 1986.

Effects of Postmortem Storage by Freezing on Ligament Tensile Behavior. Woo SL-Y, Orlando CA, Camp JF, Akeson WH, *Journal of Biomechanics* 19:399-404, 1986.

A New Methodology to Determine the Mechanical Properties of Ligaments at High Strain Rates. Peterson RH, Woo SL-Y, *Journal of Biomechanical Engineering* 108(4):365-367, 1986.

Structural and Functional Properties of Normal and Healing Ligaments (Project Extension)

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Purpose—The objective of this research is to evaluate the ligament repair process in a model synovial joint system. Specifically, we plan to study the functional role of the healing medial collateral ligament (MCL) and how its injury would change the kinematics of the knee joint. Two forms of MCL

tears (one by simple, sharp transection of its midsubstance, the other by Z lengthening plus the removal of 2 mm of ligament material) will be studied. A variety of treatment and activity conditions will be used in order to determine which set of conditions will maximize the ligament healing, function, and strength. Furthermore, how the functional role of the anterior cruciate ligament (ACL) affects MCL healing will be evaluated. To achieve these goals, it will be necessary to first determine the influence of surgical repair versus conservative treatment on the size and strength of the repair/healing ligaments. These experiments will be followed by a series of studies to evaluate the factors such as ACL deficiency, rigid immobilization, cage activity, normal activity, controlled passive motion, and rigorous daily exercise programs on the ligament repair process. The timing of the onset of these manipulations and their magnitude and frequency will have to be optimized in order to achieve the most rapid and complete remodeling of the repaired/healing ligaments.

We are also interested in studies involving the use of therapeutic agents to counteract contracture developed secondary to immobilization. Promising agents such as 17β-estradiol and hyaluronic acid will be tested, as these agents have been proven to be useful in minimizing the joint stiffness secondary to rigid immobilization.

Evaluation of the quality of ligament healing and repair will include correlative studies using morphologic, histologic, bioengineering, and biochemical techniques. With the new biomechanical testing procedures developed in our laboratory, it will be possible to study the laxity of the knee, the properties at the repair line, and the remainder of the bone-ligament complex independently. This is of great importance because the effect of treatment on the elements along the ligament-bone complex, vis-a-vis area of repair, area of ligament proximal, and viscoelastic characteristics of the repair ligaments will also be analyzed and compared to normal ligaments. In addition, the study of joint laxity using our newly developed tools will aid in the evaluation of the ligament function during physiological knee movements. Histological studies and biochemical quantification of water content, total hexosamine as representation of glycosaminoglycans, cellularity (DNA), total collagen, types of collagen, and the reducible crosslinks of collagen of the repair and normal sites will also be done. As a result of this interdisciplinary study, correlation between histological, biochemical, and biomechanical changes of normal and repaired ligaments (various injury models, treatments, and activity levels) will be possible.