Classification of Paraspinal Muscle Impairments by Surface Electromyography

The purpose of this article is to provide an overview of research to develop surface electromyographic (EMG) measurements for classification of paraspinal muscle impairments in persons with low back pain (LBP). The process of developing laboratory and clinically based protocols is described. Results of studies to evaluate the reliability of these measurements and their relationships with impairments and function are discussed. Research efforts to incorporate EMG spectral measurements, such as the median frequency, into a classification system to identify different types of muscle impairments are documented. Discriminant functions have been calculated based on case-control studies to identify 2 kinds of LBP impairments from constant-force isometric tasks: (1) excessive fatigue due to muscle deconditioning and (2) inhibition of muscle activation secondary to pain or pain-related behaviors. New areas of investigation designed to improve the classification accuracy of such functions using procedures other than discriminant analysis are described. Work in progress to extend the application of the technique to tasks other than those involving just isometric contraction, including those involving repetitive trunk movement, is also described. [Roy SH, Oddsson LIE. Classification of paraspinal muscle impairments by surface electromyography. Phys Ther. 1998;78:838–851.]

Key Words: Classification, Diagnosis, Electromyography, Erector spinae, Low back pain, Median frequency, Muscle impairment.

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The lack of a diagnosis of pathology for most low back pain (LBP) disorders has led specialists in the field to devise classification schemes to quantify the extent of the disorder, facilitate clinical decision making, evaluate quality of care, and improve research. Classification systems have been proposed based on LBP symptoms, physical and psychological impairments, and disability. At times, patients with LBP disorders have been classified on the basis of a pathoanatomic approach to identifying compromised spinal structures. Anatomically based diagnoses, however, rarely identify the source of most LBP symptoms, with fewer than 15% of diagnoses confirmed by imaging techniques. Furthermore, there is a high incidence of false-positive findings from spinal imaging, which can lead to inappropriate treatment.

Symptom-based classification systems for LBP, such as that proposed by the Quebec Task Force on Spinal Disorders, were developed, in part, to overcome the limitations of traditional pathoanatomic diagnoses. The Quebec classification scheme is among the most widely recognized classification systems and is based on history, physical examination, radiological findings, and responses to treatment. This scheme is among the very few that have been evaluated for prognostic ability and predictive ability. Although the Quebec classification scheme has been used successfully for patients with LBP and pain radiating into the lower extremity, it has been criticized for its complexity (ordinal and nominal measures are mixed), and there is a lack of documented reliability. Functional assessments are among the most widely used classification schemes and include methods to evaluate the functional capacity of the trunk, general disability for activities of daily living, or combinations of the two. Although the importance of functional outcome measures cannot be overemphasized, we are reminded by Jette that the expanded role of disability measures in physical therapy research should not preclude the importance of research directed at physical impairments, particularly to gain a better understanding of the interrelationship between impairment and outcomes.

Treatment approaches for LBP disorders are based, for the most part, on reversing and preventing the recurrence of impairments of the musculoskeletal system, with the expectation that such changes will lead to improved function and reduced disability. Back pain specialists traditionally have relied on a variety of qualitative and quantitative methods to characterize the musculoskeletal integrity of the spinal complex and identify related impairments. Paraspinal muscle function has been characterized by the use of dynamosimeters. These machines provide a means of measuring mechanical variables such as the torque, speed of movement, or displacement of the trunk. The measurements are based entirely on mechanical output and thereby share what we consider a common flaw. The kinematic and force variables measured, in theory, can be purposefully altered in a manner that can affect the variables being measured. As a result, in our view, maximal physical performance may not be completely isolated from factors related to motivation and secondary gain. In addi-
Assessment approaches based on surface electromyographic (EMG) signal techniques have been proposed to overcome some of the problems believed to be present with dynamometers. One approach favors the use of EMG variables derived from the frequency spectrum of the EMG signal rather than the more familiar variables that measure amplitude. This preference is based on the usefulness of spectral measures as a fatigue index. As a contraction is sustained, the EMG signal propagates at a slower speed. The signal also undergoes an alteration in shape that corresponds to changes in the depolarization zone of the muscle membrane. Changes in membrane excitability have been associated with accumulations of muscle metabolites (eg, H\textsuperscript{+} and K\textsuperscript{+}) at the sarcolemma, and these accumulations have been implicated as sites where fatigue may occur, resulting in a progressive loss of contractile force development. The EMG components to these phenomena are referred to as “myoelectric manifestations of fatigue” and are typically measured during a contraction as a decrease in the EMG median frequency (MF) (ie, the frequency of the EMG signal that divides the signal into 2 halves of equal power).

The state of lumbar paraspinal muscles can be described by use of an information map derived from MF measurements obtained from an array of surface EMG electrodes placed on the lumbar region of the back. The technique requires the use of multiple concurrent EMG recording sites to capture the complex interplay of activation and load sharing among paraspinal muscles. The variables most commonly used to describe the MF during a contraction are calculated using either a linear or nonlinear regression analysis of the MF versus a contraction-time plot. For the linear regression model, which is described in this article, the initial value of the median frequency (IMF) is the intercept of the regression line. The rate of change of the median frequency (MF slope) is the slope of the regression line. These 2 variables describe the primary features of MF behavior during fatigue-inducing tasks. The electrodes are placed at anatomical locations corresponding to contralateral and ipsilateral regions of superficial paraspinal muscles. Differences in the information map at the beginning and at the end of the contraction are analyzed to classify the impairment.

Subject motivation is minimized as a possible confounding factor by limiting the test to a specified duration, rather than having the subject maintain the contraction for as long as possible. The information from the EMG signals is not derived from a single muscle group or a single variable, but rather it is the result of the concurrent behavior of many coactive muscle groups. We assume that the subject is likely to be unaware of, and therefore cannot volitionally control, variables derived from such a measurement scheme.

In this article, we provide a historical overview and description of research developments of EMG-based spectral measurement techniques to assess and classify paraspinal muscle impairments in patients with LBP. First, the process of developing laboratory-based and clinically based protocols and procedures are described, followed by the results of studies to evaluate the reliability of these measurements and their relationship to impairment and function. Preliminary results are discussed that address the question of how the technique has evolved into a classification system to identify different types of impairment and to monitor the progress of patients with LBP undergoing rehabilitation. Finally, new areas of investigation are described to improve classification methods and extend their application to more “natural” tasks, including those involving repetitive trunk movement and nonisometric muscle actions.

**EMG-Based Methods to Identify Paraspinal Fatigue**

**Background**

Before the advent of recent technological advances that have incorporated data acquisition and digital signal processing capability into personal computers, EMG-based approaches to LBP assessment were limited primarily to studying back muscle activity during different postures and loads. These approaches may be extremely useful for deriving kinesiological information about back function or for developing biomechanical models of the trunk. Methods that rely on amplitude variables of the EMG signal, however, are limited in their ability to provide information about muscle fatigue. One of the earliest applications of EMG spectral measurement techniques to assess the fatigability of paraspinal muscles was conducted for a static task of maintaining a flexed trunk position for as long as possible during standing. The results demonstrated a consistent increase in the low-frequency components of the EMG signal (consistent with a decrease in MF) that paralleled reports of discomfort and inability to maintain the contraction. Andersson and colleagues extended this work by using a much larger array of surface EMG electrodes and specifying the relationship between trunk angle and load on the rate of change in the EMG spectrum. In the 1980s, a flurry of activity appeared applying EMG spectral techniques to patients with spinal impairments.
Development of Clinical Test Procedures

A first step in developing an EMG spectral technique for clinical use for patients with LBP was to develop test procedures that could categorize muscle impairments on the basis of reliable and valid EMG measurements. Spectral estimate procedures based on the fast Fourier transform require that EMG signals be obtained during constant-force, isometric contractions when signal stationarity (ie, constant variance over time) can be assured. Contractions that are not isometric introduce erratic signal variations due to changes in muscle fiber length, muscle force, and movement of electrodes with respect to the underlying active muscle fibers. Although new analysis procedures, discussed later in this article, may eventually remedy this problem, during the development of spectral techniques, test protocols at constant force were necessary to maintain a stationary signal and were therefore a common feature of all back tests involving EMG spectral measurements. Two types of isometric testing were used: (1) testing in which the subject was positioned standing, either in a test frame with load cells and force-feedback or while holding a weight, or (2) testing in which the subject was positioned prone with the trunk unsupported (ie, performing a modified Sorensen test).

Our group developed the "Back Analysis System" (BAS) in an attempt to strictly maintain isometric constant-force conditions during standing. The device, depicted in Figure 1, includes the following key components: (1) a torque feedback system to maintain constant muscle force, (2) an adjustable test frame to maintain posture and isolate the lumbar paraspinal muscles, and (3) an EMG acquisition and processing procedure that is designed for high-fidelity and near real-time display of EMG MF data.

A study using the BAS was first conducted to determine whether differences in fatigability were present between persons with chronic LBP (n=12) and subjects without LBP (n=12). We also assessed whether differences in EMG measurements between these subjects were influenced by isometric force levels and the muscle sites being monitored. The subjects with LBP in this study were diagnosed as having nonspecific, mechanical LBP characterized by frequent exacerbation and remissions. These subjects were pain-free at the time of testing and had histories of LBP for an average of 5.2 years (range = 1.5–13), during which time they avoided exercise and more than minimal activity. The results, summarized in Figure 2, confirmed our hypothesis that subjects with chronic LBP would have more fatigable paraspinal muscles than would the subjects without LBP. The differences in EMG MF data between groups were muscle-site specific and load-dependent. We believe the higher fatigue rates among the subjects with LBP, as measured by a steeper decline in the MF, were due to a shift toward anaerobic metabolic pathways and a predominant use of type II fibers resulting from chronic disuse. Although no biopsy data or direct measurements of fiber activity were taken of the paraspinal muscles in this study, the possible role of fiber-type differences was suggested by (1) the finding that differences in EMG indexes of fatigue were present only at the relatively higher force levels of contraction when type II fibers are most likely recruited in addition to the type I fibers and (2) studies identifying fiber-type impairments in patients with chronic LBP.  

Back muscle biopsies were taken as part of a recent study, and the fiber-type percentages were compared with EMG MF data. A close correlation (r = .88–.95)
The data are plotted separately for the longissimus muscle (upper panel), the iliocostalis muscle (middle panel), and the multifidus muscle (lower panel). Between these measurements was reported. Other work by our group using an in vitro model in the rat, compared. Asterisk (*) indicates $P < .05$ for significance of difference between means based on a 3-factor analysis of variance. Reprinted with permission from Roy et al. 31

![Figure 2](https://academic.oup.com/ptj/article-abstract/78/8/838/2633313)

Figure 2.
Mean slope (and standard deviation) of median frequency acquired from contralateral paraspinal muscle groups for tests conducted at 40%, 60%, and 80% of maximal voluntary contraction. Isometric contractions were sustained for a maximum of 60 seconds at each contraction level. The data are plotted separately for the longissimus muscle (upper panel), the iliocostalis muscle (middle panel), and the multifidus muscle (lower panel) as well as for left and right-sided muscle groups. Control subjects ($n=12$) and patients with chronic lower back pain ($n=12$) are compared. Asterisk (*) indicates $P < .05$ for significance of difference between means based on a 3-factor analysis of variance. Reprinted with permission from Roy et al. 31

between these measurements was reported. 34 Other work by our group using an in vitro model in the rat, which unlike humans has more homogeneous muscles relative to fiber type, showed that the fiber type proportion can be predicted by a multiple linear regression of MF variables with an $r^2 = .89$. 39

The findings of lower IMF values at the upper lumbar muscle sites in patients with LBP may be due to muscle atrophy, because a reduction in average muscle fiber cross-sectional area results in a reduction of EMG signal conduction velocity along the sarcolemma. 37 Reduced conduction velocity causes the MF to assume lower values because of the broadening of the shape of the EMG signal waveform. Paraspinal muscle atrophy has been reported in patients with chronic LBP. 40-42 Studies using animal models have demonstrated a linear relationship between MF and average muscle fiber cross-sectional area in healthy muscle ($r = .92$) and atrophied muscles ($r = .85$). 39, 43 There is strong evidence that EMG spectral measures may provide a relative measure of the changes in muscle fiber properties related to force and endurance. These measures, therefore, may be used to characterize the presence of related impairments in patients with LBP. Electromyographic techniques may have the added advantages of providing muscle-specific information as well as theoretically being less influenced by the subject’s motivation compared with techniques that are based entirely on mechanical measures of force and endurance.

A poorly understood type of impairment may be present in persons with LBP, an inhibition of muscles associated with pain. In the presence of pain, the central nervous system may respond by reducing the level of activity of some muscles, thereby accommodating a lesser share of the mechanical loads displaced across the joints they support. As a result, normal patterns of muscle activity among synergistic muscles may become altered—a so-called “favoring” of muscle use. The EMG methods described in this article have been used to measure such changes for superficial paraspinal muscles. The possible relevance of this impairment to LBP injury, treatment, and prevention is 2-fold: (1) muscle favoring, which is a pain-related behavior due to unreasonable fear and avoidance of activity, may be a source of disability among some patients with LBP 34, 45 and (2) alterations in muscle activity during tasks that load the spine may lead to overuse injuries due to inadequate stabilization of the spine because muscles that would normally be functioning are not contracting with sufficient force. 32, 23

Evidence for altered neuromuscular control of paraspinal muscles from measurements recorded in the BAS is shown in Figure 3. Electromyographic and force data are from a patient with subacute nonspecific LBP (Fig. 3A) and a comparison subject (Fig. 3B) of the same age and sex. Data are compared for tests using a “staircase” force protocol in which brief, sustained contractions were produced at progressively higher force levels following periods of rest. In this instance, subjects were tested at similar percentages of ideal body weight, thereby avoiding the need for deriving percentages of voluntary effort to normalize the target force levels. The example demonstrates that, despite the ability of the 2 subjects to produce similar relative forces, there were differences in neuromuscular control and muscle fatigability. A consistent pattern of increasing root-mean-
Examples of root-mean-square (RMS), median frequency (MF), and force data recorded during a "staircase" protocol in the back analysis system in (A) a subject with subacute LBP and (B) a control subject. The staircase protocol required the subjects to sustain a constant-force isometric contraction for progressively higher target force levels. In this instance, the subjects were tested at 20%, 50%, 70%, and 90% of their ideal body weight. Each contraction was held for 30 seconds.

Square (RMS) values with increasing force was observed in the comparison subject, whereas the changes in RMS values with force were highly variable and nonsymmetric in the subject with LBP.

Similar results are apparent for the MF curves. For the comparison subject, the MF decreased more rapidly as the force increased, and the pattern was highly symmetric and well ordered in contralateral muscle groups. In contrast, in the subject with LBP, the MF appeared to stay more or less constant for most muscles, decreasing slightly near the end of the contraction at the higher force levels. The lack of a gradual decay of MF in the subject with LBP may represent a characteristic loss of the ability of paraspinal muscles to produce greater forces as needed when external loads or torques are increased. We propose that these differences in EMG measurements reflect a characteristic signature of pain-related impairments that are likely the result of muscle inhibition and avoidance behavior.\textsuperscript{16,23,33} Work currently in progress is discussed in the EMG-based classification section of this report, as well as in the section on future development.

Reliability of the EMG Measurements

The reliability of measurements obtained for EMG spectral variables used to reflect the frequency shift of EMG signals from paraspinal muscles during isometric trunk extension has been investigated.\textsuperscript{31,54,66,47} Within-day reliability for control subjects (n=4) tested in the BAS resulted in 2% error for the IMF and 6% error for the MF slope, as calculated by the coefficient of reliability using a single-factor analysis of variance.\textsuperscript{31} Data were pooled for 6 different muscle sites. Differences in within-day reliability between MF measures also were found during a modified Sorensen test, where intraclass correlation coefficients (ICCs) for recordings from the ilio-costalis lumborum muscle were .93 for IMF and .80 for MF slope.\textsuperscript{33} Between-day variability of MF data for these modified Sorensen tests was always higher than within-day variability. For example, the ICCs for recordings
from the iliocostalis lumborum muscle for between-day trials were .86 for IMF and .56 for MF slope.

Thompson and Biedermann46 studied between-day variability for MF data for experiments performed 5 days apart in which subjects fatigued their back extensors during a weight-holding task. They reported correlation coefficients within a range of .75 to .96 for IMF values recorded from the multifidus and iliocostalis muscles. In their study, the reliability of IMF measurements was consistently higher for the iliocostalis muscle than for the multifidus muscle. Similar differences in the reliability of IMF measurements for these same muscle recording sites were reported for modified Sorensen tests performed by other researchers.33 Interestingly, comparisons of MF slope reliability for the modified Sorensen test resulted in higher reliability estimates for multifidus muscle sites (within-day ICC = .82, between-day ICC = .78) than for iliocostalis muscle sites (within-day ICC = .37, between-day ICC = .56).59 Mannion et al34 studied the reliability of MF measurements for trials performed on different days for 10 subjects with no history of LBP tested during both a modified Sorensen test and a sustained 60% of maximal voluntary contraction in a device similar to the BAS. They reported similar ICC values for the 2 test procedures and for comparisons between contralateral muscle groups for the iliocostalis lumborum muscle. The ICC values ranged from .80 to .98. In summary, this collective body of data demonstrates that several factors (eg, type of task, subject population, time period between repeated tests, muscle test site, specific MF variable being measured) must be considered when monitoring patient progress by repeating tests at different sessions.

Some researchers31,40 have identified sources of measurement variability that arise from errors in relocating the electrodes at the same site when repeating a test and from the effects of crosstalk due to volume-conducted far-field potentials. Crosstalk is a source of measurement variability because surface EMG techniques do not completely isolate EMG signals from a single muscle. The amount of crosstalk between adjacent erector spinae muscles has been estimated using a technique in which EMG electrodes are placed on the contralateral muscle and only one muscle is electrically stimulated.48 A crosstalk index was calculated as the ratio between the amplitudes of the EMG signals recorded from the nonstimulated and stimulated muscles. Crosstalk indexes in the range of 6% to 7% were reported for the longissimus dorsi muscles of 6 subjects.48 Interestingly, these crosstalk indexes were considerably less than the crosstalk index of 16.6% reported between the peroneus brevis and tibialis anterior muscles of the leg using a similar technique.49 Differences between low-back and lower-extremity crosstalk indexes may be due to the lumbodorsal fascia attenuating far-field potentials generated by neighboring muscles. Efforts to reduce crosstalk include the use of spatial filtering techniques50–52 and the selection of electrodes with smaller interelectrode spacings.17,20

Recently, some investigators53 have proposed the use of a “branched” electrode recording technique to reject constant voltage gradients across the electrode detection sites. With this technique, 3 electrode sensors are placed in parallel with the underlying muscle fiber direction, with the center electrode connected to the negative input and the 2 lateral electrodes connected to the positive input of a differential preamplifier. Results using this method demonstrated higher reliability of MF measures than traditional bipolar techniques for EMG signals recorded during a modified Sorensen test.53,54 Specifically, ICC values ranged from .56 to .78 for the branch point technique, as compared with .39 to .47 for the bipolar technique. Part of this difference may be attributable to the different subject groups investigated in the 2 studies (subjects without back pain versus subjects with back pain). Further considerations and recommendations on the issue of surface EMG electrode placement were summarized recently.20

**EMG-Based Classification Procedures**

**Background**

To be clinically useful, muscle impairment classification systems should provide a method of identifying the presence of abnormal muscle functioning in a manner that will suggest a form of treatment. Classification systems are typically based on models or procedures that converge toward a particular impairment type that is based on a single measurement or a group of measurements. We believe these systems, at the very least, provide methods for obtaining reliable measurements that can be used to identify whether there is a deviation from normal. More preferable, in our view, is a system that can also characterize the type of abnormality present as well as provide a measure of confidence for the classification. Classification assignment errors can be conveyed by a “distance” measurement from some threshold or the probability of false positives or false negatives.54

Impairment classifications, in our view, should describe categories or types of conditions that provide a basis for treatment. Simply assigning subjects to groups “A, B, C, D, . . . n” is of little clinical value, even if these assignments are without error. For instance, it would be of little value for physical therapists to know only that the EMG spectral measurements of their patients’ back muscles were not “normal.” We believe it would be more helpful if a specific classification of impairment were made, such as “poor endurance consistent with decon-
ditioning” or “muscle inhibition consistent with a pain-related behavior.” These 2 examples of impairment categories would suggest different methods of treatment because they describe different underlying conditions.

The discussion in this article regarding the application of EMG spectral measurements for back muscle impairments strongly argues for the need for such a classification scheme. Electromyographic measurement techniques that rely on multi-electrode arrays to characterize the behavior of the paraspinal muscles during fatiguing tasks are logistically complex. Algorithms that can take this complexity and formulate interpretable results are a great benefit to the user.

Examples of EMG-Based Impairment Classifications

Several EMG classification schemes, although still in their infancy, have been proposed for the purpose of identifying impairments. Within our group, we have relied on the use of a statistical discriminant analysis approach to develop formulas for categorizing EMG results and identifying which variables are most sensitive as discriminators of impairment. The statistical problem consists of developing a linear equation or “discriminant function” on the basis of variables derived from a group of subjects with LBP and a group of control subjects. From a statistical perspective, discriminant function is formulated such that the ratio of the between-group sum of squares to the within-group sum of squares (referred to as the “discriminatory power”) is maximized. Variables are selected by using a stepwise procedure that includes the variable with the most significant F value at each step after adjusting for the variables already in the model, until no more gain in discrimination can be achieved by including additional variables. A cutoff point for allocating individuals to 1 of the 2 groups is specified so that an individual is assigned to one group if his or her score exceeds the cutoff point and to the other group if the score does not exceed the cutoff point. The function is referred to as the “Fisher discriminant function” and uses a completely symmetrical classification rule to designate the cutoff point, which is normalized to zero.

The Fisher discriminant function score (or “z score”) will take on either a positive value or a negative value, indicating the group to which the individual is assigned. The magnitude of the z score will indicate the distance from the cutoff point and, therefore, how strongly that classification was made compared with the learning set. The z scores also can be converted to probabilities of being classified incorrectly into the group of subjects with LBP (ie, a false-positive result) or into the control group (ie, a false-negative result).

An example in which the discriminant classification scheme was used is depicted in Figure 4. The data were derived from 28 patients with chronic LBP apparently resulting from work-related injuries (mean age=35.3 years, SD=8.9; mean LBP duration=26.3 months, SD=31.4) and 42 control subjects with no history of debilitating LBP (mean age=26.7 years, SD=5.2). All subjects were tested in the BAS, and tests for patients with LBP were done just prior to their participation in an intensive, full-time, multidisciplinary functional rehabilitation program involving physical therapy, occupational therapy, and counseling over a 30-day period. Patients were screened by use of a battery of tests that included isometric strength testing, a modified Sorensen test for endurance, a visual analog scale for pain, and an Oswestry test for assessing disability. The discriminant analysis procedure provided a relatively high level of classification accuracy (an average of 87%) on the basis...
of 5 out of the 12 EMG variables considered. Classification accuracy was calculated by dividing the number of correctly classified subjects from a particular group by the total number of subjects from that group. The most striking difference in the pattern of EMG spectral values between the 2 groups appeared to us to be an asymmetry between contralateral IMF and MF slope for the patient group but not for the control group. Furthermore, there was a marked decrease in MF slope among contralateral muscle groups. This finding suggested to us that muscles were not contracting at a high enough force level to cause fatigue and, instead, the load was being shifted to other muscle groups. We also believe that these differences were not simply the result of weaker muscles in the patient group, because including maximal voluntary contraction in the discriminant analysis procedure did not substantially change the results.

To be certain that these results could be generalized to populations outside of the learning set, we tested another group of patients and control subjects (ie, a "holdout" sample) and analyzed their data using the discriminant function from the learning set. The results (Fig. 5) demonstrate the same level of accuracy in classification. Use of a holdout sample in addition to the learning sample also tests whether favorable classification results may be attributable to overfitting of the data (ie, having too many variables relative to the size of the subject population). Our hypothesis that the muscle abnormality identified was a manifestation of muscle inhibition related to pain was reinforced by reanalyzing the data to calculate a ratio of MF values from contralateral muscle groups (normalized so that perfect symmetry assumes a zero value and positive and negative values indicate the degree of asymmetry toward the right or left side of the back). We found that, in the patients with distinct, well-localized pain corresponding to a particular electrode location, the ratio value was below normal, indicating reduced activation at that site (Fig. 6). Furthermore, following a vigorous reconditioning program emphasizing functional outcomes, these abnormal ratio variables returned to within a normal range.

In other studies using similar analytical procedures, we have developed a discriminant function to identify abnormally high muscle fatigability associated with generalized deconditioning and disuse among patients with chronic LBP.31 We also have identified that, because of the sensitivity of EMG spectral measures to identify patients with LBP, these measures are superior discriminators compared with clinical measures of spinal mobility and strength.47

Other research groups have used similar procedures to classify patients with LBP using EMG spectral measures. Biedermann et al.50 used a discriminant classification procedure to identify subgroups of patients with LBP partitioned as physically active “confronters” (n=15) or physically passive “avoiders” (n=9) based on their response to a pain behavior checklist. They postulated that these categories reflected the clinical observation that some patients remained very active despite reported back problems, whereas other patients tended to avoid physical and social activities as much as possible, apparently to protect their painful condition. The discriminant analysis results had less than 10% classification error, based on the ratio of correct classifications to the total number of subjects in each group. There were strong similarities indicating a relatively high resistance to fatigue for the “confronters” and control subjects, whereas the “avoiders” formed a distinctly separate group characterized by high muscle fatigability as measured by the EMG indexes.
Independent retrospective and prospective EMG studies have supported the notion that the EMG spectral techniques can provide noninvasive measures of response to training of paraspinal muscles. For instance, Thompson et al. studied sedentary women randomly assigned to a control group (n=24) or to a 1-hour fitness class 3 to 5 times per week for 12 weeks (n=22); the EMG MF of the multifidus and iliocostalis muscles was compared before and after training with adaptive changes associated with physical fitness such as aerobic capacity, back strength, and flexibility. Changes in EMG spectral measurements following training indicated a 35% reduction in fatigability for the multifidus muscle but not the iliocostalis muscle. Improvements in aerobic capacity, back strength, and flexibility were reported for the training group but not for the control group. Thompson et al. reported on studies conducted among persons with subacute low back pain (LBP), all of whom had well-localized pain on the left side of their back. The symbols distinguish data from L1, L2, and L5 lumbar levels. Asterisk (*) indicates those patients with abnormal ratio parameters who had imbalances corresponding to the site of their pain. The shaded area indicates ±2 standard deviations of the mean from a normative database. If a training effect were present, it would be helpful to know whether, on the basis of EMG discriminant functions, this training effect could shift the classification of "LBP" to "normal." Subjects with chronic LBP and complaints of pain at the time of the study participated in 20 training sessions (progressive trunk strengthening in extension and flexion, flexibility and aerobic exercises) over a 10-week period. The results were similar to findings among subjects without LBP in demonstrating "improvement" in the MF variables used to measure fatigability following training. Thompson et al. also reported that these differences resulted in a reclassification of patients from "inactive patient with LBP" to "control subject" on the basis of the discriminant function analysis. Their findings provide a basis for concurrent and predictive validation of the technique.

Changes in MF following strength and endurance training should represent physiological adaptations to muscle involving changes in muscle metabolism and hypertrophy. The EMG MF has been directly associated with intramuscular pH, muscle fiber type, and muscle cross-sectional area. A recent study using an animal model of hind-limb unloading to induce atrophy in the soleus muscle demonstrated a correlation of r = .92 between muscle cross-sectional area and EMG MF. In only one study that we are aware of have fiber-type proportions in paraspinal muscles been shown to reflect

Figure 6. Ratio parameters indicating imbalances in median frequency (MF), defined as the ratio of the right to left initial MF values, are plotted for 8 patients with subacute low back pain (LBP), all of whom had well-localized pain on the left side of their back. The 3 symbols distinguish data from L1, L2, and L5 lumbar levels. Asterisk (*) indicates those patients with abnormal ratio parameters who had imbalances corresponding to the site of their pain. The shaded area indicates ±2 standard deviations of the mean from a normative database.

Future Developments
Classification of paraspinal muscle impairment by EMG spectral measurements is still in its infancy, but promising initial findings suggest a potential for clinical use. Two areas of study currently in progress should help to improve the clinical usefulness of surface EMG for classifying paraspinal muscle impairments: (1) the use of more effective classification procedures and (2) the development of new EMG methods to characterize spectral variables during movement (ie, contractions that are not isometric).

Improving Classification Procedures
Discriminant classification procedures have been used to assign individuals to LBP and control groups based on EMG data. There are several limitations to this procedure that have led investigators to adopt other classification schemes for their measurements. One of the primary limitations of conventional discriminant analysis is that it is based on linear classification boundaries (ie, the discriminant functions are formulated by a linear combination of the measurements). This method of linear discriminant analysis cannot be adequate when
the true class boundaries are nonlinear. Quadratic discriminant analysis can produce nonlinear boundaries by dropping the conventional assumption that the covariance matrices for the different classes are the same. This method of nonlinear analysis still may not suffice when highly nonlinear class boundaries are present, and other forms of nonlinear discriminant analysis have been shown to be more effective.

Discriminant analysis techniques are traditionally applied to dichotomous groups, which further limits their applicability for classifying a variety of possible impairments common to LBP disorders. Much quicker nonlinear methods for classification have been formulated based on classification using splines and classification and regression trees. These techniques allow for a greater ability to describe interactions among variables than does discriminant analysis. A new method of classification, referred to as the "neural network method" and based on models of the nervous system, has produced very promising results in a wide variety of applications, including EMG classification of motor units. The downside to this approach is that the models associated with the derived network are complex and difficult to interpret. In addition, this procedure works best with very large data sets and does not allow the user to investigate possible interactions among variables.

A recent article by Marras et al provides an excellent example in which many of these different methods are compared for classifying LBP impairments. The study used 3-dimensional motion measures of the spine, recorded during various symmetrical and asymmetrical movements of the trunk, to form a composite measure of the trunk musculoskeletal control system. The resulting "motion signatures" distinguished between the subjects without LBP (n=339) and the 10 subgroups of subjects with chronic LBP (n=171) studied. Subject classification was evaluated using a 2-stage approach that included conventional discriminant analysis, a neural network approach, a nonparametric classification procedure, and 2 other procedures. The first stage of classification divided the subjects without LBP from the subjects with LBP disorders. The second stage of classification divided the subjects with LBP into the 10 different LBP categories, which included anatomic (eg, spinal stenosis, herniated intervertebral disk, spondylolisthesis) and Quebec Task Force classifications. The results demonstrated that the model could be used to classify subjects into the LBP subgroups on the basis of 6 variables derived from symmetric testing conditions and from 2 variables related to the subjects' ability to twist the trunk. A modified classification-using-splines technique was the only procedure among those used that could classify the patients into the appropriate categories, with an average sensitivity of 69% and a specificity of 96%.

Marras et al contend that further validation of the procedure is needed and can be accomplished by using a larger "independent" data set (ie, a data set that does not include the original "training" data set) than the relatively few data sets that were analyzed in their study. Whether the technique can be used to classify other persons with LBP from different clinical practices or with different pain and psychological histories is not known. Marras et al recognize that the complexity of the spine will severely limit the ability to use kinematic procedures to correctly identify the injured tissue. They envision that the technique will provide a tool for measuring trunk performance, quantifying functional deficits, and assisting in the process of confirming a diagnosis. In this regard, their work parallels our efforts to achieve the same capability. In theory, the 2 methods could be combined to strengthen our ability to understand more about the mechanisms underlying specific muscle impairment classifications.

Extending the Application to Contractions That Are Not Isometric

Unfortunately, the measurement of localized muscle fatigue by EMG spectral techniques is restricted to constant-force, isometric contractions because of limitations inherent in the processing methods used to obtain spectral measurements. Traditional methods for estimating the power density spectrum, such as the use of the correlogram or periodogram, operate under the assumption that the signal is "wide-sense stationary" or of constant variance. If the assumption that the signal is stationary does not hold, it is not possible to apply basic theorems that define the power spectral density function of a signal as the Fourier transform of its autocorrelation function. This precondition is satisfied if EMG signals are recorded during constant-force, isometric conditions. When muscle contractions depart from these constraints, the EMG signal can no longer be assumed to be stationary. This is a serious limitation to the technique because many trunk functions involve movement and such activities are commonly associated with injuries involving LBP. We recognize that back tests that rely on one contraction type may not be generalized to activities that incorporate different contraction types.

To assess electrical manifestations of localized muscle fatigue resulting from contractions other than isometric contractions, it is necessary to use EMG methods that allow for processing of nonstationary signals. Recent developments in the field of signal processing have produced methods of time-frequency (TF) analysis that are able to extract spectral information from nonstationary signals. The TF approach to signal analysis describes
signal characteristics in both the time and frequency domains using various transformations. Preliminary work has demonstrated that specific transforms belonging to the Cohen class appear robust enough to derive spectral indexes of fatigue from nonstationary EMG signals recorded during cyclical contractions that are not isometric such as repeated extension of the knee using an isokinetic dynamometer or repetitive trunk extension while lifting a constant load in the sagittal plane. We have demonstrated that instantaneous MF variables can be derived by applying a moving average window with respect to the time axis and treating each time slice as an instantaneous power spectrum. Modification to the frequency content of the EMG signal from repeated use of paraspinal muscles can be represented as changes in the instantaneous MF calculated for the same phase of each lift.

At this point in the evolution of the procedure, it is necessary to describe the mechanical position of the trunk, or object being lifted, in order to accurately select the same mechanical phase of each repetitive activity. Factors such as muscle length, muscle force, and location of the electrode with respect to the underlying muscle fibers are known to alter the EMG spectrum and, therefore, would confound attempts to relate spectral changes to fatigue. We propose that constraining the analysis to the same relative phase of the contraction where these factors are likely to exert a constant influence will limit the confounding effect of muscle length, force, and electrode position. Further studies are needed to verify the effectiveness of this procedure in measuring EMG-based fatigue indexes for cyclical activities and to expand its applicability to noncyclical tasks.

Summary
Surface EMG has evolved from its beginnings as a technique utilizing a single sensor to indicate the presence of muscle activation and the magnitude of the EMG signal to much more complex systems involving multielectrode arrays and measures derived from the frequency and time domains. The evolution has occurred because clinical applications and research dealing with elaborate neuromuscular systems, such as paraspinal muscles, have demanded that improved quantitative tools be developed. The technology needed to support such efforts is available. What is lacking, however, are validated protocols and procedures to formulate paraspinal muscle impairment classifications on the basis of these measures. This overview of the state of the art describes the efforts of our group and of other groups to achieve this capability. Further research and development are needed to accomplish the long-term objective of providing assessment procedures to clinicians. Initial results are promising for identification of 2 kinds of LBP impairments observed during constant-force isometric tasks: (1) excessive fatigue due to muscle deconditioning and (2) inhibition of muscle activation secondary to pain or pain-related behaviors. The classification procedures used to identify such impairments on the basis of EMG spectral measures have relied primarily on discriminant analysis methods. Newer and possibly more effective techniques are described as an area for future development. The availability of more advanced signal-processing techniques to derive EMG spectral measurements from contractions that are not isometric also are briefly described.

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