For well over a decade my associates and I have been developing an objective, noninvasive technique to evaluate the performance of low-back muscles, with emphasis on being able to distinguish between healthy and dysfunctioned backs. Our approach is based on the well-known fact that the EMG signal undergoes a compression in the frequency domain during a sustained muscle contraction. In particular we track the median frequency of EMG signals detected from six muscles in the lower back during an isometric extension of the trunk. The measurements are taken with the Back Analysis System which consists of a postural restraining device, special electrodes for detecting the EMG signals, a muscle fatigue monitor which calculates the median frequencies, and the appropriate software. We have found that the pattern of fatigue exhibited by the six median frequency curves can be used to distinguish individuals who have low-back pain from those who do not with an accuracy of at least 84%. An even more relevant and timely application of our technique is for quantifying the progression of the performance of low-back muscles during a rehabilitation program. Although more work is required to explore the intricacies of the technique, present results provide a convincing indication that it is reliable and that it is ready to be placed into practice.

Key words: low-back pain • EMG signal • fatigue • muscle performance • spectral parameters

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USE OF THE SURFACE EMG SIGNAL FOR PERFORMANCE EVALUATION OF BACK MUSCLES

CARLO J. DE LUCA, PhD

During the past 15 years, my colleagues (Serge H. Roy, Roberto Merletti, L. Donald Gilmore, Marco Knaflitz, Zvi Ladin, Mark Emley, Kesenia Kozak, and Viktor Tiegerman), my students (Foster Stulen and David Casavant), and I have been evolving objective means for evaluating the performance state of low-back muscles in normal conditions and subsequent to injury, low-back pain, or physical exercise. We have applied the EMG spectral variable technique to assess the state of a group of muscles in the lower back during a regulated isometric constant-force contraction. To date our work has not addressed the issue of causality or etiological specificity. We realize that these factors are of fundamental interest to many clinicians. For the time being, we have focused on providing means that can assist in determining the presence of a dysfunction, monitoring the outcome of a prescribed treatment, and possibly determining when an individual is capable of safely performing work tasks. We see our test as a component of the battery of tests that would be performed on a patient to arrive at a diagnosis or a course of treatment.

This article expresses a personal point of view on the merit and applicability of the technique. The article is not designed to provide evidence for the stated positions, but rather to present facts in a concentrated fashion with reference to the published work containing the supporting details. The author is keenly aware that more work is required to firmly and indisputably establish the practical application of described approach. This statement of position has a twofold purpose: to inform the reader on the recent advances of this approach, and to invite the reader to explore its applicability.

From the NeuroMuscular Research Center, Biomedical Engineering Department, and Neurology Department, Boston University, Boston, Massachusetts.

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Address reprint requests to Dr. Carlo J. De Luca, NeuroMuscular Research Center, Boston University, 44 Cummington Street, 5th Floor, Boston, MA 02215.

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OTHER CURRENT APPROACHES

All currently used techniques and devices used for evaluating the performance of the back muscles measure mechanical variables associated with force, velocity, or displacement of the trunk. All approaches share a common flaw in that the measured kinematics and force variables are cognitively perceived by the central nervous system, and thus can be voluntarily regulated in a manner that can meaningfully affect the values of the variables being measured. For example, a highly motivated individual interested in knowing the upper limits of his/her strength would perform to the full extent of his/her physical capability. Whereas an individual with less motivation would perform at a lesser level, thus not revealing his/her full capabilities.

OUR APPROACH

Our approach circumvents subjectivity by extracting information directly from the EMG signal. But, unlike previous approaches to using EMG signals for assessing the performance state of the back, we do not analyze the amplitude of the signal. Instead we derive a fatigue index from the frequency spectrum of the signal. We detect the EMG signal from six sites, three on each side of the back, located at L-1 of the longissimus thoracis, at L-2 on the iliocostalis lumborum, and at L-5 on the multifidis. Our approach consists of placing the back muscles in a fatiguing mode by requesting the subject to sustain a high-level constant-force isometric extention of the torso. The contraction lasts for 30 seconds. After a brief period of rest (1 minute) the subject is instructed to elicit a brief (5 seconds) contraction at the same force level to assay the recovery process of the preceding fatiguing contraction. The EMG signals are processed to obtain the value of a spectral variable, the median frequency. We construct an information map which consists of the initial value and the slope of the median frequency of the EMG signal detected during the sustained contraction and the value of the median frequency from the recovery contraction; this is done for all six locations. This information map describes the performance state of the muscles. A discriminant analysis is subsequently performed to distinguish and characterize the differences between normal and abnormal behavior in the information map. We look for differences in the values of the information map at the beginning of the contraction and how they change with respect to each other during the contraction and recovery phase. The useful information is not contained in any one muscle, but rather it is extracted from all the monitored muscles simultaneously.

Because the test requires the subject to perform a submaximal constant-force isometric contraction and because the duration of the contractions is not a measured variable subject is not cognitively aware of the EMG variables that constitute the information map.

THE PREMISE OF OUR APPROACH

We have hypothesized that the behavior of the median frequencies in the information map of the monitored muscles in the lower back is more similar among individuals who have no dysfunction (induced by injury, pain, or possibly congenital defect) than among those who do. The reasoning is that if a relative dysfunction exists in some muscles, then the other muscles will work to compensate the deficit. This orchestration provides an imprint which is particular (but not necessarily unique) to the characteristics of the dysfunction. Thus, by determining the information map we expect to infer the presence of injury, pain, and other disabling causes.

A criticism that has been leveled against our approach is that we only detect signals from surface muscles, when in fact there are muscles in deeper layers located about the spinal column which contribute to extension and rotation of the trunk. Although this is so, the long surface muscles of the back enjoy a greater moment arm about the center of rotation of the spine, thus they contribute the major share of the monitored torque during extension. Empirically our results have shown that the surface-muscle subset provides considerable information that can be used to construct statistically significant discriminations between normal and abnormal behavior.

THE BASIS OF OUR APPROACH

It has been known for nearly eight decades that during a sustained contraction, the EMG signal undergoes a frequency compression.[15] More recently, we have also learned that the shape of the frequency spectrum may also change during sustained contractions.[12] The net effect of these phenomena cause EMG spectral variables, such as mean, median, and mode frequencies to decrease during sustained contractions. This characteristic of the EMG spectral variables has been accepted by many investigators as an index of muscle fatigue which occurs during sustained contractions.

However, because the diminution of the EMG spectral variables also occurs during constant-force contractions, their use as fatigue indices has raised a controversy between a recent generation of investigators who apply EMG spectral measures of muscle fatigue to objectively evaluate human physical performance and the health scientists who follow the classical (and in my view less useful) definition of muscle fatigue. Traditionally, muscle fatigue has been defined as the failure of a muscle to maintain a prespecified force level.[7] By this definition, during a constant-force contraction, a muscle does not fatigue until the force output diminishes. This approach was useful and convenient (but in my view limited) when no other facile means of assessing muscle fatigue were available. More recently, Bigland-Ritchie and Woods[3] have advanced the concept of monitoring the rate of decline of force output during a sustained maximal voluntary contraction. Although this approach improves on the use of force as the variable of measure, it remains susceptible to the capability and/or willingness of the individual to continue to elicit maximal effort during a test.

It is useful to recall that while, in a macroscopic sense, the net contractile force of the muscle may remain acceptably constant, there are time-dependent physiological processes that microscopically alter the means for generating force during sustained constant-force contractions. Some of them are: (1) motor units may be recruited and derecruited; this has not been proven beyond doubt, but remains plausible. (2) The firing rates of most motor units decrease; this phenomenon was first reported by Person and Kudina[14] and independently by us.[6] (3) The force twitches of motor units potentiate.[4] In addition to these physiological phenomena, there are practical considerations which reduce the usefulness of the contractile force measure of fatigue in evaluating human physical performance; these are: (1) contractile fatigue is susceptible to subjectivity because contractile force may decrease due to psychological factors as well as to physiological factors. The EMG spectral variables monitored during constant-force isometric contractions are not subjected to the psychological factors. (2) Contractile force can only be conveniently measured by monitoring the torque about a joint to which more than one muscle can contribute. In contrast, the EMG signal can be detected from individual muscles; thus the spectral variable fatigue index can be used to describe the performance of individual muscles. (3) The spectral variables decrease continuously from the onset of contraction, thus providing an indication of the rate of the fatigue process early in the contraction. Contractile fatigue, as currently measured, requires the expenditure of considerable effort prior to being measurable. This is a limitation for clinical usage.

There has been a flurry of activity directed at describing the behavior of and understanding the relationship between the EMG spectral variables and physiological and biochemical processes which occur during muscle contractions. An early review of relevant work was written by De Luca in 1985,[5] a more current review has been written by Merletti et al.[11] We have shown the EMG spectral variables to be causally related to the pH of the extracellular fluid and possibly to the intracellular fluid.[8] It has been suggested, but not proven, that the concentration of potassium ions and the duration of the polarization zone on the membrane may also affect the EMG spectral variables. The exploitable aspect of these relationships and associations is that through the analysis of an EMG signal detected painlessly on the surface of the skin above the muscle, it is possible to obtain useful time-course estimates of processes that fatigue during a muscle contraction.

Given that both the EMG spectral variables and the force variable of the contractile mechanisms undergo changes during the progression of fatigue, it is inevitable to ask if a relationship exists between the two. The answer is undoubtedly yes. The more interesting question is if the relationship is causal. This issue is not clear at this time, and a considerable amount of work is required before meaningful statements can be made to illuminate this issue. Nonetheless, the lack of proof of a causal relationship does not logically preclude the use of the spectral-variables fatigue index, especially when empirical evidence reveals its usefulness.

THE EMBODIMENT OF OUR APPROACH—THE BACK ANALYSIS SYSTEM (BAS)

Our concept is embodied in a device and technique called the BAS, which is comprised of four functional elements: (1) special surface EMG electrodes which have specific architecture and electrical properties for the detection of signals suitable for spectral analysis; (2) a muscle fatigue monitor which processes the EMG signals to obtain the spectral variable; (3) a postural restraining apparatus which constrains the posture of the subject so that the sensed force is related, as much as possible, to the force generated by the monitored muscles in the lower back. Also, the torso is immobilized to limit the required extension to an isometric contraction and to provide a means for standardizing the posture of the subject during the test. This is an important feature because, with current knowledge, the EMG spectral technique can only be used properly when the muscle length remains fixed[5]; and (4) software for system calibration, signal-quality monitoring, test configuration, data collection, signal analysis, and statistical evaluation.

PROPER USE OF A NEW TECHNIQUE

When a new technique is used in the research and clinical environments, it is incumbent on the users to apply it with proper respect for, and knowledge of, its limitations and idiosyncrasies. All new technology has unexplored fringes that require careful considerations. Unchecked usage will provide inconsistent and possibly conflicting results. When using the EMG spectral technique the following considerations must be respected.

Technical Considerations. (1) The electrode should be sufficiently small and placed well within the borders of the muscle so as to detect the EMG signal from the muscle in question and not crosstalk signal from adjacent muscles. Signals from adjacent muscles will be subjected to greater spatial filtering, thus reducing the value of the spectral variables of the detected signals. We have developed a special electrode which, in most cases, can satisfy the two conditions. The detection surfaces of our electrode consist of two parallel bars, each 1.0 cm long and 1.0 mm wide spaced 1.0 cm apart. (2) The spacing between the detection surfaces inversely scales the value of the spectral variables. (3) The orientation of the detection surfaces with respect to the muscle fibers also affects the value of the spectral variables. (4) The temperature of the muscle directly affects the spectral variables. Tests made for comparison should be made at similar temperatures or scaled appropriately. (5) Ambient electromagnetic radiation, motion artifacts, clipping of the signal during detection, and poor signal-to-noise ratio all adversely affect the value of the EMG spectral variables.

Physiological Considerations. (1) The thickness of the fatty tissue between the electrode and the muscle affects the amount of spatial filtering on the signal. We anticipate that this approach will not work well on obese individuals. (2) The pH in the environment of the muscle membrane is a function of the net H^+ produced and removed. Thus, the rate of blood flow in the muscle can affect strongly the behavior of the EMG spectral variables. This is one reason for performing the tests at relatively high force levels where the internal pressure of the muscle is sufficient to collapse the arterioles and interrupt blood return, and also for performing the contraction in an isometric mode where the internal pressure remains reasonably constant and does not alter the rate of blood flow as is the case in dynamic contractions.

RELIABILITY AND REPEATABILITY OF EMG SPECTRAL MEASUREMENTS

Prior to recommending a new technique it is incumbent on the proponents to prove that it is reliable and provides repeatable results. We have performed two series of experiments. In one series, we ascertained the error induced in the value of the EMG spectral variable by repeating a contraction within 15 minutes under similar conditions; the error was found to be 2% for the initial value and 6% for the slope of the median frequency.[16] Performing similar evaluations on test/retest measurements, Biederman, Shanks, and Inglis[2] found that the error in the repeatability of the median frequency slope measurement increased to approximately 10% when the electrode, identical to ours, was removed and the tests were separated by 5 days.

OUR RESULTS TO DATE

In collaboration with my associate, S. Roy, four studies have been completed. The first[16] compared the information map consisting of the initial value and the slope of the median frequency of 12 patients and 12 age-and-height–matched control subjects who had never experienced low-back pain. The patients had a convincingly documented history of chronic low-back pain which persisted repeatedly over a period of at least 1 year, with an average duration of 5.2 years. At the time of the tests the patients were not experiencing pain. None of the patients had previous back surgery or current radiographical evidence of structural disorders of the spine. The test was able to identify the control subjects with an accuracy of 84% (10 of 12) and the low-back pain patients with an accuracy of 91% (11 of 12) purely on the basis of the EMG spectral variable test. It is particularly interesting to note that the two groups had a maximal voluntary contraction that was statistically indistinguishable at the 95% confidence level.

The second study[17] was performed on rowers (men's collegiate varsity crew at Boston University); 13 were port rowers and 10 were starboard rowers. This cohort was tested without a priori knowledge of who, if any, of the subjects suffered from low-back pain. After the tests, 6 of the rowers had supporting evidence that they had low-back pain. Four had acute pain but were not experiencing pain during the tests; 2 had chronic pain, and were in pain during the tests. In this study the information map consisted of the initial value, the slope, and the value of the median frequency after 1-minute recovery. The test identified 100% (6) of the patients with low-back pain and 93% (14 of 15) of the subjects without low-back pain, 100% of the starboard rowers, and 100% of the port rowers.

The third study[10] compared conventional clinical measurements with EMG spectral variable measurements for the identification of individuals with low-back pain. The subjects were 24 freshman sweep rowers, 8 of whom had low-back pain (4 chronic and 4 acute). None were experiencing pain during the tests. The clinical measurements consisted of the range of motion of the trunk in the forward, backward, and lateral directions, as well as rotation of the trunk and maximal voluntary contraction force in isometric extension. The information map consisted of the initial value, the slope, and the value after 1-minute recovery. The EMG spectral variable test identified 88% (7 of 8) of the patients with low-back pain and 100% (9) of the subjects without low-back pain. In contrast, the conventional clinical tests were less accurate: identifying 57% (4 of 7) of the patients with low-back pain and 67% (10 of 15) of the subjects without low-back pain.

The fourth study[18] compared the information maps of 5 patients with fibromyalgia syndrome who complained of pain in the back, 12 patients who had been diagnosed as having idiopathic low-back pain, and 10 age-and-weight–matched control subjects who stated that they had never experienced a debilitating episode of low-back pain that impeded them from executing their normal daily activities. The fibromyalgia patients were identified according to currently proposed diagnostic criteria. We were particularly interested in how the information map might be altered in the fibromyalgia patients who reported a diffused sensation of pain in the back compared with the more focused pain reported by the low-back pain patients. By using orthogonal t-tests we found that the information map of the low-back pain patients was statistically distinct ($P < 0.05$) from that of both the control subjects and the fibromyalgia patients: The latter two groups were statistically indistinguishable at the $P = 0.05$ level.

The above studies were directed at proving the EMG spectral technique, if properly used, could distinguish between individuals with and without low-back pain. The results are favorable and apparently superior to those of other clinical techniques. Thus, from a scientific point of view, our results provide evidence that the approach has merit and may be useful. However, if one were to place this approach into practice either in a clinical or ergonomics setting, a much larger number of control subjects would be required to establish the range of normalcy. It may even be necessary to categorize separate sets of normal low-back muscle performance for individuals with distinctly different body shapes and those with different life styles. We have begun to accumulate such a data base.

There is one application of the approach which does not require a sound data base of normals for statistical comparison, i.e., the monitoring of a treatment outcome. In this utilization, the individual becomes his/her own control. With the collaboration of several clinical colleagues, we are currently documenting the progression of modifications of the information map toward normalcy in over 100 patients with different etiologies and undergoing various forms of rehabilitation programs.

The issue of causality remains a complex one. Our work has only established an association between the performance of low-back muscles and the presence of pain. The question of which causes which remains open for consideration. For example, in soft tissue injuries, does the presence of pain cause the muscles to work differently?; or, does muscle insufficiency, present for extended periods of time, eventually cause a physical disturbance that induces pain? Is it possible to distinguish the effect on the information map caused by different etiologies? These are difficult questions to address and are certainly necessary to be studied if the approach is to be used for diagnostic purposes.

RELATED WORK OF OTHERS

Other than our work there are four other relevant reports in the literature which describe the use of the EMG spectral technique to evaluate the performance of back muscles. Kondraske et al.[9] used a technique similar to ours; the spectral variable was the mean frequency. They detected EMG signals from the right and left erector spinae muscles of normal healthy subjects. Their results paralleled ours in indicating the viability of the technique and the importance of the specificity of the details of the procedure. Subsequent work by this group[13] employed the EMG spectral technique to test and compare reconditioned low-back pain patients to healthy control subjects. Test procedure differed from their earlier work in that a Roman chair device was used to activate the back extensor muscles and the EMG signals were detected from two locations, i.e., on the L-3 level of the left and right longissimus muscles. They asked the subjects to perform 10 trials of brief (15 seconds) extensions of the back separated by 10 seconds of rest. They calculated the initial value of the mean frequency for each contraction. Their results conformed with ours, indicating a greater rate of change of the spectral variables across the different trials in low-back pain patients. These results notwithstanding the authors continued to express a concern, voiced in a previous publication,[19] that the spectral technique was not a sufficiently good index of muscle fatigue. They drew attention to two observations: (1) the high variability of their normative data, which was interpreted to indicate lack of sensitivity and/or a reflection of different fatigue processes among subjects; and (2) the mean frequency decreased nonlinearly with consecutive trials. They viewed this behavior as problematic for a fatigue index because it would not be independent of the end point of the contraction. Their reasoning has two possible flaws. First, it appears that they were attempting to interpret the behavior of the EMG spectral variables as contractile variables, the distinction between these two categories of variables has been made earlier in the text. Second, the ambiguity they see in their results can easily be explained by the procedures they used to isolate and elicit contractions from the back muscles, as well as the procedure used to detect and process the EMG signals. Seven years ago we experienced similar difficulties. We found that it was absolutely critical to restrict the positioning of the back in a fixed and consistent position, carefully monitor the isometric contraction so that it is as consistent as possible among tests, use more than two detection sites, and adhere to the technical and physiological considerations described earlier. The high variability of their results can also be explained by the repeated calculation of the initial median frequency whose estimate is inherently a random variable due to the stochastic nature of the EMG signal. (We have found it more useful to monitor the spectral variable continuously as a function of contraction time.) The repeated trials with numerous test periods also contributed to the variability of the data because the blood flow in the muscle is not restricted, as described previously. In summary it is clear to us that the difficulties experienced by the above investigators may well be a function of the methodology rather than a limiting flaw in the approach.

In contrast, a report from Biederman et al.[1,2] described an approach more similar to ours than that of the previous group. They tested 22 healthy subjects and 24 patients with chronic low-back pain. The patients were further separated into two groups: confronters[15] who consistently reported lower pain sensation, and avoiders[9] who consistently reported higher pain sensation. They detected EMG signals from four sites on the back simultaneously and calculated the median frequency spectral variable. The electrodes were placed on the right and left multifidus and iliocostalis lumborum. They performed the tests carefully, used our electrodes, placed them in anatomically correct locations, and respected technical considerations described previously. Their results were qualitatively and quantitatively consistent with ours. The test identified 89% (8 of 9) of the avoiders and only 8% (3 of 37) of the normals, and confronters were misclassified as belonging to the avoider patient group.

CONCLUSION

It is my opinion that the majority of available evidence favors the notion that the EMG spectral technique, when used correctly according to definable criteria, does provide means for objectively evaluating the performance of back muscles.

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