

Muscular Response to Sudden Load

A Tool to Evaluate Fatigue and Rehabilitation

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Study Design. Subjects were exposed to fatiguing and restorative interventions to assess their response to sudden loads.

Objectives. To investigate the erector spinae and rectus abdominis response characteristics to "sudden load" and the effect of fatigue and rehabilitation.

Summary of Background Data. Unexpected loads, which people often experience, can lead to high forces in the spine and may be a cause of low back injury.

Methods. Muscle responses to sudden load were mediated by fatigue, walking, expectation, method of load application, exposure to vibration, and cognitive-behavioral rehabilitation in patients with chronic low back pain. A novel technique, perfected in this work, called *wavelet analysis*, was used to analyze these data.

Results. Reaction time was affected by fatigue and expectation. Vibration exposure significantly increased the muscle response time. Walking was able to ameliorate that effect. Back muscles responded differently, depending on whether loads were applied to the back through the hands or through the trunk. Electromyographic reaction time and magnitude decreased in patients after a 2-week rehabilitation program.

Conclusions. Sudden loads can exacerbate fatigue effects. Walking after driving reduces the risk to the back caused by handling unpredictable loads. Vibration exposure guidelines should be more conservative. Patients have longer response times than healthy subjects, but patients can improve their response to sudden loads via rehabilitation. Patients exhibit a flexion-extension oscillation at 5 Hz in response to a sudden load, suggesting that the 5-Hz, seated, natural frequency observed during whole-body vibration may result from neurophysiologic control limits. [Key words: chaos, electromyography, expectation, fatigue, muscle, natural frequency, neurophysiologic control, rehabilitation, sudden load, synchronization, vibration] **Spine**

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Musculoskeletal injuries are one of the most common types of injury in the workplace. Although the literature is controversial on the etiology, it seems evident that mechanical factors cause most disorders of the lower back, aggravate low back pain (LBP), increase the risk of recurrence, and are important for the disability because of this pathology.^{7,12,18,30} There is strong evidence about the risk associated with lifting,⁸ whole-body vibration,^{9,22} and sudden unexpected movements or loads.^{4,23-25}

Sudden loads can take many forms and can be found in leisure pursuits and in the workplace. Slipping or tripping are two examples of sudden load application through the lower limbs. Unexpected slipping of an object being held in the hands or being lifted is another. Nurses handling patients²⁷ and physical therapists working with patients²⁶ are especially prone to this problem. Drivers unloading their cars or trucks are exposed to catching materials when loading or unloading goods. There are other less obvious unexpected sudden load conditions, many occurring while sitting: vertical impact in a high-speed boat, lateral impact in a train or subway, a pothole strike by a vehicle with stiff tires and stiff suspensions (forklifts and terminal tractors), pothole strikes in more common vehicles such as tractor-trailer trucks, and rough rides in off-road situations (mining, logging, border patrol, racing). Unexpected load conditions can occur in the fore-aft direction because of the "slack-action," resulting from velocity changes in trains, subways, and tractor-trailer sets with one or more trailers. These examples are important for the clinician to keep in mind when considering the etiology of a patient's LBP and the conditions to which a patient with LBP may be returning.

Because of the relatively short moment arm, the internal muscle force must be large to respond to an external load to achieve equilibrium and stabilize the spine. It is believed that this large muscle force is responsible for the majority of the compressive and shear loads on the spine and consequently is responsible for resulting back injuries when these loads become extreme. When a sudden load is imposed on the body, the muscles will respond rapidly to stabilize the body, *i.e.*, they will try to maintain balance and posture. In addition, sudden load includes a

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dynamic component of the external force, which will increase the internal load. This adds to the spinal loading created by the musculoskeletal system to stabilize the spine.¹⁷ This phenomenon explained roughly 12% of accidental injuries described by Manning et al.²⁴ Marras et al²⁵ studied the muscle response to expected and unexpected sudden load and found that expected and unexpected sudden load increased the average muscle force compared with static loading. For the unexpected loading, the mean muscle force was more than twice as large as for the expected loading, and peak muscle forces were on average 70% greater. Previous studies of sudden load showed a lower electromyographic (EMG) amplitude for unexpected load compared with expected in healthy subjects and those with back problems.^{2,20} The incongruity of the results in the study by Marras et al²⁵ and those of Magnusson et al²⁰ and Aleksiev et al² is explained by differences in load application methods. Whereas Marras used a load application technique that included the hand-arm response, in this study, the sudden load was applied directly to the trunk, bypassing the kinetic chain of the hands and shoulders. The direct comparison of patients with LBP and their matched control subjects showed that the patients had a delayed response and a lower EMG amplitude, which implies an unwillingness or inability to use their muscles as effectively. The higher EMG baseline that was found in the patients indicates that they have a continuous tension of their muscles to protect their back from sudden or uncontrolled events. This increased "base-tension," however, most likely fatigues the muscles, thereby preventing a rapid response to unexpected load.

In addition, the increased muscle tension stiffens the spinal system, thereby magnifying the impact of the sudden load. It also is possible that patients with chronic LBP are scared to move, and by activating their muscles may not respond to small applied loads. It is likely, therefore, that patients with chronic LBP respond to expected and unexpected sudden load differently from healthy subjects. Slower reaction times were related to traumatic musculoskeletal injuries in young men.³² Taimela et al³³ also observed slow reaction time in patients with chronic LBP and suggested this to be one factor in the development of LBP or a consequence of existing LBP. Decreased motor skills may be an effect of some musculoskeletal injury. The question has been raised whether decreased motor skills, coordination, and postural control are risk factors for musculoskeletal disorders, and if so, is it possible to improve that kind of inhibited motor function (IMF).

For sudden events, there are two types of anticipation: *spatial anticipation*, which means the prediction of what is going to happen, and *temporal anticipation*, which is the prediction of when something will happen. The concept of IMF suggests the presence of spatial anticipation and tests hypotheses about differences in EMG during sudden loads with and without temporal anticipation.

The aims of these studies were to investigate how the back muscles respond to sudden load and how these responses were modified after lack of temporal anticipation, after fatigue, after vibration, and after rehabilitation of patients with chronic LBP. The hypotheses were as follows, with reasons for posing the hypotheses in parentheses:

1. Fatigue increases reaction time and reduces the magnitude of the EMG. (Preferential loss of the fast twitch fibers, in the shift to lower frequencies, reduces reaction time);
2. Vibration exposure (induced fatigue) will increase reaction time and reduce predicted reaction magnitude. (Similar to #1);
3. Walking after seated vibration exposure will "re-set" the system and normalize reaction time and predicted reaction magnitude. (Fatigue will be reduced);
4. The low back muscle reaction time can be improved with rehabilitation. (The response should be modifiable through training or rehabilitation); and
5. In patients with LBP, the more painful side will respond differently compared with the nonpainful side. (Inhibition effect).

■ Materials and Methods

Study 1: Vibration As a Fatiguing Intervention and Walking As a Control Intervention. Muscle response was measured in terms of reaction time and peak EMG response to an unexpected sudden load in patients with chronic LBP and healthy subjects exposed to various types of sitting and vibration (as fatiguing) interventions and walking as a control intervention. Sixteen healthy subjects (10 women and six men, with an average age of 31.4 years, average height of 171 cm, and average weight of 68.6 kg) and six patients³⁶ (two women and four men, with an average age of 45.8 years, average height of 173.3 cm, and average weight of 77.2 kg) participated in the ethics committee-approved study. All but one subject were right-handed. Two of the patients had spinal stenosis, another two had disc herniations at L4-L5 and L5-S1, respectively, one had L5-S1 disc degeneration, and one had facet arthrosis. Although the sample size of patients was small, power analysis had indicated it was sufficiently large to show relevant effects.

Electromyographic electrodes were fixed to the skin at L3, 3 cm lateral to the midline. A voluntary muscular effort was performed to record muscular activity of the erector spinae muscles for calibration purposes. Sudden unexpected loads were applied in groups of at least six per assessment, using a weighted ball (6.4 N), falling approximately 1.8 m onto a pan that was equipped with microswitches for indicating the moment when the ball hit the pan (Figure 1). Aural, visual, and sensory cues as to moment of impact were masked. Learning effects were minimized by randomizing the moment when the weighted ball was released, therefore, even the investigator did not know when the weighted ball would begin its descent. As the weight began to fall, four seconds of data were collected at a rate of 1024 samples per second from erector spinae EMG electrodes and the switches in the instrumented pan. Data collection was performed using a data acquisition system contained in a personal computer.



Figure 1. The set-up for the sudden applied load as used in the vibration study (Study 1). A weighted tennis ball was dropped onto a pan, equipped with microswitches for indicating the instant when the ball hit the pan.

The goal of this experiment was to determine the effect of these interventions on EMG reactions and to see if walking could be used as a way of reducing the effects of sustained (static or vibratory) sitting. The outcome measure, response to unexpected load, was taken before and after exposure to bouts of sitting vibration and before and after bouts of walking. The interventions that preceded the unexpected load applications were, in random order, static sitting and seated whole-body vibration for 40 minutes. The sinusoidal vertical vibration input was 5 Hz frequency and 0.315 ms^{-2} rms acceleration, the ISO 8-hour FDP level.¹¹ Sitting exposures used a foot rest and an inclined backrest. Walking for 5 minutes after any of the exposures was another intervention used as a control measure. The test matrices are presented in Appendices 1 and 2.

Data were analyzed by four examiners to find the instant of peak muscle response, defined as that peak that was approximately twice as large as the rms level of the resting EMG signal. The reaction time was the temporal difference between the switch closure and the first reaction peak. Amplitude of the peak reaction was defined as when the EMG activity reached a peak. Only the response to the first of the six repetitions of sudden unexpected load was analyzed in this group because no significant differences between the six repetitions were noted.

Study 2: Isometric Extension as a Fatiguing Intervention and Rehabilitation as a Control Intervention. EMG responses to expected and unexpected load were recorded before and after muscle fatigue and before and after a 2-week general rehabilitation program. The rehabilitation program encompassed physical conditioning together with a cognitive-behavioral approach.¹⁴⁻¹⁵ Eleven patients with chronic LBP (six men; average age, 39.5 years; standard deviation [SD], 8.7; five women; average age, 43.0 years; SD, 7.8) were tested under an approved protocol.

The subjects stood with extended knees, their arms positioned along the body, and pelvis against a board to push off. In this position, a sudden load was applied by a "guillotine" mechanism (Figure 2). A weight (2 kg) was attached to a string and loosely guided to ensure a straight vertical drop. The string was attached via a load cell to a harness around the subject's shoulder. The weight was dropped from a height of 45 cm, applying a sudden forward bending moment at T4. Thus, the technique of application of the load was different, in that it removed the additional effect of the movement of the upper extremity on the back muscle response.

A series of sudden expected and unexpected loads were assigned randomly to each subject. The low back muscles were fatigued by isometric extension effort equal to 20% of individual maximum voluntary contraction (MVC) for 60 seconds. The work by Biedermann et al⁵ had shown that this was sufficient to cause measurable fatigue in patients. A voltmeter connected to the load cell was used for continuous force biofeedback. Immediately after each fatiguing exposure, sudden

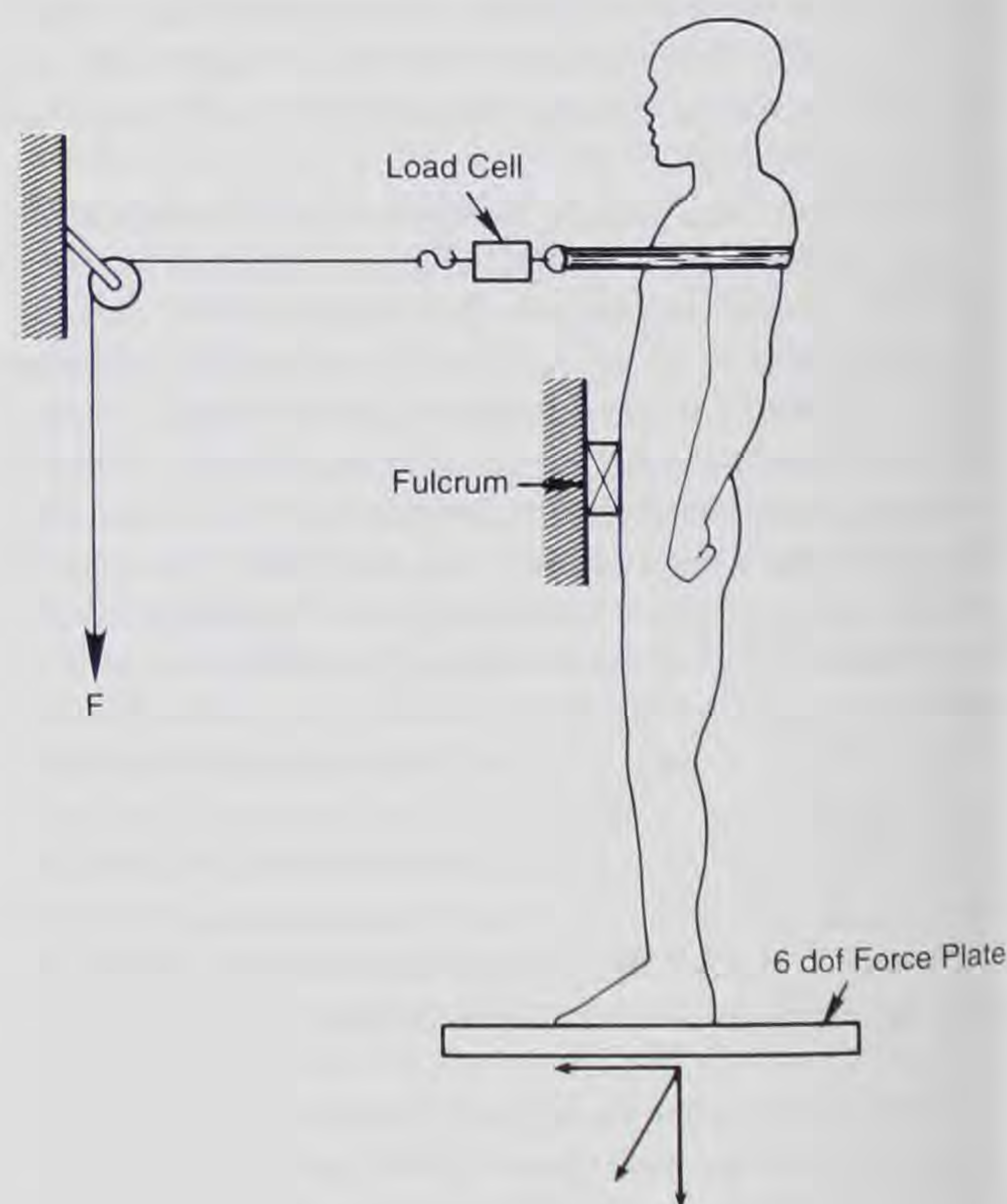


Figure 2. The set-up for the suddenly applied load (F) as used in Study 2. A weight (2 kg) was attached via a load cell to a harness around the subject's shoulders. The weight was dropped from a height of 45 cm.

expected and unexpected loads were applied randomly. Data were collected (via ASYST v4.0, Keithley Instruments Inc., Taunton, MA) for 4 seconds from right and left erector spinae EMG, the right rectus abdominis, and a load cell sensing the sudden load applied to the upper trunk. EMG and load-cell datafiles were prepared via software written in Quick Basic (by Wilder) for wavelet transform analysis.

In this experiment, EMG response data were analyzed only for 1 second after the load application to obtain the early muscle responses because responses after 1 second are likely to be controlled consciously. Wavelet transform analysis (S+Wavelets, MathSoft, Inc, Seattle, WA) was optimized for analyzing specific EMG signals (by Aleksiev), thereby revealing the maximum energy of the "crystals" in the response signal. The wavelet analysis then was performed in an automatic fashion. Peak detection software was written in Quick Basic (by Wilder, DeVoecht, and Aleksiev) for extracting the onset time, amplitude, and duration characteristics of the wavelet-processed signal. The wavelet analysis combines the advantages of time and frequency analysis, ideally suited for signals with high transient change content and short bursts of activity, as found in responses to sudden loads.²⁹ The wavelet analysis preserves the full time-dependent and frequency characteristics of the signal.

■ Results

Study 1

In all 16 healthy subjects, exposure for 40 minutes to seated vertical vibration significantly increased the pooled (across right and left sides) erector spinae muscle reaction time (from 87 msec to 108 msec; $P < 0.025$) and amplitude (from 55% to 67%; $P < 0.025$) to the first unexpected load. Static sitting significantly decreased reaction time (from 107 msec to 89 msec; $P < 0.025$) and tended to decrease reaction amplitude (from 61% to 52%, $P =$ not significant). Walking decreased the reaction time after seated vertical vibration exposure (from 108 msec to 99 msec, $P =$ not significant) but not to a significant level. Walking significantly decreased the amplitude of the muscle response to the first unexpected load after exposure to vertical sinusoidal vibration (from 68% to 50%; $P < 0.005$). Walking after static sitting significantly increased the total reaction time from 89 msec to 109 msec ($P < 0.05$), but the response amplitude did not change significantly (from 52% to 50%; $P =$ not significant).

In patients, static sitting led to a significant increase in reaction time from 92 msec to 133 msec ($P < 0.05$). Exposure to seated, vertical vibration led to nonsignificant decreases in reaction time (from 116 msec to 114 msec; $P =$ not significant) and amplitude (67% to 58%) to the first unexpected load. Walking showed trends of decreasing the muscle reaction time and increasing amplitude after vibration exposure. Walking showed trends of decreasing the muscle reaction time and decreasing amplitude after sitting statically. During each loading condition, the muscles on the dominant side reacted 73–108 msec faster than those on the nondominant ($P < 0.0005$).

The patients with LBP did not exhibit any learning effect in coping with the unexpected loads.³⁶ The average (across all subjects and all trials) reaction times showed no trend of either a shortening or lengthening reaction time.

Study 2

The patients exhibited a series of bursts (a train) of EMG activity (Figure 3) in response to sudden load. Each burst in the train was defined by the time it began, its duration, and the time and amplitude of its peak. The following characteristics of the series of bursts of EMG activity were analyzed: reaction time (time from the onset of load to the beginning of the first burst of EMG activity); duration of first burst; peak amplitude of response (of the first burst); and time period between bursts (after first burst).

When evaluating reaction time of the first response (Figure 4), there was a significant ($P < 0.045$), five-level interaction between gender, fatigue state, expectation, time (before and after rehabilitation), and EMG site. The reaction time generally decreased significantly after rehabilitation. Men improved their reaction time more than women after rehabilitation. The reaction time of the abdominal muscle was significantly longer than the reaction time of the erectors. The reaction time of painful side erectors was longer than the nonpainful side reaction time.

When evaluating the duration of the first response (Figure 5), there was a significant ($P < 0.042$) four-level interaction between gender, time (before and after rehabilitation), expectation, and fatigue state. Although this interaction was most affected by rehabilitation (noted as time in the figures), fatigue also had an effect. Without previous fatigue, there was a general increase in sudden load (expected or not) response duration after rehabilitation. With previous fatigue, there was a general decrease in sudden load (expected or not) response duration after rehabilitation. Men improved duration (shorter time) better than women after rehabilitation.

When evaluating the amplitude of the first response (Figure 6), there was a significant ($P < 0.021$) four-level interaction between gender, time (before and after rehabilitation), expectation, and surface EMG site (painful side, nonpainful side, rectus abdominis), but was most affected by rehabilitation. The EMG response always decreased after rehabilitation, suggesting that rehabilitation improves response efficiency. Women reduce amplitude more after rehabilitation than men.

There were other general findings of interest from this study. There were differences in reaction time, duration, and amplitude resulting from gender. Generally, men had shorter reaction times and response durations than women. Women improved (decreased) in amplitude more than men because of rehabilitation. Women re-

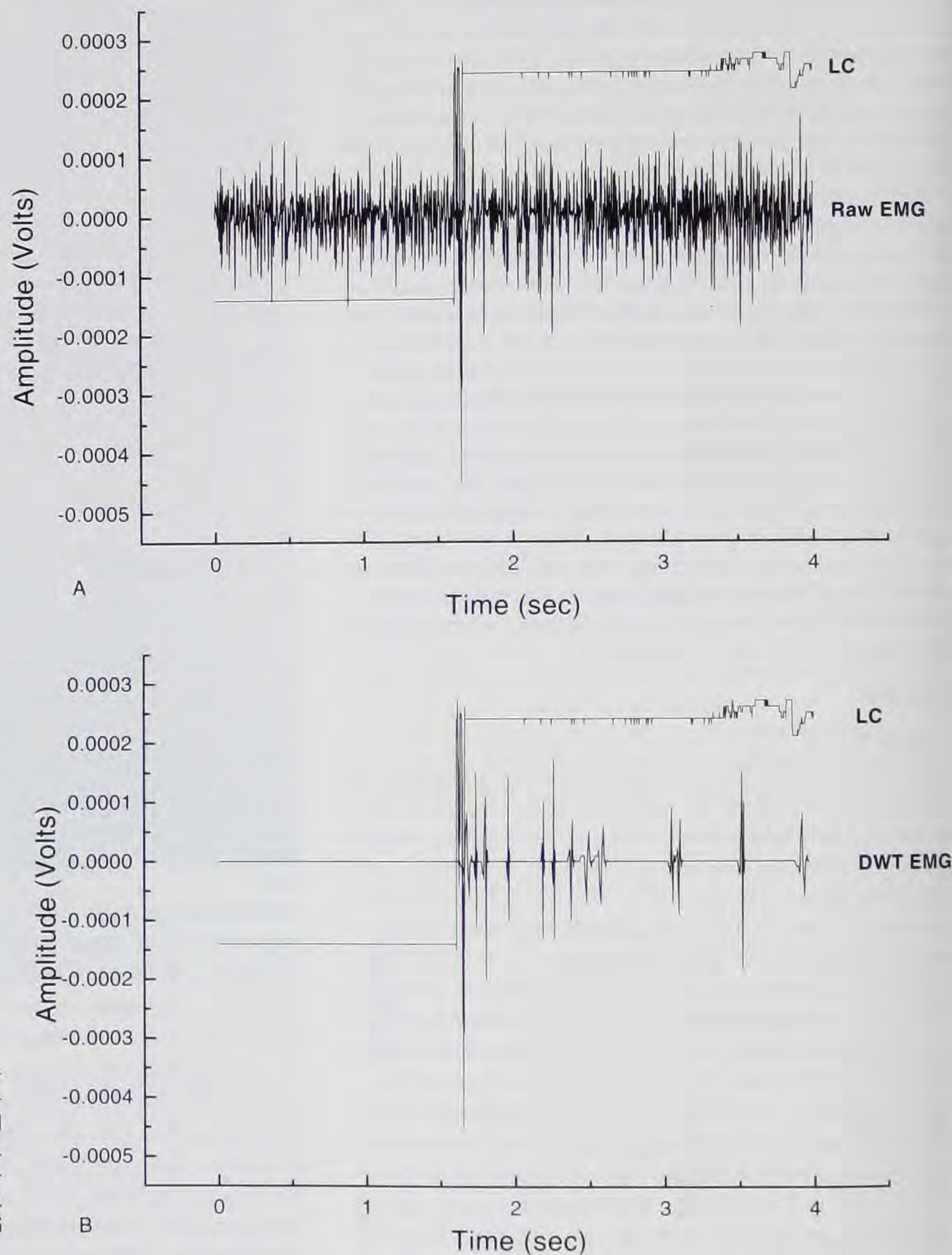


Figure 3. Typical raw electromyographic (EMG) activity in response to a suddenly applied load at the upper trunk (**A**). Wavelet transformation of sudden load and EMG signals (**B**). Note the train of bursts of EMG activity.

sponded with higher amplitudes in their abdominal muscles than in their erector spinae. Men were the opposite, having more extensor reflex than the women.

The train of bursts of EMG activity had some striking behavior. The peak amplitude and duration decreased in successive bursts of EMG activity in the train of responses. In the companion paper to the present study by Magnusson et al,¹⁹ there was a trend for rehabilitation to correlate with fewer bursts of activity in response to a sudden load. In general, the activity bursts were separated by a period of 200 msec, the reciprocal of a frequency of 5 Hz.

When evaluating the number of responses (Figure 7), there was a significant ($P < 0.049$) three-level interaction

between expectation, fatigue, and surface EMG site. The painful side (EMG1) tended to increase the number of responses during expected load after fatigue, but there was no such opposite effect on the nonpainful side.

Using a linear model, the condition of the first response had an effect on the number of responses observed. A longer duration in the first response correlated to fewer responses ($r = -0.6194$; $P < 0.0001$). An increased amplitude in the first response reduced the number of responses ($r = -0.21376$; $P < 0.0005$). A shorter reaction time correlated to more bursts of EMG activity ($r = -0.1855$; $P < 0.0025$). The increased amplitude of the first response also correlated with an increased duration of the first response ($r = 0.24599$; $P < 0.0001$).

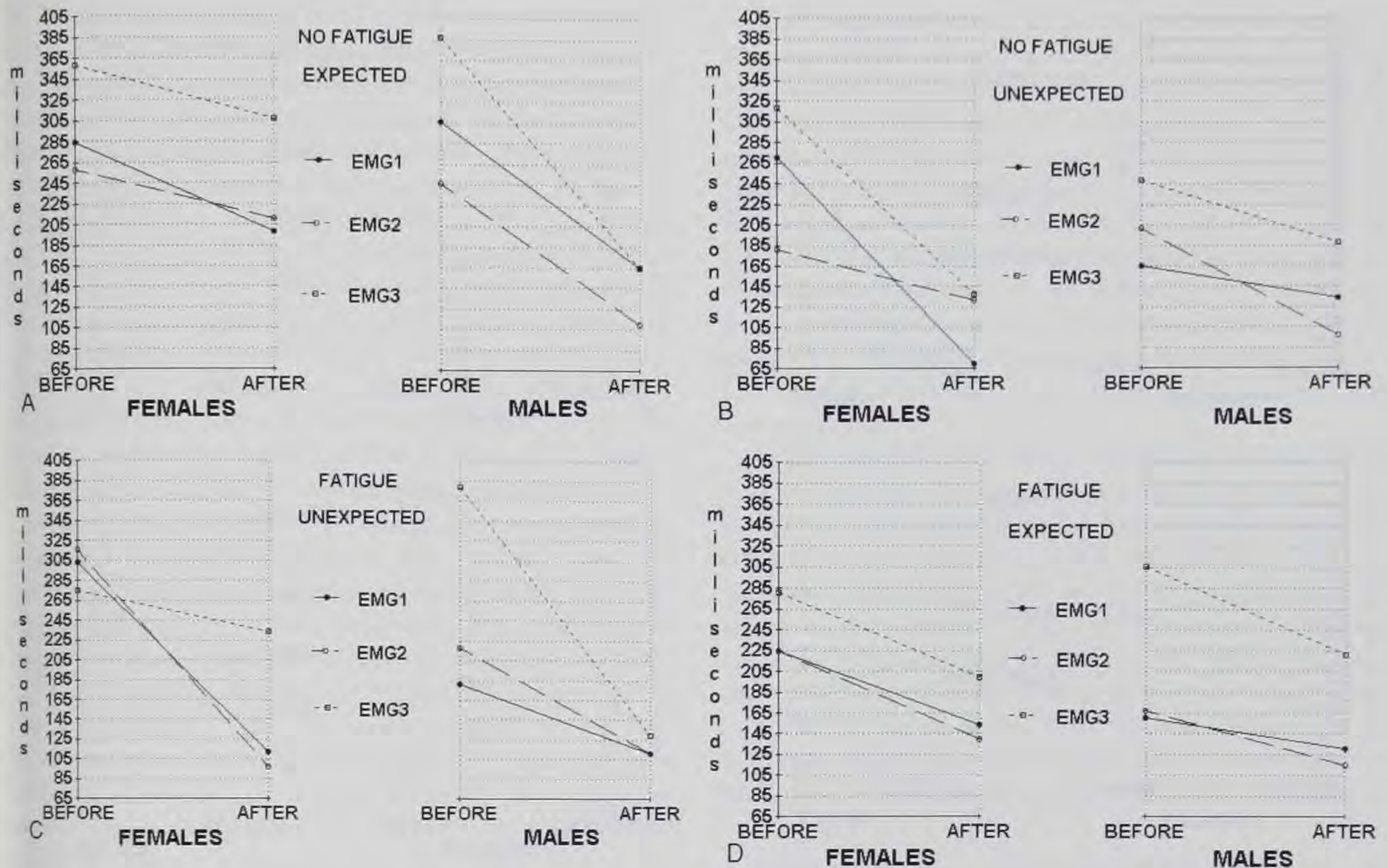


Figure 4. MANOVA test criteria for the hypothesis of overall five-level interaction between gender, fatigue state, expectation, time (before and after rehabilitation), and electromyographic (EMG) site on the dependent variable, reaction time ($P < 0.045$). EMG1 is the painful erector spinae; EMG2 is the nonpainful erector spinae; and EMG3 is the right rectus abdominis.

Discussion

Study 1

The subjects did not learn to cope with the unexpected loads over a short-term period. Had they done so, they would have reacted with increasing speed from the first to the last applied load. Consequently, individuals with chronic LBP should avoid situations that expose them to unexpected loads. Physicians and human resource personnel should keep this in mind when designing workplace accommodations for patients with chronic LBP returning to work.

One aim of the present study was to determine if walking would be a reasonable control measure for recovering from fatiguing environments. Walking had an effect after the calibration procedure and the vertical vibration exposure but not after static sitting. It may be that static sitting, with a reclined backrest, is a reasonable way to avoid fatigue and to recover from fatigue.

The overriding response of the nondominant side back muscles raises challenging questions. These muscles, located opposite the dominant hand, should be in better condition because they experience more involuntary exercise. However, the consistently slower reaction times show a system with significant, inherent load-response asymmetries, which are unaffected by walking

or sitting as control measures. In addition, erector spinae responses were determined individually to detect a response difference between the right and left erector spinae. The reaction time difference between sides matches the time it takes for the lumbar motion segment to buckle.³⁵ This raises the possibility that the muscle activity may prompt a buckling event and muscle spasm.

The increased reaction times found as a result of vertical vibration are most likely caused by fatiguing effects and increase of lower frequency components of muscle activity.^{21,28} The increased EMG response amplitudes indicate an overcompensation as reported by Marras et al.²⁵ This can be explained partially by the *in vitro* finding that the balance point of the motion segment has moved posteriorly^{34,35} as a result of sustained sitting. When the effective fulcrum within the intervertebral disc moves posteriorly, the moment arm over which the erector spinae muscles can act decreases, requiring greater forces (hence, more EMG activity) to cope with the same externally applied moment. Greater muscle forces lead to greater loads imposed on the disc.

Walking after seated vertical vibration exposure reduced the EMG response to an unexpected load. Thus, walking can probably move the effective fulcrum anteriorly, increasing the moment arm of erector spinae and

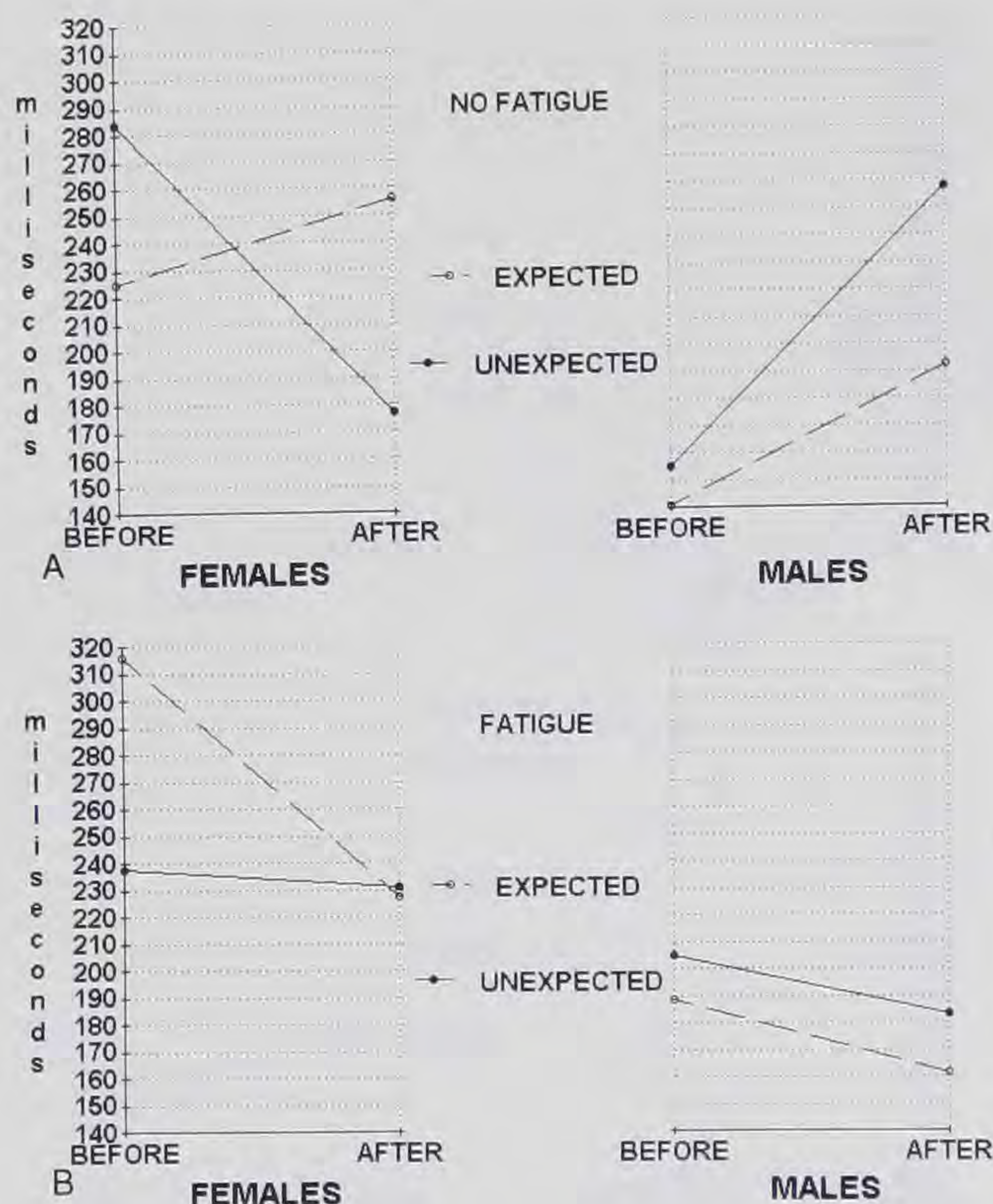


Figure 5. MANOVA test criteria for the hypothesis of overall four-level interaction between gender and fatigue state, expectation, and time (before and after) on the dependent variable duration ($P < 0.042$).

decreasing the load on the disc during a load event. Walking also tends to decrease the muscle reaction time, implying recovery from the fatigue induced by the seated vertical vibration exposure. Walking for 5 minutes after a vibration exposure is, thus, beneficial because it "resets" the system. Walking after exposure to vertical vibration tended to shorten the back muscles' reaction time and significantly decreased the peak muscle EMG activity, reducing the predicted muscle forces generated and applied to the intervertebral disc.

The finding of different reaction times on the dominant and nondominant sides in patients with chronic LBP suggests that there is the potential for asymmetric loading of the lumbar region. The greater the reaction time difference, the greater the load application asymmetry between dominant and nondominant sides. It is not clear, however, whether the patients' ability to respond to unexpected loads was the cause or the result of their LBP.

Study 2

Spinal loading applied through a chest harness at T4, during upright posture, has some specific features. An important feature of the coordinating compensation for unexpected loads within the conceptual model is that as the latency of the response becomes shorter, the response

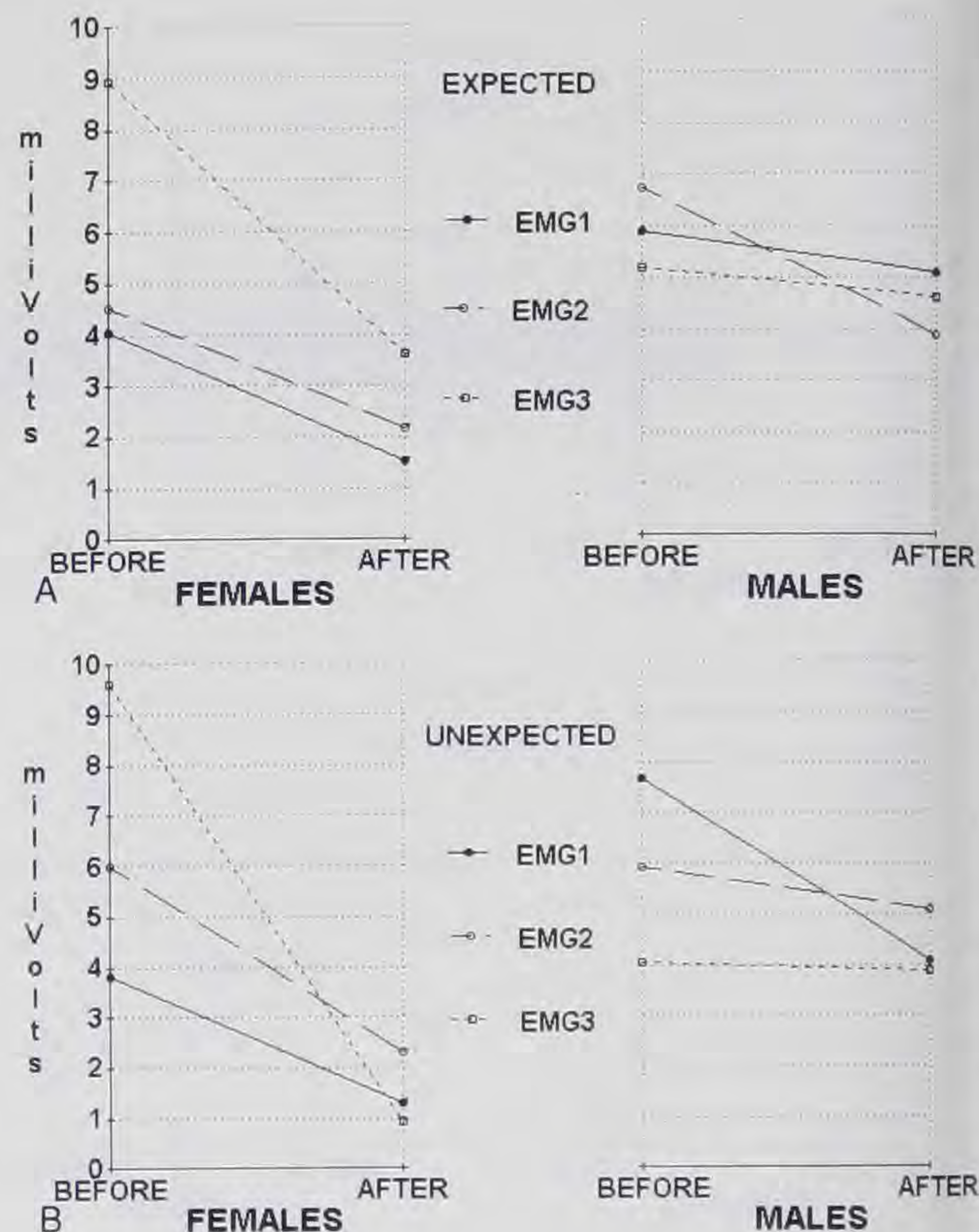


Figure 6. MANOVA test criteria for the hypothesis of overall four-level interaction between gender, expectation, time (before and after rehabilitation), electromyographic (EMG) site on the dependent variable, amplitude ($P < 0.021$). EMG1 is the painful erector spinae; EMG2 is the nonpainful erector spinae; and EMG3 is the right rectus abdominis.

becomes systematically more rigid.³¹ If more flexibility is needed, more sources of sensory information are taken into account to define the action, which requires more time.

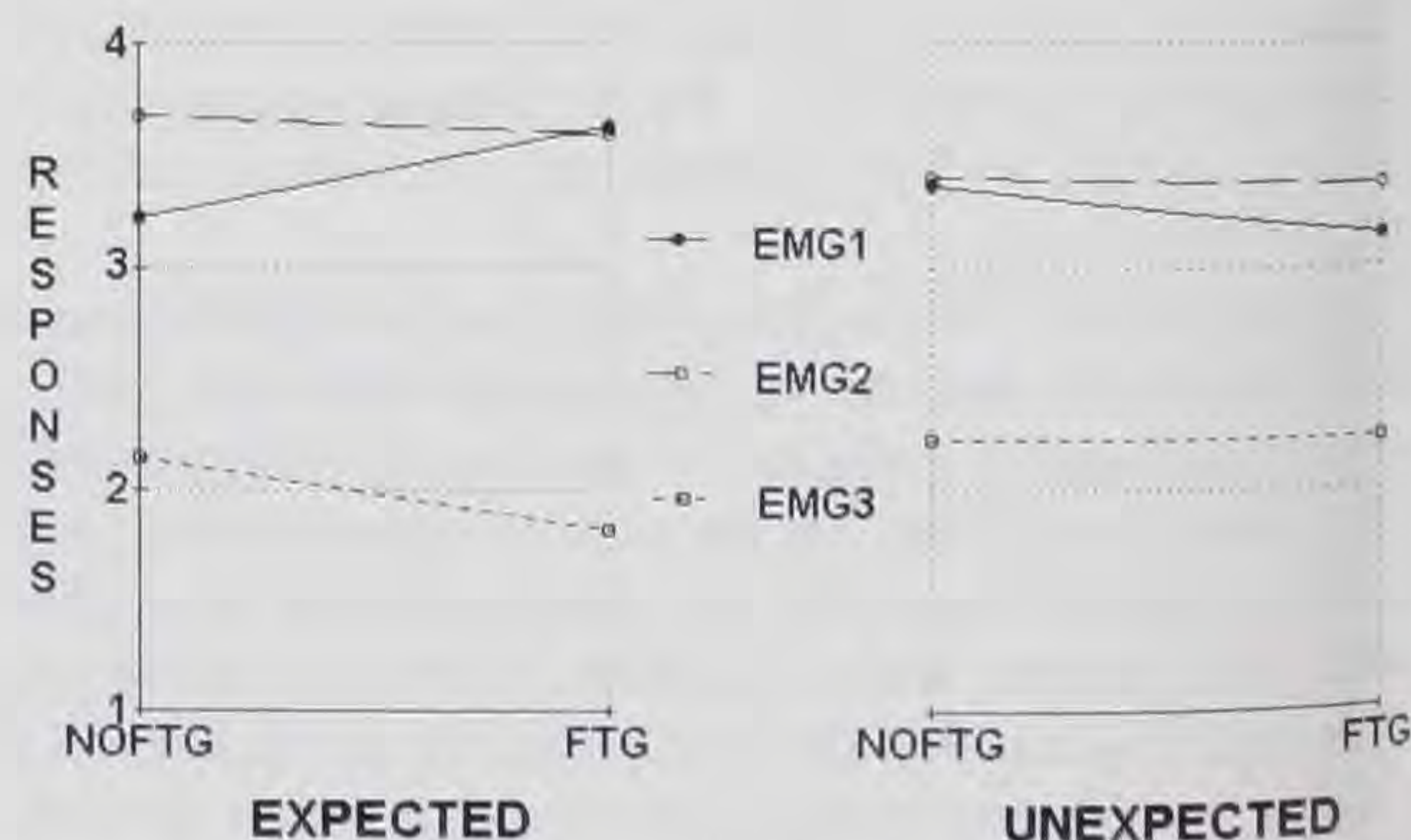


Figure 7. MANOVA test criteria for the hypothesis of overall three-level interaction between fatigue state, expectation, electromyographic (EMG) site on the dependent variable number of responses ($P < 0.049$). EMG1 is the painful erector spinae; EMG2 is the nonpainful erector spinae; and EMG3 is the right rectus abdominis.

There is a background (postural) EMG activity necessary to hold the torso in an upright position. After the load is added, several modifications to this background EMG activity represent the compensation for the added load: monosynaptic stretch reflex (M1 reflex) with latency of 30–50 msec;³¹ functional polysynaptic stretch reflex (long loop reflex or M2 reflex) with latency of 50–80 msec³¹ or 90 ms;¹⁰ triggered reactions with latency 80–120 msec;³¹ proprioceptive visual and vestibular responses triggered by changes in posture and taking approximately 150 msec;³ and voluntary reaction time (M3 response) with latency from 120 to 180 msec.³¹ Results of this study showed that the first detectable EMG response after sudden load is around 150 msec, *i.e.*, close to the duration of the triggered reactions.

Coordination of the three systems (proprioceptive, visual, and vestibular) permits smooth and efficient postural control in the event of expected or unexpected external disturbances to body position.¹ The visual system is involved later in motor control in the case of sudden load acting in the condition of temporal nonexpectation. Our results showed that this leads to significant increase of the reaction time. The longer reaction time also may result from, in part, decoupling the vestibular system by restricting the body's motion and using the fulcrum and harness during the tests. The visual system was decoupled when subjects' eyes were closed.

The M2 (polysynaptic) response originates from the muscle spindles, with higher amplitude, longer duration, and contributes more to the movement compensation than the M1. It allows for some sources of information to be integrated into the response, including proprioceptive afferents from joint positions and muscle length because it travels to higher centers (motor cortex or cerebellum). Disregarding that it is too fast to be voluntary, M2 can be modulated by conscious processes,³¹ which probably explains one reason improvement was measured before and after treatment. Although another possible explanation for improvement would be a learning effect, this work showed it was not possible to learn to cope or adapt to a series of unexpected load events. Pain decrease over the treatment time may be another explanation for improved response to the sudden loads; the treated patients were no longer scared to move and did not behave as rigidly because of tensed muscles. One aspect of management was to treat the fear of pain. The patients who had the most severe pain when entering the program improved more than the patients with less pain as measured by the visual analog score (VAS). At the end of treatment, there was no difference between them. Although there was an overall trend of pain decrease because of the rehabilitation program, it was not at the $P < 0.05$ level of significance. Medication such as nonsteroid anti-inflammatory drugs also may have had an influence on the outcome because reduction in pain would allow more flexibility and less stiffness. Additional studies are needed to address this question.

The triggered reaction is too fast to be voluntary, but it is too slow to be an M2 or M1 response. It follows Hick's Law¹³ and has moderate adaptability. Voluntary reaction time (M3 response) is powerful and sustained, can affect all of the musculature, follows Hick's Law, and is the most flexible of all. The reaction time frequently is defined as an interval of time from a suddenly applied, expected or unexpected, stimulus until the beginning of the voluntary response. It can be modified by many important factors—number of stimulus–response (S–R) alternatives (Hick's Law), stimulus–response compatibility, amount of practice, stress, arousal, deconditioning, and anticipation.³¹

Using the application of sudden load to the trunk with wavelet analysis of the response, some basic characteristics of the trunk musculature that have practical applications have been uncovered. The objective observation is that rehabilitation generally improves the efficiency and speed of back muscle behavior. There is a significant effect of rehabilitation on the erector spinae reaction time, the duration of the first response to a sudden load, and the amplitude of the first response. Rehabilitation generally shortened reaction time and decreased reaction amplitude. There are three possible reasons for these results:

1. Beneficial effect of the rehabilitation;
2. Learning effect; and
3. Time-dependent natural history of the disease.

Item 3 is unlikely because it is unlikely that passing of 2 weeks would improve the condition of a patient with chronic LBP. Item 2, as shown in Study 1, is unlikely because patients are not able to learn to improve their responses to multiple unexpected, sudden loads. This leaves Item 1, rehabilitation, as the likely reason for improvement. The improved reaction time, reaction duration, and amplitude indicate a more efficient response by the control system. It has the added benefit of reducing predicted loads on the disc. Even when subjected to fatigue, the rehabilitated patient with chronic LBP, was able to respond to a sudden load with a shorter burst of EMG activity, which means the muscles may retain some of their high-frequency response characteristics, usually lost with fatigue.

Gender influences also exist. Men respond faster with shorter duration of activity. Women responded more to rehabilitation in decreasing the activity of the erector spinae. Women responded with higher amplitudes in their abdominal muscles than in their erector spinae. Men were the opposite, having more extensor reflex than the women. In terms of evolution for men, a powerful extensor reflex would augment change to a sudden defensive crouch stance or prevent one from falling backward. The larger female flexor response may be correlated to their greater lumbar lordosis. Additional influences could involve muscle length differences, fiber-type ratio differences, or ligament stiffness differences.

Accommodating someone returning to work after experiencing LBP, which is of vital importance to do quickly, should involve reducing the risk of unexpected load events. This can be done by improving the response in patients, training (to anticipate sudden loads), or by changing the risks in the workplace. In a related study, patients with LBP underreacted to sudden loads. Their back muscles took more time and reacted with lower activity than matched control subjects.^{2,20} If suddenly applied loads are not actively damped and absorbed by the properly timed paying-out of the back muscles, the passive, viscoelastic components of the system will necessarily be more involved. The passive components are sensitive to the rate of loading and include vertebrae, discs, and ligaments, but they also could include unreactive muscles that remain at one length. Repeated applications of impact can deform an object, unless the object has a mechanism or strategy for dissipating the load.

Sudden load application is a mechanical shock to any mechanical system. Mechanical systems are designed in anticipation of their operating requirements. They are engineered either to be robust and broadbased to cope with impact, or their stability is maintained by a control system that can respond fast enough to the sudden load challenge.

Although humans have evolved to accommodate a particular range of sudden loads, such as those experienced during walking or running, they have not yet evolved to accommodate those associated with some, particularly machine-related, shock-load environments. Athletes train to excel at accommodating a particular range of sudden expected or unexpected load applications and releases. Wrestling, in particular, comes to mind: two participants trying to "surprise" each other enough to overcome their control systems. Football (soccer) goalkeepers need to be able to trap a direct kick efficiently so as to protect themselves and retain and control the ball. These are two athletic endeavors in which the participants have trained to accommodate unexpected circumstances and loads. Therefore, this shows the potential to train those, such as nurses, who are subjected to sudden loads.

Although humans can train to anticipate certain unexpected conditions, there are many unexpected conditions to which they can only react. When the event occurs faster than the human's control system can respond, they are at risk of mechanical damage or injury. When engineering a system, one method for accommodating sudden load is to make the engineered object stiffer and stronger. In previous studies, patients who are scared to move increased their baseline back muscle EMG activity in a similar fashion, trying to become stiffer and stronger and more resistant to motion.^{2,20}

Finally, one of the more fascinating discrepancies will help define the roles in postural control of the back and the upper limbs. Marras et al²⁵ showed that unexpected loads led to a 250% increase in back muscle response

activity. Results from previous work^{2,20} showed a decrease resulting from unexpected load and an additional decrease resulting from fatigue and caused by deconditioning from LBP. The differences are rooted in the way the loads were applied to the back. In this study and studies by Magnusson et al²⁰ and Aleksiev et al,² the loads and moments were applied directly to the upper trunk with a harness, bypassing the kinetic chain of the hands and shoulders. It is clear there are different control strategies invoked between these two conditions. Applying loads unexpectedly to the hands may invoke a resonance in the interaction of control between the trunk and the arms. Although Lavender et al¹⁶ suggest that the trunk acts like an underdamped system without preview of the impending load, they do not explain why the two-load application methods (load applied at the hands *vs.* load applied at the trunk) produce different results. It is known that the seated driver has a natural frequency of 4.5–5.5 Hz,³⁷ most likely because of rocking of the pelvis, a condition mediated by the leg muscles. The afferent control signals to the leg muscles have a 200 msec period, the inverse of a 5-Hz frequency. In a system demanding redundant methods for providing stability, a method for moving another mass is necessary. The arms provide that function in the human. To accomplish that end, the system from the hands to the shoulders would need to move rapidly, but not much faster than the speed dictated by the natural frequency of the trunk postural control system. Therefore, it is reasonable that if the control system for the upper limbs is surprised with an unexpected load, it will overcompensate. That force of overcompensation will be transferred to the trunk and will generate an overcompensation there.

Related to the previous discussion, successive bursts of EMG activity were separated by 200 msec, the reciprocal of a 5-Hz frequency. With unexpected load applied to the chest, there is a train or series of responses, reminiscent of the oscillations that result from an object being struck. Of particular importance in that train is that there is a 200 msec period between responses after the first response, suggesting that the "natural frequency" of 5 Hz previously observed in whole-body vibration studies may be of neurophysiologic control origin. Rehabilitation improves the ability of the systems to damp oscillations, resulting from unexpected load, because there were fewer pulses in the response train after rehabilitation in the patients with chronic LBP.¹⁹

The suddenly loaded human responds, in a general sense, like a vertical cantilever, fixed at the ground. When struck, it oscillates several times before its motion is damped out. Within the 1-second period after sudden perturbation, the erector spinae exhibited up to 4 bursts of activity, with decreasing amplitude, a behavior similar to the decreasing-amplitude oscillations of a damped system with a constant natural frequency.

This finding raises at least two questions about the system's seated natural frequency. If it were based solely

on mechanical parameters such as mass and stiffness, one would expect that with standing and sitting, being different postures with different pelvic orientations, disc orientations, and trunk and upper extremity muscle lengths, that there would be different trunk stiffnesses and different natural frequencies. That is unless the "natural frequency" is wholly or partly based on neurophysiologic parameters. It was observed that the response of the erector spinae group was to oscillate or exhibit bursts of activity at a 5-Hz frequency. Part of the explanation of the 5-Hz oscillation is related to the timing of Sherrington's reciprocal inhibition between the trunk flexors and extensors; as one set fires, the other set is inhibited from firing. If this limit is the case, humans, as a species, need to be wary of mechanical shocks and vibrations that occur at a rate faster than they can accommodate. With a stimulus occurring faster than the human feedback and control capabilities, people risk desynchronizing the activity of their back muscles from the mechanical needs of the spine, creating a chaotic, nonlinear oscillator with no feedback.⁶ It also was noted that after rehabilitation, patients were able to respond to a sudden load with fewer bursts of muscle activity, which strongly suggests that the trunk muscles (erectors and abdominals) have been "tuned up" by the rehabilitation to become better dampers of sudden loads. Therefore, rehabilitation improves the neurophysiologic ability to actively damp out undesirable oscillations.

■ Conclusion

Unexpected loads, which humans often experience, can lead to high forces in the spine and, thus, may be a cause of LBP. This article used sudden loading as a tool to assess the trunk. Several conclusions can be made from this work. Walking for 5 minutes after 40 minutes of exposure to vehicular vibration reduces the risk to the back caused by unexpected forces resulting from bending over, lifting, or handling unpredictable loads. International vibration exposure guidelines are not conservative enough to protect the trunk from the effects of subsequent unexpected loads. Patients with chronic LBP have less ability to protect themselves from sudden loads, but they can be trained to improve their response. The short-term, beneficial effect of a general back rehabilitation program for patients chronic with LBP has been shown objectively using a method that combines suddenly applied loads with wavelet analysis of trunk muscle response. The EMG analysis by wavelet transform gave a higher level of precision in exploring the information associated with the neural commands and mechanical behavior in response to externally applied loads. The work also showed the importance of keeping the back and abdominal muscles in good condition. Patients exhibit a flexion-extension oscillation at 5 Hz in response to a sudden load. The 5-Hz, seated, natural frequency observed during whole-body vibration may result from neurophysiologic control limits.

Summary of Clinical Relevance

1. Unexpected loads can cause large forces in the low back tissues that could be an important source of LBP.
2. Patients with chronic LBP do not learn to accommodate to sequential sudden loads over a short-term (no learning effect) period.
3. Fatigue should be avoided because it affects adversely healthy patients' and those with chronic LBP responses to unexpected load.
4. Unexpected loads should be minimized.
5. Response to unexpected flexion load and moment is multisynaptic in the erector spinae.
6. Rehabilitation has a significant effect and opens up possibilities to design specific rehabilitation protocols for these patients. This may be a useful strategy to optimize return to work.
7. Walking for 5 minutes can reduce the effect of 40 minutes exposure to vehicular vibration and is important to do before bending over, lifting, or handling unpredictable loads, such as unloading a vehicle.
8. Current vibration exposure guidelines are not conservative enough.
9. Prevention programs in the workplace might help to save thousands of man-hours out of work and millions of dollars.
10. The results of the present study might help to evaluate more precisely the risk associated with some activities in particular tasks.
11. The trunk muscles are active dampers of undesirable shocks and vibration and work better if kept well conditioned.

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■ Appendix 1

Test Matrix for Vibration Study of 16 Healthy Control Subjects

1. After giving consent, EMG electrodes were connected, and muscle activity was calibrated by having the subject perform a maximum voluntary muscular extension effort.
2. Erector spinae EMG responses to six repetitions (reps) of sudden unexpected load were measured.
3. The subject then walked on a treadmill for 5 minutes.
4. Erector spinae EMG responses to six sudden, unexpected loads were measured.
5. The subject was exposed to the first (randomly chosen) of two sustained (40 minutes) loading regimens to simulate common load environments (sitting statically [1], vertical [2], lateral [3], or combined vertical and lateral vibration [4] while sitting upright).
6. Erector spinae EMG responses to six reps of sudden unexpected load were measured.
7. Walk for 5 minutes.
8. Erector spinae EMG responses to six reps of sudden unexpected load were measured.
9. Subject exposed to the second (randomly chosen) of three remaining sustained (40 minutes) loading regimens.
10. Erector spinae EMG responses to six reps of sudden unexpected load were measured.
11. Walk for 5 minutes.
12. Erector spinae EMG responses to six reps of sudden unexpected load were measured.
13. Subject was exposed to the third (randomly chosen) of two remaining sustained (40 minutes) loading regimens.

14. Erector spinae EMG responses to six reps of sudden unexpected load were measured.
15. Walk for 5 minutes.
16. Erector spinae EMG responses to six reps of sudden unexpected load were measured.
17. Subject was exposed to the remaining sustained (40 minutes) loading regimens.
18. Erector spinae EMG responses to six reps of sudden unexpected load were measured.
19. Walk for 5 minutes.
20. Erector spinae EMG responses to six reps of sudden unexpected load were measured.

■ Appendix 2

Test Matrix for Vibration Study of 6 CLBP Patients (Wilder et al, 1995)

1. After giving consent, EMG electrodes were connected, muscle activity was calibrated by having the subject perform a maximum voluntary extension muscular effort.
2. Erector spinae EMG responses to six repetitions (reps) of sudden unexpected load were measured.
3. The subject then walked in the laboratory hallway for 5 minutes.
4. Erector spinae EMG responses to six reps of sudden unexpected load were measured.
5. Subject was exposed to the first (randomly chosen) of two sustained loading regimens to simulate common load environments (sitting still (1) or vertical vibration while sitting upright (2)).
6. Erector spinae EMG responses to six reps of sudden unexpected load were measured.
7. Walk for 5 minutes.
8. Erector spinae EMG responses to six reps of sudden unexpected load were measured.
9. The subject was exposed to the remaining loading regimen to simulate common load environments.
10. Erector spinae EMG responses to six reps of sudden unexpected load were measured.
11. Walk for 5 minutes.
12. Erector spinae EMG responses to six reps of sudden unexpected load were measured.