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Trunk kinematics and trunk muscle activity during a rapidly applied load

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Abstract

This study investigated the trunk kinematics and electromyographic (EMG) activity of eight trunk muscles when “expected” and “unexpected” loads were applied directly to the torso. Twenty individuals (mean age: 25.1 yr; range 20–33 yr) participated in this mixed model study in which gender was the between-subjects factor, and expectancy and symmetry of the applied load were within-subject factors. The sudden load was delivered to the subject via a cable attached to a thoracic harness and motion was restricted to the lumbar spine by strapping the pelvis to a rigid fixation apparatus. Surface EMG was recorded bilaterally from the longissimus thoracis (LGT), erector spinae (ERS), rectus abdominis (RAB) and the external obliques (EXO). Trunk kinematics were measured with a Lumbar Motion Monitor™. During expected loading conditions, the peak muscle activity was reduced for the RAB and EXO bilaterally, and for the ERS(R) ($p < 0.01$) relative to the unexpected conditions. Conversely, the normalized area of EMG activity prior to the onset of load was increased for the ERS and EXO bilaterally, and for the RAB(R) ($p < 0.05$) during an expected loading event. Trunk motion in the sagittal and frontal planes was reduced during expected loading. Activation of the trunk muscles just prior to a rapid loading event increases trunk stiffness, decreasing trunk displacement and peak muscle activity.

Keywords: Sudden loading; Gender; Trunk muscle activity; Biomechanics; Spine

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1. Introduction

Lower back pain is a significant and costly health problem in the United States, and is the second leading symptom for which people seek medical care [1]. Estimates of the prevalence of lower back pain vary from 14% to 85% of the population [1–3] and, according to the Bureau of Labor Statistics, there are over one million work-related back injuries reported in the United States annually [4].

Material handling has been cited as one of the most frequent causes of back injuries, although sudden (forceful, unexpected) movements have been associated with more costly injuries [3,5,6]. Sudden exertions can occur due to slips or falls, lifting of unstable loads (i.e., a container partially filled with a liquid) or failed two-person lifts. In each example, a rapid unexpected perturbing force or load is exerted on the body, to which the central nervous system (CNS) must respond rapidly in order to restore postural equilibrium. Given that sudden perturbing events are both dynamic and novel, there is a tendency for the CNS to “overshoot” in response to these events [7]. This overshoot is characterized by an increase in the number of muscles activated, the onset rate of muscle activity, and the magnitude of muscle activity [8,9].

Studies of the effects of unexpected loading show consistent trends across the literature. Unexpected perturbations generally lead to increased muscle activity and greater displacements of the body’s center of mass compared with expected perturbations [9,10]. Furthermore, repeated exposure to a similar perturbing force results in the subject reducing their muscular response and decreasing the magnitude of postural disturbance [9]. With regard to the lumbar spine, an unexpected pertur-

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bation which results in increased trunk muscle activity creates greater compressive loads on the spine and is a potential mechanism for injury to contractile and non-contractile spinal structures [11].

Marras et al. [8] investigated the effects of sudden loading on trunk muscle activation in healthy men and reported that the peak EMG data from the trunk muscles were on average 1.7 times higher, and the mean EMG data were 2.4 times higher, when comparing "unexpected" and "expected" loading. Unexpected loading was defined as those trials in which visual and auditory cues indicating the temporal onset of the perturbation were removed. Furthermore, the onset rate of muscle activity, which was defined as the rate of change in the surface EMG signal immediately after the load application, increased significantly for all muscles during unexpected loading conditions.

In a similar experimental paradigm, Lavender et al. [11] measured the effects of task preview time and task symmetry on human postural response. Peak EMG and mean EMG activity of the anterior and posterior trunk muscles were highest for the 0 ms preview time (i.e., unexpected loading) and decreased as the task preview time increased to 400 ms. The onset rate of muscle activity was also greater for the reduced preview times. Asymmetric loading of the torso resulted in an increase in the peak and mean EMG of the trunk muscles contralateral to the applied load, and a decrease of the peak and mean EMG for the trunk muscles ipsilateral to the applied load. According to the authors, the imbalance in trunk muscle activity during asymmetric loading leads to increased shear forces on the lumbar discs and increases the risk of injury to these structures [11].

An increase in the activity of anterior trunk muscles (e.g., the non-stretched abdominals) as well as the posterior trunk extensors in response to a sudden ventral perturbation of the torso has been reported [10,12]. Cresswell et al. [10,12] found that unexpected ventral loading of the trunk resulted in activation of the anterolateral muscles in advance of the trunk extensors by as much as 39 ms and suggest that pre-activating abdominal muscles serves to increase intraabdominal pressure (IAP) and stiffen the torso, thereby minimizing postural disturbances in response to expected rapid ventral loading of the torso. However, the work of Lavender et al. [9] found that subjects generally did not employ a strategy of increasing IAP in response to repeated exposure to a rapid loading event. Lavender et al. [9] utilized a protocol in which subjects received a ventral perturbing force once a minute for 30 min. Only one subject out of four reduced their extensor torque contribution through increased IAP [9].

The experimental paradigms of Marras et al. [8], Lavender et al. [9,11,13] and Cresswell et al. [10,12] examined the response of the trunk muscles to a sudden perturbation in a free-standing posture in which the contributions of the lower extremities to the postural response were not controlled. Furthermore, none of these investigations had an adequate number of female subjects to determine if gender influences the response strategy employed during a rapid loading event. There is some evidence to suggest that males have greater trunk stiffness than females [14]. The potential effect of this difference in passive stiffness on trunk muscle response to a sudden perturbation is unknown.

The purpose of this investigation was to examine closely the effects of a perturbing force applied directly to the torso on the trunk muscular and kinematic responses when motion was restricted to the lumbar spine. Additionally, this investigation studied the influence of gender on the trunk muscle response prior to, and during, rapidly applied loads.

2. Methods

2.1. Subjects

Twenty subjects (10 male and 10 female), 20 to 33 years of age (mean = 24.5 yr), were recruited to participate in this study. The subjects were screened for history of lower back dysfunction. Only individuals with no history of lower back pain in the last year were allowed to participate in the study.

2.2. Experimental design

This experiment was a mixed design, in which the independent variable gender was a between-subjects factor and the independent variables of expectancy of applied load and direction of applied load (symmetry) were within-subject factors. The session consisted of three trials of each experimental condition with a minute's rest between trials. The sequence of trials was randomized.

The dependent measures were the trunk kinematics as measured with the Lumbar Motion Monitor™ (LMM) (Chattanooga Corp.) and the normalized surface EMG from the left and right longissimus thoracis (LGT), erector spinae (ERS), external oblique (EXO) and rectus abdominus (RAB).

2.3. Apparatus

The subjects stood in a reference frame constructed of steel tubing. In the center of the reference frame was a smaller structure which allowed the experimenter to secure the subject in an upright position so that motion below the lumbar spine was restricted. The rapidly applied load (RAL) was delivered to the subject via a cable attached to a thoracic harness. The cable was run through pulleys and attached to a bag of lead shot, which was dropped 1 metre (Fig. 1). The weight of the bag was normalized to a value that was 5% of each individual's maximum isometric trunk extensor strength. The applied load was delivered in the mid-sagittal plane, and in an oblique plane rotated 45° to the right of the mid-sagittal plane, for the symmetric and asymmetric conditions respectively. A load cell attached to one of the pulleys was utilized as an event marker.

Disposable surface EMG electrodes manufactured by Nikomed (Nikomed Corp.) were used for this study. The inter-electrode distance was 2 cm. The EMG signals were pre-amplified (gain of 1000) close to the recording electrodes and sent to the main amplifier via shielded cables. The signals were amplified and rectified with a bandpass frequency range of 15 to 1000 Hz and integrated at a time constant of 30 ms. The integrated signals were sampled at 120 Hz. The raw amplified EMG signals were monitored on a sweep oscilloscope for signal quality.

Trunk position data were obtained with the LMM, which is essentially a triaxial torso electro-goniometer, and collected at 60 Hz utilizing LMM software. The LMM attaches to the thoracic spine via a chest harness, and to the pelvis at the level of the sacrum with a pelvic harness. The unit weighs approximately 1.4 kg and does not restrict lumbar motion. The reliability of the instrument has been reported by Marras et al. [15].

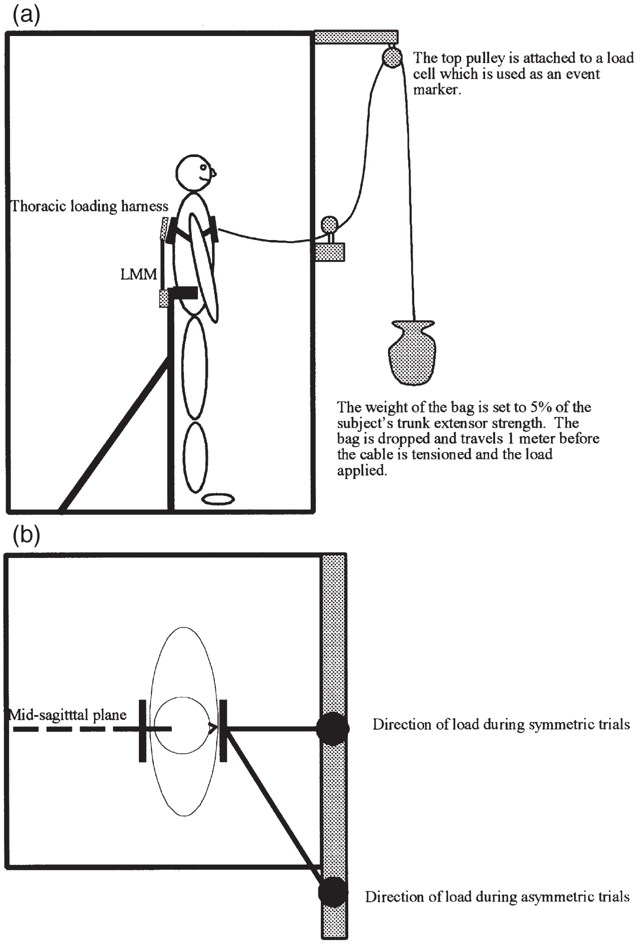

Fig. 1. The reference frame utilized in this experiment to deliver the suddenly applied load: (a) side view; (b) top view.

2.4. Procedure

Upon entering the laboratory, subjects signed an informed consent form which described the protocol of the study. The subject's height, weight, age, leg length, lumbar spine length (L5 to T1) and waist circumference were measured.

Surface EMG electrodes were placed on the skin overlying the muscle bellies of LGT, ERS, RAB and EXO muscles. The electrodes were attached at the level of T10 approximately 4 cm from the midline for the LGT, and at the level of L3, approximately 4 cm from the midline for the ERS. Electrodes for the RAB were attached at the level of the umbilicus 2 cm from the midline. Placement for the EXO was at the level of the umbilicus, approximately halfway between the iliac crest and the anterior superior iliac spine. This is usually 2 cm medially and 2 cm laterally from these respective bony landmarks and rotated 45° from the vertical. The common ground electrode was attached between the sixth and seventh rib in the mid-axillary line. The skin at these sites was cleaned with alcohol and lightly abraded. Baseline or resting EMG values were recorded with the subject standing in a relaxed posture.

Maximum isometric muscle forces for the purpose of EMG normalization were measured by having the subject perform resisted isometric trunk flexion, extension and rotation. The subject stood in the reference frame with the pelvis firmly secured, and a harness was placed over the thoracic region which in turn was connected to a dynamometer. The subject was asked to exert maximal flexion, extension and rotation forces with his or her trunk while standing in a neutral posture. These tests were repeated at 2 min intervals until the force measured from each muscle group no longer increased and the two greatest trials were within 10% of each other [16]. The maximum trunk extensor force was recorded and used to determine the magnitude of the weight dropped during the rapidly applied load.

The subject remained in the reference frame with the pelvis secured as described above. The method of attaching the LMM to a subject was modified in this experiment. The base of the unit was attached to the stand to which the subject's pelvis was secured. The LMM was adjusted so that the base was aligned with the subject's lumbosacral junction. The thoracic attachment of the LMM was mated with a modified loading harness system, and secured so that the top of the LMM was aligned with the third thoracic vertebra. The modified attachment of the LMM allowed us to restrict the contributions of the pelvis and lower extremities during RAL while not limiting trunk motion. Furthermore, modification of the thoracic attachment enabled the experimenters to deliver the RAL through the thoracic harness at the level of tenth thoracic vertebrae. Padding was placed around the EMG electrodes for the LGT to prevent compression from the thoracic harness. The subject was then instructed to stand straight with the eyes facing forward and a measure of relative neutral posture was recorded.

The load was applied either symmetric to, or asymmetric to the mid-sagittal plane. During symmetric loading, the cable was attached to the mid-point of the thoracic loading harness and run through two pulleys in the mid-sagittal plane. During asymmetric loading, the cable was attached to the mid-point of the thoracic harness and was run through two pulleys set at 45° to the right of the mid-sagittal plane, thereby creating lateral bending and twisting moments in addition to the forward bending (sagittal plane) moment. In the expected condition, the subject was able to observe the experimenter releasing the bag of lead shot. The subject then had approximately 500 ms until the cable tensioned and the load was applied. In the unexpected loading condition, the subject wore a blindfold to block any visual cues and a noise generator was utilized to mask any auditory cues of the impending load. During the unexpected RALs the interval between donning of the blindfold and the actual load application varied from 2 to approximately 30 s. Trunk kinematics and EMG data were collected for 1 s prior to the release of the load and for 2 s after the RAL.

2.5. Data treatment

The integrated EMG (IEMG) data were normalized for each subject with respect to the EMG data collected during maximal trunk exertions and the resting EMG levels according to Eq. (1):

$$\mathrm{NEMG}(i,j) = (\mathrm{IEMG}(i,j) - \mathrm{REST}(i))/(\mathrm{MAX}(i) - \mathrm{REST}(i)) \tag{1}$$

where:

i = muscles 1 to 8,
j = experimental conditions 1 to 4,
NEMG(i,j) = the normalized EMG for muscle i in condition j,
IEMG(i,j) = the current integrated EMG value for muscle i in condition j,
REST(i) = the minimum resting IEMG value for muscle i during relaxed standing and
MAX(i) = the maximum IEMG value from muscle i during a maximal isometric exertion.

The pre-load area of normalized EMG, which is a measure of the muscle activity prior to the onset of an impending load, was determined by Eq. (2):

$$\text{Pre–load area }(i,j) = \sum_{m}^{\mathrm{SAL}} \mathrm{NEMG}(i,j) \tag{2}$$

where:

i = muscles 1 to 8,
j = experimental conditions 1 to 4,
NEMG(i,j) = the normalized IEMG for muscle i in condition j,
m = sample coinciding with the onset of muscle activity and
SAL = sample coinciding with the onset of the sudden load.

The peak NEMG values, the area of NEMG activity prior to the RAL, and the time from the onset of the applied load to peak NEMG (peak latency) were analyzed in this investigation. Trunk position data were obtained from the LMM. The position data were smoothed with a three-point moving average, and the second central point difference method was used to calculate the velocity. The same procedure was repeated on the velocity data to determine acceleration. The peak displacement, velocity and acceleration for each trial were then determined.

Four-way multivariate analyses of variance (MANOVA) procedures were used to analyze the peak NEMG, the area of NEMG activity prior to the RAL, and the peak latencies. Three additional four-way MANOVA procedures were utilized in the analyses of trunk kinematic data in the frontal, sagittal and horizontal planes. Significant MANOVA findings were followed up with univariate four-way mixed model analysis of variance (ANOVA) procedures on individual muscles or kinematic variables.

3. Results

3.1. Peak EMG

The experimental conditions of expectancy, symmetry, and the interaction of symmetry by expectancy were significant for peak NEMG ($p < 0.01$). There was no significant gender effect (Table 1). Univariate analyses indicated a significant interaction of the experimental conditions of symmetry and expectancy for the left and right erector spinae (ERSL and ERSR) ($p < 0.01$), and for the right external oblique (EXOR) ($p < 0.05$). When the direction of the applied load was symmetric to the mid-sagittal plane, the peak NEMG for expected loading was equivalent to that observed during unexpected load-

Table 1
Multivariate analysis (MANOVA) and univariate analyses for peak normalized EMG

Effect	MANOVA	ERSL	ERSR	LGTL	LGTR	RABL	RABR	EXOL	EXOR
Gender	ns	nt	nt	nt	nt	nt	nt	nt	nt
Sym	$F = 53.5$ df = 8,208 $p < 0.0001$	ns	$F = 46.09$ df = 1,18 $p < 0.0001$	$F = 4.91$ df = 1,18 $p < 0.039$	$F = 34.15$ df = 1,18 $p < 0.0001$	$F = 31.71$ df = 1,18 $p < 0.0008$	ns	$F = 118.84$ df = 1,18 $p < 0.0001$	$F = 16.01$ df = 1,18 $p < 0.0008$
Exp	$F = 7.18$ df = 8,208 $p < 0.0001$	ns	$F = 8.80$ df = 1,18 $p < 0.0082$	ns	ns	$F = 6.79$ df = 1,18 $p < 0.0178$	$F = 4.72$ df = 1,18 $p < 0.053$	$F = 13.71$ df = 1,18 $p < 0.0016$	$F = 18.38$ df = 1,18 $p < 0.0004$
Sym*Exp	$F = 3.26$ df = 8,208 $p < 0.016$	$F = 8.33$ df = 1,18 $p < 0.0098$	$F = 10.73$ df = 1,18 $p < 0.0042$	ns	ns	ns	ns	ns	$F = 5.9$ df = 1,18 $p < 0.025$
Trial	ns	nt	nt	nt	nt	nt	nt	nt	nt

ns = Not significant to the 0.05 level; nt = not tested; Sym = symmetry; Exp = expectancy.

ing (Fig. 2(a)) for both ERS muscles. When the applied load was asymmetric to the mid-sagittal plane, peak NEMG of the erector spinae muscle contralateral to the applied load (ERSL) was reduced on average by 6% MVC, and the erector spinae muscle ipsilateral to the applied load (ERSR) was reduced on average 26% MVC for expected loading conditions relative to the unexpected loading conditions (Fig. 2(b)).

The EXOR's response was larger, approximately 4% MVC, in the symmetric unexpected condition (Fig. 3). When the load was applied asymmetric to the mid-sagittal plane, the peak NEMG of the EXOR was increased on average by 7% MVC for unexpected versus expected loading. Overall, the right external oblique (EXOR) and the other three anterior muscles sampled (left and right rectus abdominus, and left external oblique) had higher peak NEMG values during unexpected loading, as demonstrated in Fig. 4.

Averaging across expectancy conditions, asymmetric sudden loading resulted in a reduction of peak NEMG from the ipsilateral erector spinae ERSR, and bilaterally from the longissimus thoracis (LGTL and LGTR), relative to the symmetric loading conditions (Fig. 5(a)). Fig. 5(b) shows there was an increase in the peak NEMG of the contralateral rectus abdominis (RABL), external oblique (EXOL), and from the ipsilateral external oblique (EXOR) during the asymmetric loading conditions.

3.2. Pre-load area of normalized EMG

Table 2 shows that the MANOVA was significant for the experimental conditions of expectancy, symmetry, and the interaction of symmetry and expectancy. Gender, as was the case with peak NEMG, did not significantly affect pre-load muscle activity. During unexpected loading, the symmetry of the applied load had no effect on the pre-load activity of the ERSR and RABR muscles. However, when the applied load was expected, the pre-load activities of these ipsilateral muscles were much

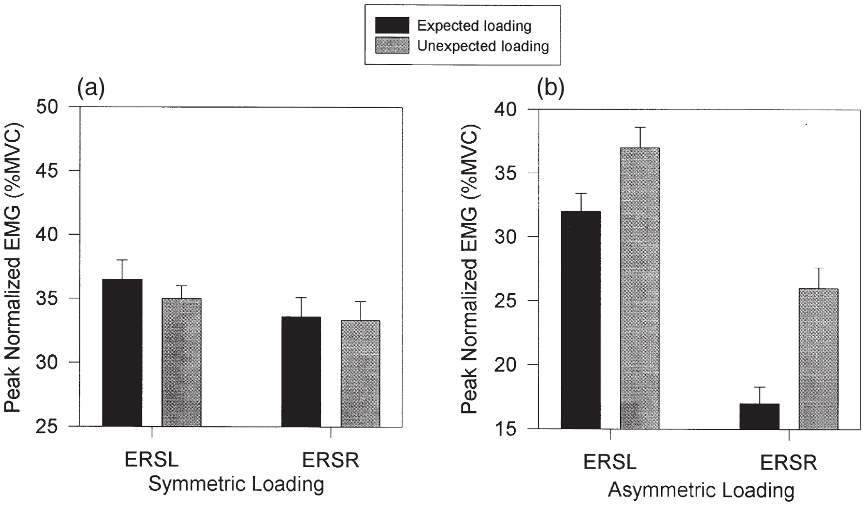

Fig. 2. The interaction of expectancy and symmetry of the applied load on peak NEMG for the left erector spinae (ERSL) and right erector spinae (ERSR): (a) symmetric loading; (b) asymmetric loading.

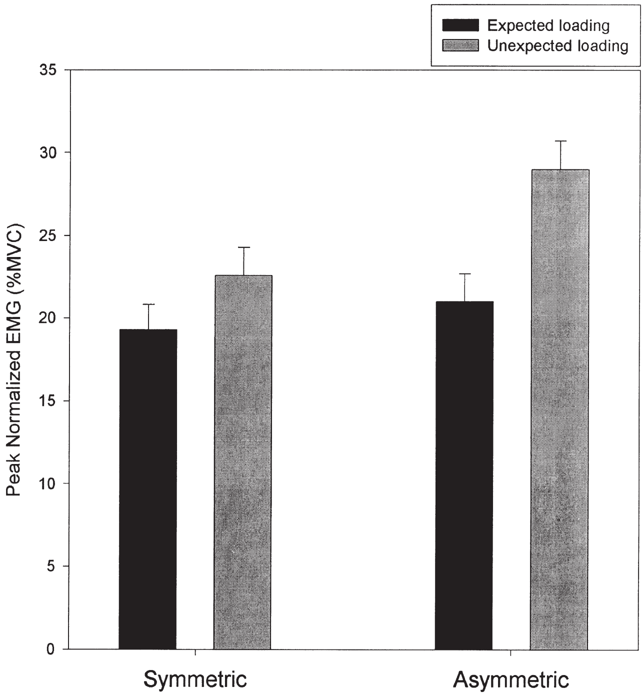

Fig. 3. The interaction of expectancy and symmetry of the applied load on peak NEMG for the right external oblique (EXOR).

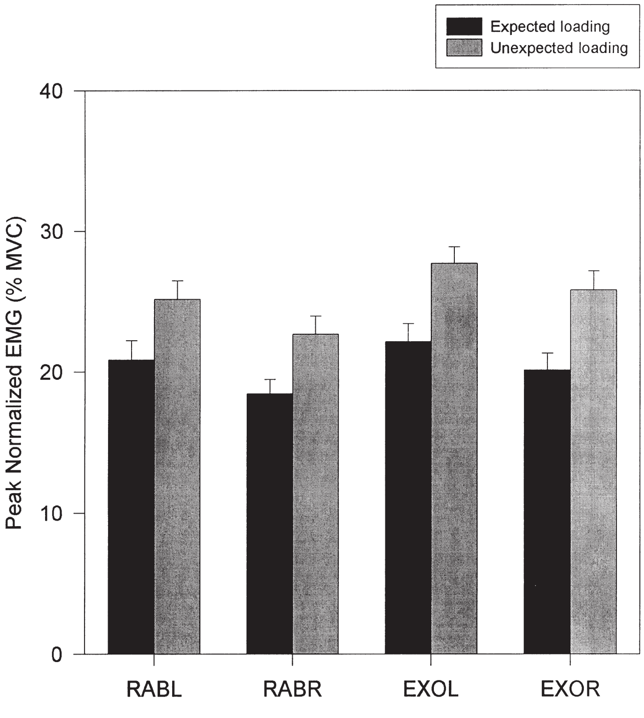

Fig. 4. The main effect of expectancy on peak NEMG for the left and right exteral oblique (EXOL, EXOR) and rectus abdominus (RABL, RABR).

lower when the direction of the applied load was asymmetric rather than symmetric to the mid-sagittal plane (see Fig. 6(a) and (b)).

When averaging across the experimental condition of symmetry of the applied load, the pre-load activities of both the left and right erector spinae and external oblique were much greater when the applied load was expected (Fig. 7).

3.3. Peak latency

Multivariate analysis of the times between the onset of the applied load and the peak EMG (peak latencies) showed significant changes due to the expectancy conditions and symmetry of the loading (Table 3). During expected loading the peak latencies ranged between 171 and 178 ms (mean = 175 ms) for the posterior trunk muscles and between 210 and 250 ms (mean = 228 ms) for the anterior trunk muscles (Fig. 8(a)). However, during unexpected loading the average peak latencies were 15% shorter for the posterior muscles and ranged between 195 and 220 ms (mean = 205 ms). The peak latencies of the anterior muscles were unaffected by the expectancy condition ($p > 0.05$) and ranged between 220 and 240 ms (mean = 230 ms).

Four muscles showed significant ($p < 0.01$) changes in peak latencies due to symmetry of the applied load. Three of the four muscles were ipsilateral (the right erector spinae, longissimus thoracis and external oblique) with respect to the applied load. The fourth muscle, the contralateral (left) erector spinae, not only showed a significant change but also was the last posterior muscle to reach its peak value during asymmetric loading (Fig. 8(b)).

3.4. Trunk kinematics

On average, the trunk displacement in the sagittal plane during unexpected loading was 19° and was reduced to 12° for expected loading. Trunk motion in the frontal and transverse planes each averaged between 5 and 6° during unexpected loading, and between 4 and 5° for expected loading. The MANOVAs for each plane of motion were significant for the conditions of symmetry and expectancy, but not gender. In sum, the magnitudes of trunk displacement, as well as peak velocities and accelerations, were decreased in all three planes of motion when the applied load was expected (Table 4). As expected, asymmetric loading increased the side bending and twisting motions, but resulted in reduced forward bending relative to symmetrically applied loads.

4. Discussion

The results of this study indicate that during a sudden perturbation there is increased trunk displacement and

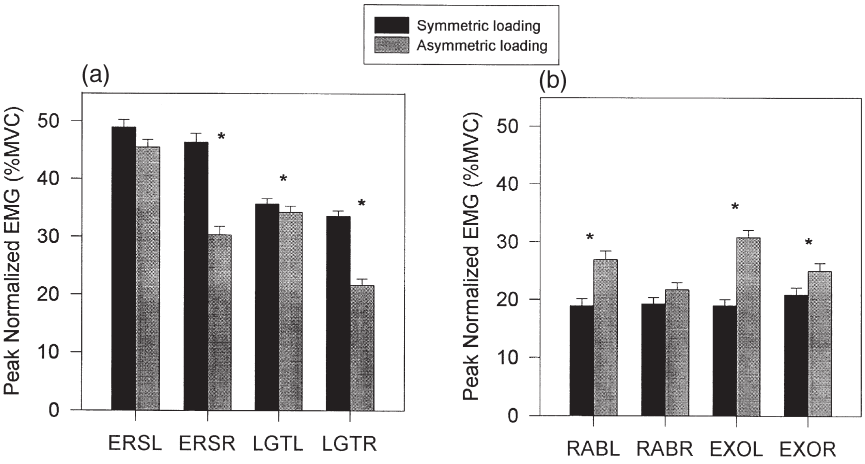

Fig. 5. The main effect of symmetry on peak NEMG of the (a) the trunk extensors and (b) the trunk flexors. q indicates $p < 0.05$.

Table 2
Multivariate analysis (MANOVA) and univariate analyses for pre-load area of normalized EMG

Effect	MANOVA	ERSL	ERSR	LGTL	LGTR	RABL	RABR	EXOL	EXOR
Gender	ns	nt	nt	nt	nt	nt	nt	nt	nt
Sym	$F = 3.08$ df = 8,208 $p < 0.0028$	$F = 5.5$ df = 1,18 $p < 0.0317$	$F = 21.41$ df = 1,18 $p < 0.003$	ns	ns	ns	ns	ns	ns
Exp	$F = 10.99$ df = 8,208 $p < 0.0001$	$F = 22.4$ df = 1,18 $p < 0.002$	$F = 9.6$ df = 1,18 $p < 0.0069$	ns	ns	ns	ns	$F = 10.80$ df = 1,18 $p < 0.0046$	$F = 7.85$ df = 1,18 $p < 0.0128$
Sym*Exp	$F = 2.5$ df = 8,208 $p < 0.011$	ns	$F = 20.073$ df = 1,18 $p < 0.0004$	ns	ns	ns	$F = 8.9$ df = 1,18 $p < 0.0085$	ns	ns
Trial	ns	nt	nt	nt	nt	nt	nt	nt	nt

ns = Not significant to the 0.05 level; nt = not tested; Sym = symmetry; Exp = expectancy.

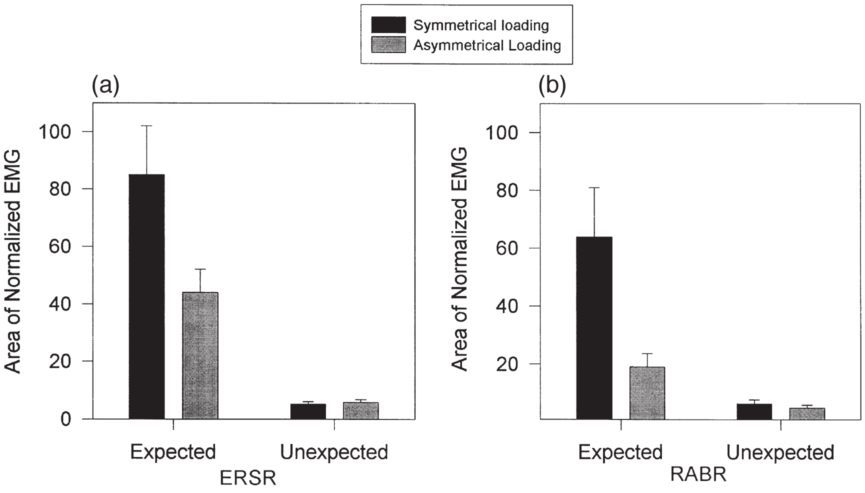

Fig. 6. The interaction of expectancy and symmetry of the applied load on the pre-load area of NEMG for (a) the ERSR and (b) the RABR.

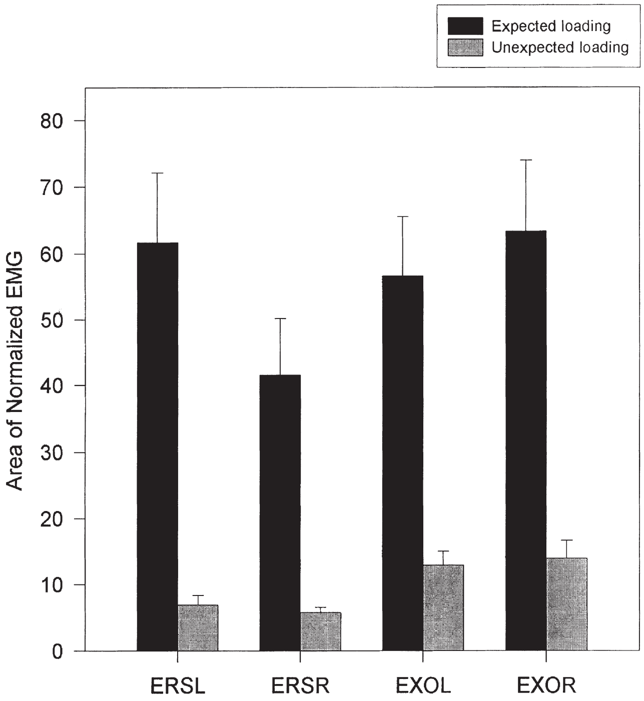

Fig. 7. The main effect of expectancy on the pre-load area of NEMG for the left and right erector spinae (ERSL, ERSR) and external oblique (EXOL, EXOR).

increased trunk muscle response when the exact temporal onset of a perturbing force is unknown. With ample warning of an impending load, the erector spinae and external oblique muscles were active prior to load onset and trunk displacement was reduced. Addtionally, there was a distinct latency between the peak muscle activity of the trunk extensors and trunk flexors during expected loading. However, gender was not a factor in peak NEMG, pre-load area of NEMG, latency of peak muscle response, or trunk kinematics.

The findings in this investigation are in general agreement with the literature regarding the muscular response to a sudden perturbation, although the specific patterns of muscle activity are in conflict with previous published reports. Previous investigations have found an increase in the peak NEMG response to unexpected loading of both anterior and posterior trunk muscles [8,13]. Marras et al. [8] and Lavender et al. [9,11,13] found large differences in the peak response of the trunk flexors and extensors between expected and unexpected sudden loading conditions. In contrast, we found only small changes in peak response of the primary trunk extensors (erector spinae) and moderate changes in the trunk flexors (rectus abdominus and external oblique) when comparing expected and unexpected loading (Figs. 2 and 4). Furthermore, sagittal plane trunk displacement was increased on average only by 5° during unexpected loading (Table 5). These differences may be due to the methods of applying the perturbing force. The experimental protocols utilized by Marras et al. and Lavender et al. delivered a perturbing force by dropping a weight 1 m into a box that the subject held while in a free-standing position. In our investigation the perturbation, a bending moment, was applied directly to the torso at the level of the tenth thoracic vertebra and the subjects were constrained so that motion was limited to the lumbar spine. By significantly reducing the available degrees of freedom to attenuate the forces applied during a rapidly applied load, the variability of response strategies was reduced, potentially accounting for the difference in trunk muscle responses and trunk displacement between the current and previous studies investigating sudden loading.

However, even in a constrained paradigm, it appears that preparation strategies of pre-activating trunk muscles were used to minimize the disequilibrium caused by the rapidly applied load. Subjects increased pre-load activity of the erector spinae and the external oblique bilaterally (Fig. 7), which suggests that a strategy of trunk muscle contraction was utilized to stiffen the spine in preparation for the rapidly applied load. This is supported by our data which shows that when the loading was expected, the pre-load activity of the erectore spinae and external obliques increased, and trunk displacements were reduced. Lavender et al. [9] reported that three of four subjects utilized a strategy of co-acti-

Table 3
Multivariate analysis (MANOVA) and univariate analyses of the time from the onset of the applied load to peak NEMG (peak latency)

Effect	MANOVA	ERSL	ERSR	LGTL	LGTR	RABL	RABR	EXOL	EXOR
Gender	ns	nt	nt	nt	nt	nt	nt	nt	nt
Sym	$F = 9.6$ df = 8,184 $p < 0.001$	$F = 12.0$ df = 1,16 $p < 0.003$	$F = 15.8$ df = 1,16 $p < 0.001$	ns	$F = 2150$ df = 1,16 $p < 0.001$	ns	ns	ns	$F = 8.0$ df = 1,18 $p < 0.01$
Exp	$F = 8.9$ df = 8,184 $p < 0.001$	$F = 44.0$ df = 1,16 $p < 0.001$	$F = 30.5$ df = 1,16 $p < 0.001$	$F = 19.4$ df = 1,16 $p < 0.004$	$F = 21.7$ df = 1,16 $p < 0.001$	ns	ns	ns	ns
Sym*Exp	ns	nt	nt	nt	nt	nt	nt	nt	nt
Trial	ns	nt	nt	nt	nt	nt	nt	nt	nt

ns = Not significant to the 0.05 level; nt = not tested; Sym = symmetry; Exp = expectancy.

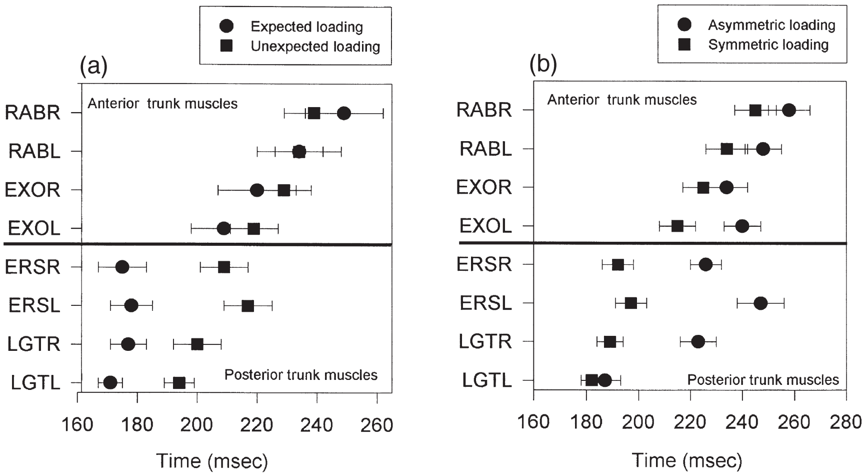

Fig. 8. The time from onset of the applied load to peak NEMG for the eight trunk muscles: (a) expected and unexpected loading; (b) symmetric and asymmetric loading.

Table 4
Multivariate analyses (MANOVA) and univariate analyses for trunk motion

Effect	MANOVA	Position	Velocity	Acceleration
Lateral bending				
Gender	ns	nt	nt	nt
Sym	$F = 100.0$ df = 5,209 $p < 0.0001$	$F = 79.0$ df = 1,18 $p < 0.0001$	$F = 4.36$ df = 1,18 $p < 0.05$	$F = 38.2$ df = 1,18 $p < 0.0001$
Exp	$F = 3.65$ df = 5,209 $p < 0.0033$	$F = 5.40$ df = 1,18 $p < 0.032$	$F = 9.30$ df = 1,18 $p < 0.0067$	$F = 4.8$ df = 1,18 $p < 0.040$
Sym*Exp	$F = 2.70$ df = 5,209 $p < 0.0217$	$F = 5.83$ df = 1,18 $p < 0.027$	ns	ns
Forward bending				
Gender	ns	nt	nt	nt
Sym	$F = 11.18$ df = 5,209 $p < 0.0001$	$F = 9.75$ df = 1,18 $p < 0.0059$	$F = 10.89$ df = 1,18 $p < 0.004$	ns
Exp	$F = 15.50$ df = 5,209 $p < 0.0001$	$F = 32.41$ df = 1,18 $p < 0.0001$	$F = 21.40$ df = 1,18 $p < 0.0002$	$F = 13.3$ df = 1,18 $p < 0.0018$
Sym*Exp	ns	nt	nt	nt
Twisting				
Gender	ns	nt	nt	nt
Sym	$F = 167.00$ df = 5,209 $p < 0.0001$	$F = 7.09$ df = 1,18 $p < 0.0158$	$F = 125.00$ df = 1,18 $p < 0.0001$	$F = 81.23$ df = 1,18 $p < 0.0001$
Exp	$F = 2.21$ df = 5,209 $p < 0.052$	$F = 7.08$ df = 1,18 $p < 0.010$	$F = 7.23$ df = 1,18 $p < 0.015$	$F = 7.74$ df = 1,18 $p < 0.01$
Sym*Exp	ns	ns	ns	ns

ns = Not significant to the 0.05 level; nt = not tested; Sym = symmetry; Exp = expectancy.
Note: there was no significant trial effect for any of the kinematic variables.

vation of the anterior and posterior trunk muscles to reduce the magnitude of postural disturbance. Cresswell et al. [12] also reported that the pre-load muscle activity was increased in both the anterior and posterior trunk muscles during expected loading, although with abdominal activity preceding erector spinae activity. Based on their findings, Cresswell et al. suggest that their subjects utilized a strategy of increasing IAP to stiffen the spine in preparation for a suddenly applied load [12].

The time from onset of the applied load to the peak

Table 5
Trunk kinematics for the experimental condition of expectancy

Motion	Expected loading Mean ± SEM	Unexpected loading Mean ± SEM
Lateral bending		
Position (°)	3.89 ± 0.27	4.74 ± 0.38
Velocity (° s^{-1})	16.0 ± 1.00	18.7 ± 1.08
Acceleration (° s^{-2})	157 ± 6.7	178.0 ± 8.21
Forward bending		
Position (°)	11.75 ± 0.47	16.0 ± 0.62
Velocity (° s^{-1})	63.24 ± 2.5	81.68 ± 2.68
Acceleration (° s^{-2})	545.7 ± 20.16	649.7 ± 21.2
Twisting		
Position (°)	5.3 ± 0.44	6.0 ± 0.50
Velocity (° s^{-1})	31.0 ± 2.9	36.8 ± 0.34
Acceleration (° s^{-2})	290.5 ± 23.5	331.8 + ± 26.4

NEMG (peak latency) provides valuable information on the effect of expectancy and symmetry during on the muscle contractions. Cresswell et al. [12] reported that the peak response of the anterior trunk muscles occurred prior to that of the posterior trunk muscles during expected and unexpected loading, whereas Lavender et al. [11] found no effect of symmetry on the time of peak muscle response. The results from the present investigation suggest that when the applied load was expected, there was a distinct difference between the peak latencies of the posterior and anterior trunk muscles; the peak latencies of the posterior trunk muscles always preceded those of the anterior trunk muscles. The difference in the latency periods in the unexpected loading conditions was so small that the peak response of the trunk extensors and flexors appeared to occur simultaneously (Fig. 8(a)). In asymmetric loading the posterior muscles, with the exception of the left longissimus thoracis, displayed longer peak latencies that were very similar to those found in the anterior trunk muscles (Fig. 8(b)). This suggests a qualitatively different co-activation patterns in response to symmetric and asymmetric trunk perturbations. In response to symmetric sudden loads a biphasic pattern appears in which the trunk's displacement is slowed and reversed during the initial burst of posterior muscle activity. This is then followed by the peak response of the anterior muscles, perhaps as a means to prevent overshoot of the upright posture. In the asymmetric case, however, the co-activation response is more of a simultaneous response. This may be due to the complex moment placed on the spine during loading which had forward bending, lateral bending and twisting components. Thus, every muscle group sampled could potentially contribute to trunk stabilization following the loading event. These data suggest that the muscles' response to expected conditions, whether or not they are asymmetric, is more coordinated. Unexpected loading results in a greater co-activation response which potentially increases the mechanical loads placed on the spine.

The effect of asymmetric loading on peak muscle response in this experimental paradigm is also in contrast to previous reports [13]. Lavender et al. [13] reported that the latissimus dorsi and erector spinae contralateral to the asymmetrically applied load showed increased peak EMG responses during a rapidly applied load. Our investigation revealed that when the applied load was delivered asymmetric to the mid-sagittal plane, all of the anterior trunk muscles had consistently increased peak activation (Fig. 5(b)), while the posterior trunk muscles had decreased peak activation (Fig. 5(a)). These results suggest that the method used to deliver an asymmetric load in this investigation must have created a much larger twisting moment and a reduced flexion moment. The anterior trunk muscles can act to directly counter an applied twisting moment but not an applied flexion moment.

On the basis of the findings of McGill et al. [14] that female subjects had smaller passive stiffness of the torso than male subjects, we anticipated more muscle activity in female subjects prior to load onset. This would increase the stiffness of the torso, and potentialy control the magnitude of the trunk displacement. However, our analysis revealed no gender effect with regards to muscle preparation or response to the sudden perturbation. The absense of a gender effect suggests that the passive stiffness of the torso plays a much smaller role in trunk stability relative to the contribution of active trunk muscle response during posturally destabilizing perturbations. This means that previous work on sudden loading, which has been largely on male subjects, may be generalizable to the female segment of the population.

5. Conclusion

This study investigated the effects of sudden loads applied directly to the torso with motion limited to the lumbar spine. During unexpected loading, there is a significant increase in peak trunk muscle activity, there is greater displacement of the trunk, and the timing of the peak response of the anterior and posterior trunk muscles is more synchronized, which might cause an increase in the compressive load on the spine. In contrast, during expected loading, a small amount of muscle activity prior to the onset of the load reduces the peak muscle response, decreases the magnitude of trunk displacement, and results in synchronization of peak muscle forces.

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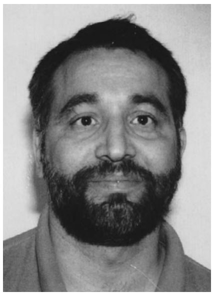

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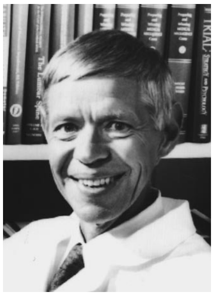

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