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The Effects of Preview and Task Symmetry on Trunk Muscle Response to Sudden Loading

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The effect of warning time (preview) and task symmetry on the trunk muscular response to sudden loading conditions was investigated. Eleven subjects were asked to catch falling weights with four levels of preview (0, 100, 200, and 400 ms) in sagittally symmetric posture and asymmetric posture. For each of the eight muscles sampled with surface electrodes, the integrated electromyographic (EMG) signal was interpreted in terms of its peak value, mean value, onset rate, and lead/lag time with reference to the weight drop. Results show linear relationships between preview times and peak EMG, preview times and mean EMG, and preview times and lead times. The results show significant change when going from symmetric to asymmetric conditions across most dependent measures. Analysis of peak changes in compression were performed across all conditions but yielded unexpected results.

INTRODUCTION

Epidemiological studies have shown the prevalence of back injury in Western society. Investigations into the circumstances in which these injuries occur have suggested a link between sudden unexpected movements or sudden unexpected loadings and low back pain (Magora, 1973; Manning, Mitchell, and Blanchfield, 1984). The body's response to external loading is composed of the necessary internal forces, generated via the muscles, to compensate for the external loading and to stabilize the body. The back muscles have a very short moment arm relative to the moment arm of the external load. Thus the internal force generated by the back muscles must be quite large to overcome their mechanical disadvantage when stabilizing the trunk.

Furthermore, it is believed that these large muscle forces are responsible for most of the compressive and shear loadings placed on the spine and, hence, responsible for the resulting back injuries when these loadings become extreme. Marras, Rangarajulu, and Lavender (1987) found peak muscle forces in the trunk to be much greater under sudden loading conditions compared with static conditions and even more extreme under conditions of sudden, unexpected loading.

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The influence of expectancy on muscle forces is evident in the patterns and intensity of muscle contractions. Patterson, Koppa, Congleton, and Huchingson (1986) suggested that higher-level control centers in the brain preset the muscle and muscle spindles to the anticipated load. Kroemer and Marras (1981) showed the rate of increase in muscle loading (onset rate) to be linearly related to the magnitude of the anticipated exertion. In addition, Marras et al. (1987) found the electromyographic (EMG) onset rate of muscular activity under sudden, unexpected loading to be greater than EMG onset rate when the load could be fully anticipated.

While testing the influence of expectation in sudden loading conditions, Marras et al. (1987) used two levels of temporal information to control the subject's expectancy as to when the loading would occur. When temporal information was present, the peak muscular forces during sudden loading averaged 35% greater than the forces observed under comparable static loading conditions. In the absence of temporal information, the peak muscular forces averaged over 50% greater than static conditions for all muscles tested. These large increases in muscular forces illustrate the substantial effect of sudden loading and sudden, unexpected loading conditions. In light of these data, the body's ability to prepare for sudden loading needs further exploration. In addition, quantification of the amount of warning necessary to reduce the effects of sudden, unexpected loading remains to be established.

Sudden loading can be expected to occur more often in nonsagittally symmetric postures. Typically, asymmetric work postures are considered more stressful. Kumar (1980) demonstrated increased erector spinae and external oblique activity during asymmetric lifts, thereby suggesting more severe loading of the spine. Similarly, Garg and Badger (1986) showed that the maximum acceptable weights, determined from a psychophysical study, and strength, measured in maximal voluntary contractions, decreased with increasing degrees of asymmetry. These results indicate that the trunk musculature and the spine are under increased stress when the posture is no longer sagittally symmetric. Sudden loading under asymmetric conditions can be anticipated to produce even more extreme loadings on the spine than comparable sagittally symmetric conditions, thus increasing the likelihood of low back injury.

The current study was designed to evaluate the effect of varying amounts of preview time before the onset of a sudden loading. In addition, this study sought to extend the results of the Marras et al. (1987) study through the investigation of the muscular response to asymmetric sudden loading. Specifically, the objectives of this study were to quantify muscular loading as a function of warning time (preview) before a sudden loading, and to quantify the effects of sudden asymmetric loading. This quantification was in terms of (1) the peak normalized EMG signal, (2) the mean normalized EMG signal, (3) the onset rate of EMG activity, and (4) the lead and lag times of muscle response to the loading.

METHODS

Subjects

Eleven male subjects, 20 to 32 years of age, with no prior incidence of back pain or injury participated voluntarily in this experiment. Mean subject height was 178.5 cm (range 172.3–189.6 cm) and mean mass was 78.1 kg (range 67.3–95.5 kg). Subjects were told that they would be catching various unknown weights in a box held in two positions (directly in front and at a 45-deg angle to their right side) and that the length of time they would be able to view the weight before it contacted the box would vary. They were not told the experimental hypotheses until the experiment was completed. The use of subjects was approved by the Human Subjects Review Committee of the university. All subjects signed consent forms approved by that committee.

Experimental Design

This test was conducted as a randomized block design, with subjects serving as blocks. The two sets of fixed treatments were preview time (with four levels: 0, 100, 200, and 400 ms) and arm position (with two levels: symmetric and 45 deg to the right side of the body). In order to control for learning effects, subjects were exposed to three static weight levels of 3, 6, and 9 kg-force. With respect to the analysis, however, only the 6 kg-force level was of specific interest. Upon impact with the box, the momentum of this weight was approximately 23.5 Ns. The order of weight levels crossed with preview levels (12 combinations total) was counterbalanced separately for each set of symmetric and asymmetric catches. Because asymmetric loading was considered potentially more hazardous than the corresponding symmetric loadings, the symmetric trials were performed first in order to "warm up" the subjects. This method gave subjects a chance to become familiar with the magnitude of the loadings, thereby reducing the risk of injury.

Dependent variables consisted of electromyographic (EMG) activity of four muscle pairs (left and right): erector spinae, rectus abdominus, latissimus dorsi, and a generalized oblique muscle. These are the larger muscles of the trunk and as such play a major role in trunk loading. They have been shown by Marras, King, and Joynt (1984) to be active during carrying and lifting tasks. Schultz and Andersson's (1981) transverse plane model examined the internal loading on the spine caused by activation of these muscles. The collected EMG signals were rectified, integrated (RMS), and normalized for each subject and each muscle in order to facilitate their interpretation. In addition to the catching tasks, subjects were tested for maximum static exertion levels and resting levels (while holding the box and weight). These maximum and resting level EMGs were used in the normalizing process.

Apparatus

The pipework frame and box used to support and catch the weights in this experiment have been described and pictured in Marras et al. (1987). One modification to the frame was a pull-down window shade installed across the top as a mechanism to control preview, as shown in Figure 1. The exact position of the shade for each preview condition was adjusted for each subject to ensure that preview times were as prescribed. The weights were always concealed in a bag so that the subject never had knowledge of which weight was being dropped. The electrodes, data acquisition system, and computer were the same as described in Marras et al. (1987).

Procedure

Subjects were asked to warm up and stretch out their back muscles. Anthropometric measurements including height, weight, and abdominal depth and breadth were taken. Eight pairs of surface electrodes (plus a ground) were applied to clean, abraded skin as described by Basmajian (1978). Electrodes were attached at the L3 level for the erector spinae and at standard muscle sites, as specified by Marras (1984), for the other three muscle pairs. Impedance between pairs of electrodes was checked for consistency. Electrode location was verified via functional muscle testing.

Maximum EMG levels for each of the eight muscles were collected through three-second maximum static exertions performed with

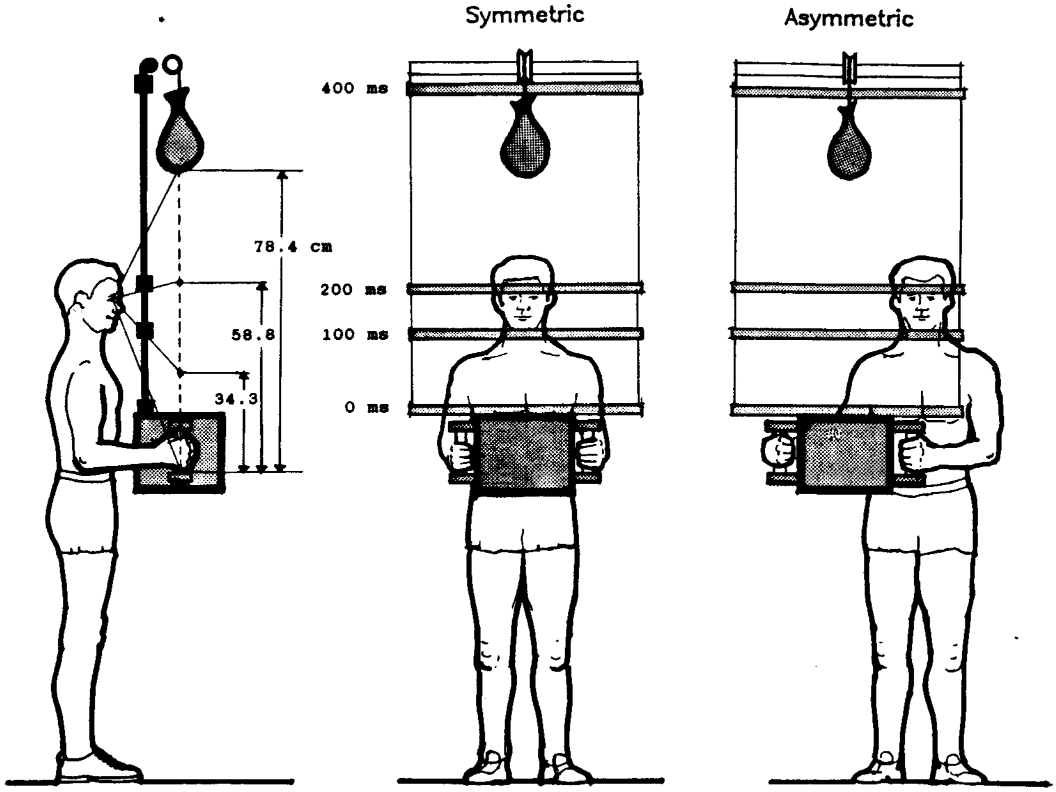

Figure 1. *Front and side views of experimental setup showing how symmetry and preview conditions were controlled.*

the subject strapped into various lab dynamometer apparatus while maintaining posture similar to that required in the experiment. Static EMG resting levels were monitored with the subject in the experimental position holding both the box and the weight in both the symmetric and asymmetric positions.

Drop tests were performed with each subject experiencing all levels of preview time, symmetry, and weight. Subjects were instructed to hold the box as the experimenters positioned it and to wait for the weight to reach the box. Consecutive trials were separated by two-minute rest periods. The counterbalanced ordering of treatment combinations was randomly assigned to subjects, with each subject following a different treatment order.

Data Treatment

Once collected, raw data were statistically analyzed. For all portions of the analyses, the problem of missing data was handled by entering cell means where missing values occurred. Further analysis was conducted on the mainframe computers of Ohio State University using the statistical package SAS.

Peak and mean EMG. The start, peak, and end times of the EMGs, as well as peak and average EMG levels, were calculated for each muscle of each subject under each drop condition (see Figure 2). EMG levels were normalized according to the following formula:

$$\% \text{ increase over static} = \frac{\text{sudden EMG}(i, (p,s)) - \text{static EMG}(i,s)}{\text{maximum EMG}(i) - \text{static EMG}(i,s)}$$

where i = muscle of interest; p = preview condition: 0, 100, 200, 400 ms; s = symmetry condition: symmetric (sym) or asymmetric (asym); sudden EMG $(i, (p,s))$ = EMG recording of muscle i in response to drop of weight in condition (p,s); static EMG (i,s) = EMG activity of muscle i required to hold box with 6 kg-force weight in symmetric condition s; maximum EMG (i) = maximum EMG activity level recorded for muscle i (this could have been observed during the maximum static exertion or during one of the drop tests).

Onset slope. The onset slope for each muscle refers to the rate of increase in muscle force over time. Higher onset slopes are considered to place more impulse strain on the muscular skeletal system, thus increasing the risk of injury. The onset slope for each muscle in each drop condition was calculated according to the following formula:

$$\text{onset slope} = \frac{\text{change in EMG } (\mu V)}{\text{change in time } (s)}$$

As shown in Figure 2, the onset slope is the slope of the line from the point of initial EMG above resting level to the point of the first peak in integrated EMG signal.

Lead/lag time. Lead/lag time was defined as the amount of time between the start of elevated EMG activity and the point at which the weight hit the box, as shown in Figure 2. A positive time (lead) indicated that the muscle responded before the weight hit the box; a negative time (lag) indicated that the muscle response occurred after the weight hit the box. The amount of lead is thought to reflect anticipation of the loading event and results in preloading of the muscles necessary to absorb the impact of the sudden external load.

RESULTS

All data were initially analyzed using a multivariate analysis of variance procedure (MANOVA). Where results from MANOVAs

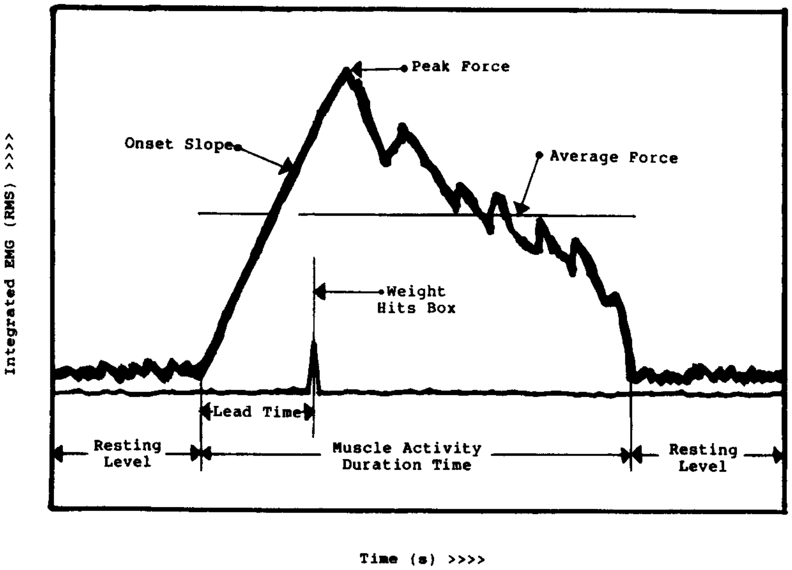

Figure 2. *Trunk muscle activity components used in the analysis.*

were significant, follow-up analyses with individual ANOVAS for each muscle were performed. Table 1 shows the results of the MANOVAs and ANOVAs.

Analyses of peaks, means, and onset slopes found the preview and symmetry effects to be statistically significant; analysis of lag times indicated significant effects for preview. Interactions between preview and symmetry were statistically significant for the peak EMG and onset rate. The results will be discussed more specifically according to each analytical method described.

Peak EMG

The MANOVA revealed that the preview, symmetry, and preview-symmetry interactions were all significant for peak EMG. Figure 3 shows average peak EMG activity for all muscles for both symmetry conditions. As indicated in Table 2, the two left posterior trunk muscles—the left latissimus dorsi and left erector spinae—produced 37.15% more muscle force in the asymmetric conditions than in the symmetric conditions. The right posterior trunk muscles produced 55.15% less muscle force, and anterior trunk muscles (the abdominal and oblique muscles) produced 34.73% less muscle force in asymmetric conditions than in symmetric conditions.

Figure 4 shows peak EMG as a function of preview. Peak EMG forces ranged from 110% to 150% of static forces. In almost all of the muscles, the 0-ms (unexpected) condition produced the highest peak EMG response, followed by the 100-, 200-, and 400-ms preview conditions, respectively. As shown in Table 3, peak EMG forces, averaged over all muscles, increased 99.2% in unexpected conditions (0 ms) over 400-ms preview conditions. The percentage increases in peak forces for the 100- and 200-ms conditions over the 400-ms condition are 83.8% and 44.9%, respectively.

TABLE 1

F Statistics from MANOVA and ANOVA

		ANOVA							
Effect	*MANOVA*	*LATR*	*LATL*	*ERSR*	*ERSL*	*RCAR*	*RCAL*	*OBQR*	*OBQL*
PEAK EMG									
P	4.4***	3.6*	6.3**	18.7***	10.3***	17.3***	7.3***	11.1***	26.1***
S	23.6*	20.3**	19.1**	135.0***	2.4	17.4**	14.1**	7.9*	0.6
P*S	1.8*	0.9	0.2	1.7	0.9	3.7*	3.2*	0.9	2.6
MEAN EMG									
P	3.2***	4.3*	4.2*	11.9***	8.0***	18.8***	8.2***	10.8***	24.2***
S	36.9**	17.5**	2.2	44.8***	0.9	16.9**	8.7*	5.1*	1.7
P*S	1.1	1.3	0.1	1.2	0.5	2.4	2.7	0.3	2.5
ONSET SLOPE									
P	3.2***	8.9***	22.7**	13.9***	8.1***	7.9***	4.6**	11.1***	24.1***
S	16.7*	26.5***	16.8**	40.1***	5.0*	2.5	8.5*	10.0*	0.1
P*S	1.7*	0.3	1.2	2.1	1.9	2.9*	1.8	0.1	1.0
LEAD/LAG TIME									
P	2.9***	14.2***	16.5***	21.3***	16.9***	0.5	6.8**	7.4***	8.9***
S	5.1	1.4	9.3*	3.7	3.5	2.6	1.0	0.4	2.7
P*S	1.6	0.3	1.3	0.8	0.1	1.3	5.1**	0.1	0.8

* Significant at .05 level
** Significant at .01 level
*** Significant at .001 level
Key: P = preview effect; S = symmetry effect; P*S = preview*symmetry interaction.
Note: F statistics for MANOVA PREVIEW have 24,67.3 d.f.; for MANOVA SYMMETRY, 8,3 d.f.; and for MANOVA PREV*SYM, 24,67.3 d.f. F statistics for ANOVA PREVIEW have 3,30 d.f.; for ANOVA SYMMETRY, 1,10 d.f.; and for ANOVA PREV*SYM, 3,30 d.f.

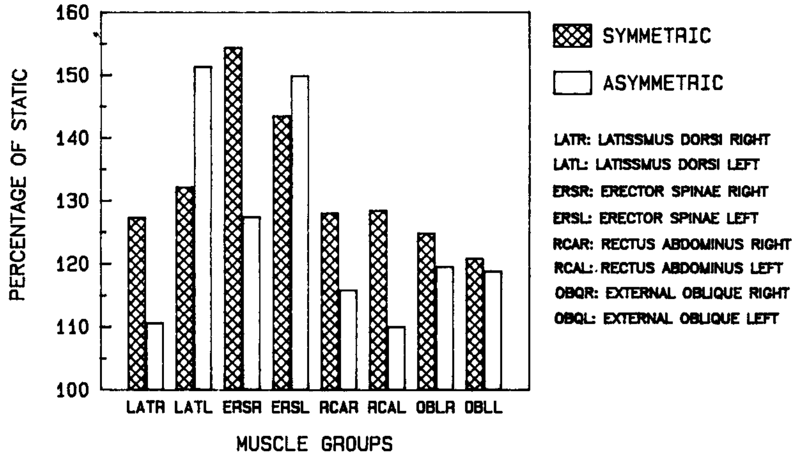

Figure 3. *Peak (maximum) muscle activity during symmetric and asymmetric loading.*

The peak EMG forces of the four posterior trunk muscles responded linearly in relation to preview conditions. The *R*-squares of the least-squares regression lines for the posterior trunk muscles' peak EMG forces versus preview conditions ranged from 0.90 to 0.98.

Although all muscles had significant preview effects for peak EMG (see Table 1), not all individual preview levels were significantly different from one another. Table 4 illustrates the statistically significant multiple comparisons among the preview levels using Duncan's test. When the peak activity of muscles was examined, the 0- and 100-ms preview levels were not significantly different from each other, but the 400 ms was significantly different from the other levels in most muscles.

TABLE 2

Mean Percentage Change of Normalized EMG in Asymmetric Conditions Relative to Symmetric Conditions

Analysis	*Right Posterior Muscles*	*Left Posterior Muscles*	*Anterior Muscles*
Peaks	−55.15	37.15	−34.73
Means	−61.05	21.20	−32.48

Accounting for the significant MANOVA interaction in Table 1 are the left and right rectus abdominus muscles. Figures 5 and 6 illustrate this interaction. The abdominals' peak EMG activity appears to vary widely in the symmetric conditions—from 10 to 50% increases in peak force over static—but in the asymmetric conditions the abdominals appear to decrease substantially, settling in a range of 10–25% increased force over static.

Mean EMG

Mean EMG relative forces had significant preview and symmetry effects but, unlike peak EMG forces, no interaction (see Table 1). Figures 7 and 8 show that mean EMG relative forces followed the same general trends as peak EMG forces.

As indicated in Table 2, mean EMG response followed the same trend as peak EMG response in regard to differences between symmetry conditions. The mean EMG force of the left posterior trunk muscles increased 21.2% in the asymmetric as opposed to the symmetric conditions, whereas the right pos-

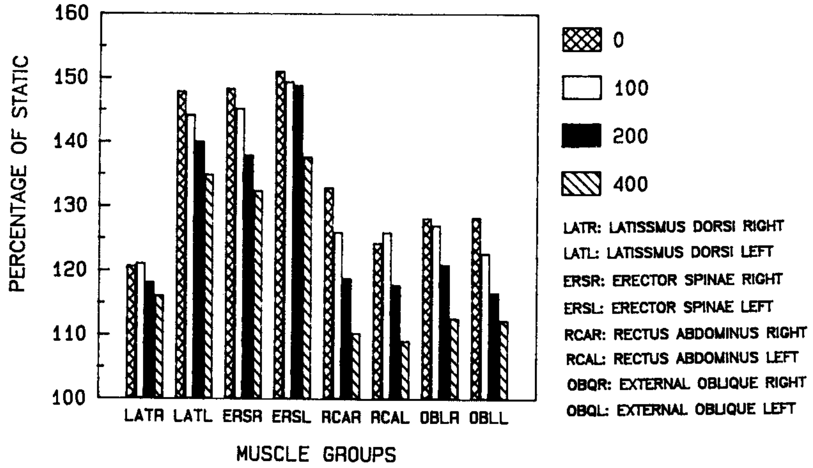

Figure 4. *Peak (maximum) muscle activity as a function of varying preview time.*

terior trunk muscles decreased 61.05%. The anterior muscles decreased 32.48% in mean EMG activity in the asymmetric conditions.

Similar to peak EMGs, mean EMG activity as a function of preview was highest in the unexpected conditions (0 ms) and decreased in the 100-, 200-, and 400-ms conditions in descending order (see Figure 8). As illustrated in Table 4, the 0- and 100-ms conditions were clustered together, whereas the 400-ms levels were generally significantly different from the other levels. Table 3 shows the percentage increase in mean EMG relative forces of the limited preview conditions compared with the full preview condition (400 ms). The percentage increases closely parallel those for peak EMG forces.

TABLE 3

Mean Percentage Change of Normalized EMG in Limited Preview Condition Relative to the Full Preview Condition (400 ms)

Analysis	*0 ms*	*100 ms*	*200 ms*
Peaks	99.2	83.6	44.9
Means	92.8	82.2	39.1

Onset Slopes

Similar to peak EMG responses, the onset slopes had significant preview, symmetry, and interaction effects, as shown in Table 1. Figures 9 and 10 show that the onset slopes were highest for posterior trunk muscles, indicating that these muscles reached their peak forces quickly or were "jerked." The anterior trunk muscles as a group had the lowest onset slopes, indicating that these muscles built up to peak force levels more gradually.

As shown in Figure 9, all of the muscles had greater onset slopes in the symmetric conditions. There was an average increase of 49.6% in onset slope in symmetric conditions over asymmetric conditions.

As illustrated in Figure 10, onset slopes as a function of preview followed the same trend as peak and mean EMG forces. Almost all of the muscles reached their peak levels the fastest in the unexpected conditions and reduced their onset rates in the 100-, 200-, and 400-ms conditions in descending order. Table 4 shows that the 0- and 100-ms preview conditions were not significantly different for most muscles, whereas the 400-ms condition

TABLE 4

Duncan's Test on Dependent Variables as a Function of Preview

<table>
<tr><th rowspan="2"><i>Analytical Method</i></th><th rowspan="2"><i>Muscle</i></th><th colspan="4"><i>Preview (ms)</i></th></tr>
<tr><th><i>0</i></th><th><i>100</i></th><th><i>200</i></th><th><i>400</i></th></tr>
<tr><td rowspan="10">Peak EMG</td><td rowspan="2">LATR</td><td colspan="3">—</td><td></td></tr>
<tr><td></td><td></td><td colspan="2">—</td></tr>
<tr><td rowspan="2">LATL</td><td colspan="2">—</td><td colspan="2">—</td></tr>
<tr><td></td><td colspan="2">—</td><td></td></tr>
<tr><td>ERSR</td><td colspan="2">—</td><td>—</td><td>—</td></tr>
<tr><td>ERSL</td><td colspan="3">—</td><td>—</td></tr>
<tr><td>RCAR</td><td>—</td><td>—</td><td>—</td><td>—</td></tr>
<tr><td>RCAL</td><td colspan="3">—</td><td>—</td></tr>
<tr><td>OBQR</td><td colspan="3">—</td><td>—</td></tr>
<tr><td>OBQL</td><td>—</td><td>—</td><td>—</td><td>—</td></tr>
<tr><td rowspan="10">Mean EMG</td><td rowspan="2">LATR</td><td colspan="2">—</td><td colspan="2">—</td></tr>
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<tr><td rowspan="2">LATL</td><td colspan="2">—</td><td></td><td></td></tr>
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<tr><td>ERSR</td><td colspan="2">—</td><td>—</td><td>—</td></tr>
<tr><td>ERSL</td><td colspan="3">—</td><td>—</td></tr>
<tr><td>RCAR</td><td colspan="2">—</td><td>—</td><td>—</td></tr>
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<tr><td>OBQL</td><td>—</td><td>—</td><td colspan="2">—</td></tr>
<tr><td rowspan="10">Onset Slope</td><td>LATR</td><td colspan="2">—</td><td>—</td><td>—</td></tr>
<tr><td>LATL</td><td>—</td><td>—</td><td>—</td><td>—</td></tr>
<tr><td>ERSR</td><td>—</td><td>—</td><td>—</td><td>—</td></tr>
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<tr><td rowspan="2">RCAR</td><td colspan="2">—</td><td></td><td>—</td></tr>
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<tr><td rowspan="2">OBQR</td><td colspan="2">—</td><td></td><td>—</td></tr>
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<tr><td>OBQL</td><td colspan="2">—</td><td>—</td><td>—</td></tr>
<tr><td rowspan="10">Lead/Lag Time</td><td>LATR</td><td>—</td><td>—</td><td colspan="2">—</td></tr>
<tr><td>LATL</td><td>—</td><td>—</td><td colspan="2">—</td></tr>
<tr><td>ERSR</td><td>—</td><td>—</td><td colspan="2">—</td></tr>
<tr><td>ERSL</td><td colspan="2">—</td><td colspan="2">—</td></tr>
<tr><td>RCAR</td><td colspan="4">****</td></tr>
<tr><td rowspan="2">RCAL</td><td colspan="2">—</td><td colspan="2">—</td></tr>
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**** Muscle activity found nonsignificant across preview conditions at the 0.05 level.

was significantly different from the other preview levels for most muscles. Compared with the 0-ms conditions, onset slopes in the 400-ms conditions decreased by an average of 62.1% for all muscles.

Lead/Lag Time

The only significant effect for lead/lag time in the MANOVA in Table 1 was the preview effect. Figure 11 clearly shows that the 400-ms preview conditions elicited the longest lead time among the muscle groups, whereas the 200-, 100-, and 0-ms conditions followed in descending order. With respect to the 400-ms conditions, the lead time decreased 30.9%, 69.2%, and 87.7% for the 200-, 100-, and 0-ms conditions.

The longest lead times were for the latissimus dorsi and erector spinae muscles. In the 400-ms conditions, they preceded the time at which the weight hit the box by 130–210 ms. The right latissimus dorsi and right erector spinae actually had a negative lead time—or lag time—in the unexpected conditions, which means that these muscles

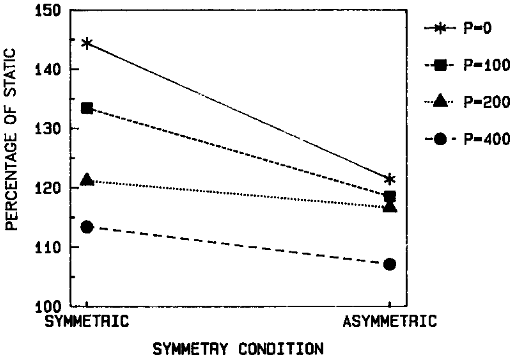

Figure 5. *Preview-symmetry interaction of peak muscle activity of right rectus abdominus.*

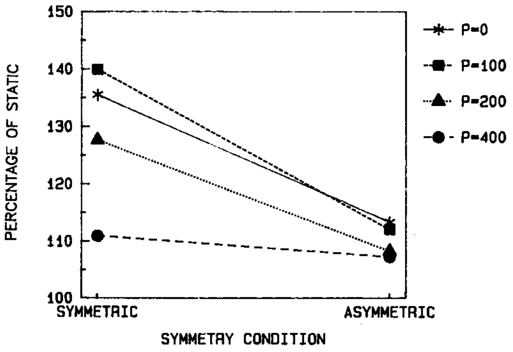

Figure 6. *Preview-symmetry interaction of peak muscle activity of left rectus abdominus.*

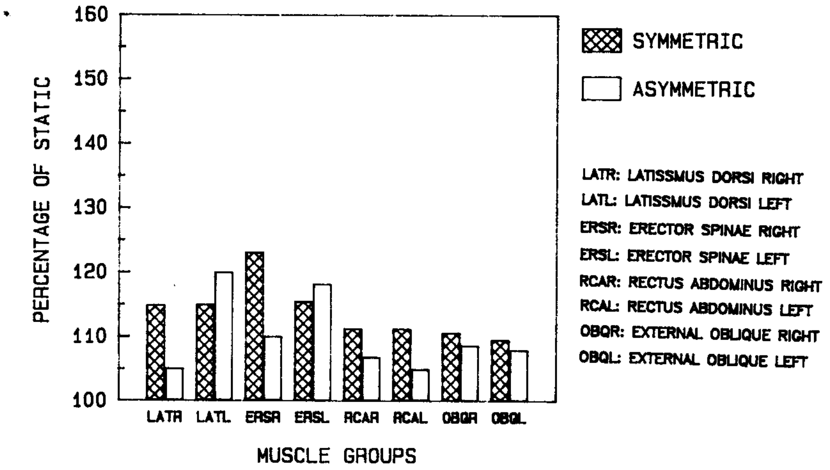

Figure 7. *Mean muscle activity during symmetric and asymmetric loading.*

did not respond until after the weight hit the box.

As shown in Table 4, there were significant differences in lead/lag time between 0- and 100-ms preview conditions in four muscles, but the 200- and 400-ms conditions were not significantly different, except for one muscle.

The lead/lag time of the latissimus dorsi and erector spinae muscles responded linearly to preview time. The R-squared coefficients of the least-squares regression lines ranged from 0.876 for the left erector spinae to 0.992 for the right latissimus dorsi. These high R-squared coefficients show that the time the major trunk muscles are activated before or after a weight hits is linearly related to the amount of preview time.

DISCUSSION

The preceding results indicate the significant roles of preview and symmetry in loading of the spine. In addition, they show that it

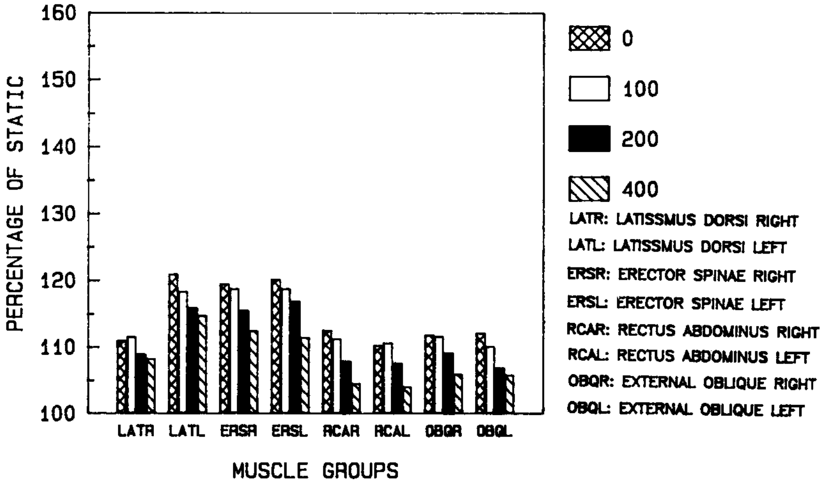

Figure 8. *Mean muscle activity as a function of varying preview time.*

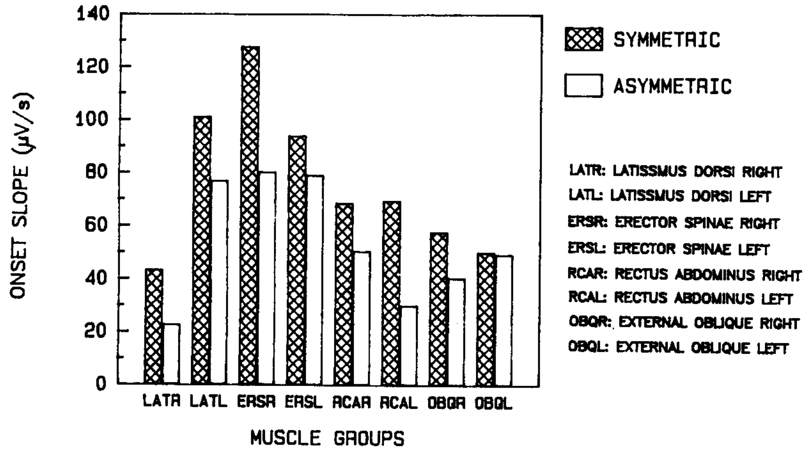

Figure 9. *Onset slopes of muscle force buildup during symmetric and asymmetric loading.*

is imperative to consider the dynamic conditions under which the trunk is loaded. Using the Simulift model developed by Reilly and Marras (1989), it is possible to estimate peak (impulse) compression values in sagittally symmetric conditions based upon EMG response. These estimations yielded peak compression values 2.0 (at 400 ms) to 3.5 (at 0 ms) times the estimated compression for the corresponding static exertion. This increased compression is the result of the substantially increased muscle forces required to maintain trunk stability during these dynamic loading conditions.

Results indicate that the full preview condition (400 ms) placed the least strain on the musculoskeletal system. Yet peak activity, averaged across all muscles sampled during this condition, was 21% greater than that observed in static conditions. Further increases in peak activity were observed with further limitations of preview time. Relative to the 400 ms preview condition, there was an increase in peak EMG activity, again averaged

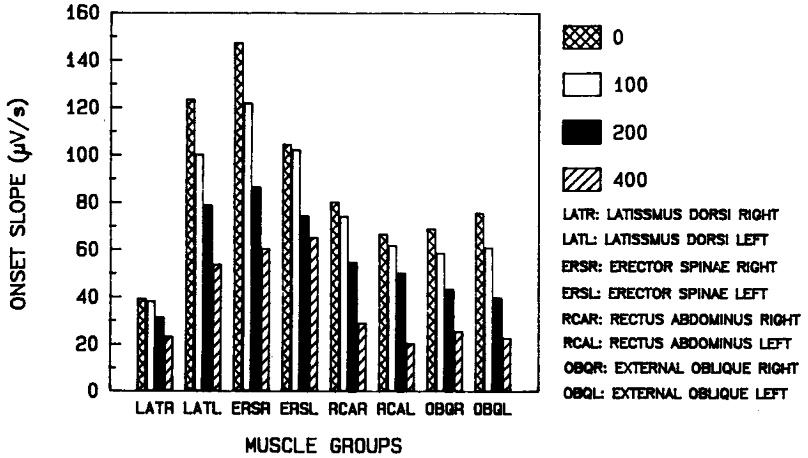

Figure 10. *Onset slopes of muscle force buildup as a function of varying preview time.*

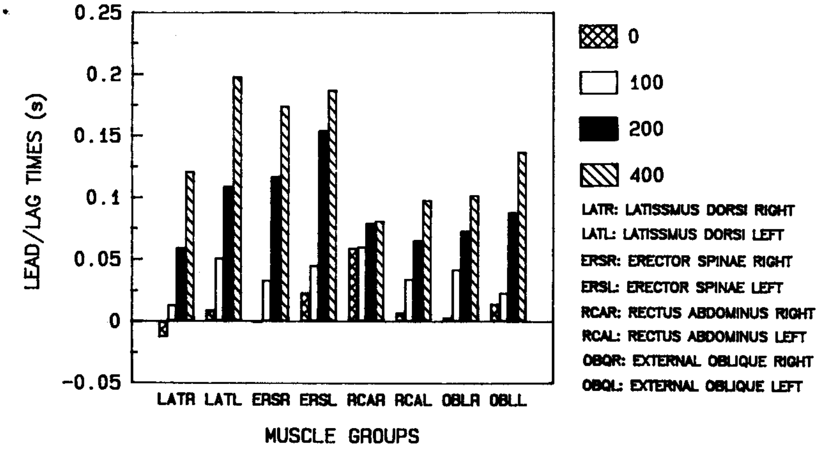

Figure 11. *Lead/lag times as a function of varying preview time. Lead times are positive, indicating that the muscle started to exert force (above resting levels) before the weight hit the box. Lag times are negative, indicating that the muscle started to exert force after the weight hit the box.*

across all muscles sampled during the particular condition: 44% for 200 ms, 83.6% for 100 ms, and 99% for the unexpected condition. This indicates that any increase in the preview of loading should decrease peak muscle forces and thereby reduce the loading on the spine.

The change in peak EMG activity seen under the asymmetric condition indicates that the system is under even greater stress because of the increased shear components that would be generated. Asymmetric loading resulted in a 37% increase in EMG activity of the left posterior muscle group relative to the symmetric condition. At the same time, there was a 55% decrease in peak activity in the right posterior muscle group. It is this imbalance in the trunk loading that leads to high shear forces and possibly back injuries, a trend supported by epidemiological evidence (Andersson, 1981).

In addition to the foregoing findings, other results required further investigation. These included the preview/symmetry interaction seen in the abdominal muscles and the lack of a significant difference in muscle force between the 0 and 100 ms preview conditions. In order to understand the statistical interpretation of these phenomena, we hypothesized as to the nature of the physical and psychological processes that occur within the body during sudden loading conditions.

The lack of significant differences between the 100-ms and the 0-ms (unexpected condition) levels in peak EMG and mean EMG is consistent with the reaction time literature. Simple reaction times to visual or auditory stimuli with some amount of temporal uncertainty typically range between 130 and 170 ms (Wickens, 1984). In both conditions the preview time is not sufficient to generate the preparatory response that results in lower peak muscle forces that are seen in the longer preview conditions. Thus the percentage increase in compression values, observed with the Simulift model (Reilly and Marras, 1989), are essentially the same for the 100-ms and 0-ms conditions. Lead times and onset slopes indicate differences between these two conditions, suggesting that the stimulus (the falling weight) is perceived earlier in the 100-ms condition but that the amount of time is insufficient for a controlled muscular reaction.

The preview/symmetry interaction in peak

EMG activity for the right and left rectus abdominus muscles is illustrated in Figures 5 and 6. In the symmetric conditions both rectus abdominus muscles appear to have their lowest peak EMG activity for the 400-ms preview conditions and increase in the 200-, 100-, and 0-ms conditions, respectively. Peak muscle activity in the symmetric conditions ranges from approximately 110% to 145% of static levels. However, in the asymmetric conditions the abdominals' peak activity appears to decrease considerably, settling in a range of 108–122% of static levels.

This interaction can be interpreted in terms of the requirements for trunk stabilization through the antagonistic forces these muscles generate. The frequency of physical oscillation of the trunk during symmetric conditions appeared to be dependent on preview time. During the unexpected and limited preview conditions, each subject's trunk displayed more oscillatory behavior than during full preview conditions. Within these oscillations, the abdominals acted in a stabilizing role and pulled the body forward, counteracting the posterior musculature. Thus as shown in Figures 5 and 6, the peak EMG activity of these antagonistic contractions increased as preview time decreased. This indicates that the trunk behaves similarly to an underdamped system during conditions of limited or no preview. As preview time is increased, behavior shifts toward that of a more heavily damped system, wherein little oscillatory behavior is exhibited.

However, in the asymmetric conditions, the rectus abdominus muscles do not play the same antagonistic stabilizing role. Because of the posture of subjects with the box held 45 deg to the right, lines of action of both the left and right abdominal muscles were not directly opposite the left posterior trunk muscles in the oblique direction. Because the line of action of the rectus abdominus muscles was not optimal to counteract agonistic forces on the subject's left side, antagonistic muscle activity was not observed. There are other, smaller muscles along the spine that would likely fill this antagonistic role and provide the damping for the oscillatory behavior, but these muscles were not sampled in this study.

The imbalance of muscle forces between the left and right sides of the torso can also be expected to yield large shear forces on the spine. These forces may themselves be a mechanism of injury resulting in low back pain. Likewise, those small muscles, which are generally not used in maintaining normal posture, are probably very susceptible to overexertion injuries while stabilizing the spine during sudden asymmetric loadings.

Seroussi and Pope (1987) concluded that as a subject moves a load farther from the sagittal plane, the EMG activity of the contralateral erector spinae increases. As indicated in Table 2, the muscular forces of the left posterior trunk muscles (erector spinae and latissimus dorsi) increased as the box was moved out of the sagittal plane, whereas forces from the right posterior trunk muscles and anterior muscles decreased. A biomechanical explanation for this phenomenon shows that trunk stabilization must be accounted for mostly through the left posterior musculature. The load now creates a lateral moment in addition to the forward moment, which results in greater demands on the contralateral musculature. The left posterior trunk muscle force increased, but by a smaller amount than the right posterior muscles decreased. Once again, it is likely that muscles on the contralateral side were active but not sampled.

Decreased antagonistic muscle activity in the asymmetric conditions relative to the symmetric conditions is consistent with the results of Patterson et al. (1986). They showed that different patterns of agonistic/antagonistic muscle activity depend on subjects' previous lifting experience. The subjects in the present study were tested in the sagittally symmetric task first and in the asymmetric task second for safety reasons. Yet the first condition may have provided enough experience to allow the subjects to learn more efficient means of damping the sudden loading, thus lessening the need for antagonistic control in the asymmetric conditions.

Some of the possible benefits that can be reaped by using the results of this study to guide workplace design should be highlighted. The results are applicable not only to manual materials handling but to any type of sudden, unexpected loading. Manning et al. (1984) suggested the role of sudden movements in preceding back injuries during slips and trips. The common denominator here is unexpected movement that causes extreme muscular contractions with very high onset rates. Sudden, unexpected loadings can be encountered in almost any work environment and occupation. Whether the task involves manual materials handling of fluids, use of large hand tools found in the mining or railroad industries, or tasks requiring physical exertions, the worker is likely to experience such unexpected loadings.

The first approach to reducing the extreme muscle contractions that occur in unexpected movements is task or tool redesign. For instance, tools that have slippery or inadequate handles could be redesigned with larger, textured handles so that the tool does not slip out of a worker's hands, causing increased muscle response. Tasks that place a worker's center of gravity close to the point of falling could be redesigned so that the worker's body is stabilized. After task and tool redesign have been implemented, workers should be trained to respond properly to sudden, unexpected loadings. For example, they might slowly absorb the impact of a falling or shifting weight, such as a falling box or shifting fluid, rather than stopping its momentum abruptly. Another example of training is anticipating and preparing for a sudden load. In summary, the three approaches of training and tool and task redesign should be investigated to reduce risk of injury from sudden muscular contractions.

CONCLUSION

This study has shown the effects of sudden loading on trunk stabilization and demonstrated the importance of the dynamic conditions under which loading occurs. The loadings seen here resulted in peak muscle forces that were substantially greater than those seen during static loading conditions. The excessive muscle force resulting from sudden loading can be modulated with preview times of at least 200 ms. When sudden loadings occurred outside the sagittal plàne, an imbalance of muscle forces resulted, with increased muscle forces generated in the contralateral trunk musculature.

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