

# A Comprehensive Evaluation of Trunk Response to Asymmetric Trunk Motion

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**An experiment was performed to determine the reaction of the trunk muscles, using electromyography, and intra-abdominal pressure to components of trunk loading commonly seen in the workplace during manual materials handling. These components included angular trunk velocity, trunk position in three-dimensional space and trunk torque exertion level. The experiment was performed using 44 subjects. Subjects produced constant trunk extension torque about the lumbosacral junction while moving the trunk under constant angular velocity (isokinetic) conditions. Significant reactions to trunk angular velocity, trunk torque level, and unique combinations of trunk position and velocity were seen in all muscles of the trunk. The other components affected the muscles selectively according to function. Intra-abdominal pressure only reacted significantly to trunk angle and some unique trunk angle-asymmetry positions. The biomechanical implications of these findings are discussed. The reactions of the muscles to the various workplace components also were described quantitatively through equations that predict muscle activity levels. [Key words: trunk motion, trunk velocity, trunk asymmetry, electromyography, intra-abdominal pressure, spine loading]**

**T**HE INCIDENCE of low-back disorders (LBD) has continued to plague mankind in recent years. Both epidemiologic<sup>4</sup> and biomechanical<sup>7</sup> studies have indicated that there is a link between the risk of LBD and occupational requirements. Specifically, lifting or manual materials handling (MMH) is associated with greater risk of LBD. The National Institute for Occupational Safety and Health (NIOSH) has studied the relationship between LBD and occupational lifting, and has found that over 60% of LBD claims were associated with overexertion.

The relationship between occupation and overexertion-related LBDs can be appreciated by examining the biomechanical system of the low back. The occupational biomechanics literature assumes that there are external as well as internal stresses (forces) acting on the body during a MMH task. The external forces produce moments about the spine due to the mass of the object lifted and the weights of the body segments and their distances from the spine. The internal forces are those supplied by the muscle forces, pressures, and passive components within the body in order to provide a counter-moment to the external moments. However, the internal forces must act at much shorter distances from the spine compared to the external forces. Thus, the internal forces are at a severe mechanical disadvantage, and must produce much larger forces in order to counterbalance the external moment. These internal forces may become even greater with trunk motion.

A review of workplace lifting conditions indicates that almost all MMH situations involve asymmetric lifts where significant trunk motion is involved. However, most of the lifting guides (ie, *Work Practices Guide for Manual Lifting*<sup>30</sup>) assume that the trunk is in a sagittally symmetric position, and the biomechanical analyses are based on static analyses of the spine. Furthermore, of the biomechanical analyses that have considered trunk motion, few have investigated the effects of concentric and eccentric motions on the spine. Lifting a load involves a concentric action or shortening of the trunk muscles, whereas lowering a load requires an eccentric action or a lengthening of the trunk muscles. Trunk loading may be very different in these two situations, as evidenced by epidemiologic studies.<sup>16</sup>

## Trunk Strength Responses to Workplace Factors

Trunk strength is one of the few measures of external force supporting capability. Several previous studies investigating external trunk strength as a function of asymmetric lifting have shown that trunk strength is greatly affected by asymmetry,<sup>15,25</sup> trunk angular velocity,<sup>20,23</sup> and the concentric vs eccentric nature of the exertion.<sup>33,39</sup> These studies show that there have been several assessments of trunk strength as a function of workplace factors. However, our knowledge of how the internal trunk structures behave (and load the spine) under these conditions is limited.

## Trunk Muscle Activity

One measure of internal force is muscle activity. Many studies<sup>1,2,26,27,29,31,32,35-38</sup> in the literature link the action of the trunk muscles to force generation by the trunk. Most evaluations use electromyography (EMG) to detect the muscle activities. There are a few studies that have attempted to quantify trunk muscle EMG under controlled dynamic trunk motion conditions. Marras, King, and Joynt<sup>20</sup> and Marras et al<sup>22</sup> investigated the activity of the trunk muscles in response to sagittally symmetric, isokinetic trunk extension velocity. They concluded that all trunk muscles were active during trunk motion. This indicates the coactivation of the antagonistic trunk musculature during trunk extension. Later studies<sup>24,34</sup> made it possible to quantify EMG activity under sagittally symmetric, isokinetic motion conditions, and thus describe the muscle sequence loading patterns.

These studies have demonstrated that knowledge of trunk muscle use has evolved over the years to the point that quantitative evaluations of trunk muscle EMG can be useful in predicting spine force during certain lifting situations. However, a major void in the evolution of this information exists. No studies quantify trunk muscle activity during asymmetric concentric and eccentric motions (common lifting motions), or examine the impact on trunk loading.

## Intra-Abdominal Pressure

Intra-abdominal pressure (IAP), another internal force, is thought, by some, to provide load relief to the spine during lifting. Although there is still controversy as to whether IAP is a measure of trunk stress<sup>2,3,8-14,28,31</sup> or not,<sup>36</sup> there are very few studies of IAP under controlled motion conditions. Marras, Joynt, and King<sup>21</sup> studied the reaction of

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Table 1. Summary of Anthropometric Characteristics

Variable	Mean	SD	Low	High
Age (yr)	26.2	5.77	19.0	40.0
Weight (kg)	75.6	14.59	53.2	120.5
Height (cm)	178.7	9.45	153.0	197.3
Trunk length (cm)	58.9	5.46	47.1	68.5
Trunk breadth (cm)	29.0	3.92	21.5	38.5
Trunk depth (cm)	21.3	3.79	15.1	34.7
Trunk circumference (cm)	83.1	10.17	62.5	110.2

IAP to torque production about the spine during isokinetic sagittal plane motions, and concluded that IAP responded primarily to trunk angle, and responded to torque only as a preparatory response. No controlled studies have observed the reaction of IAP to asymmetry or eccentric trunk motion.

### Objectives

This review has shown that our knowledge of how the internal trunk forces, which support and load the spine, behave during realistic manual material handling conditions is rather limited. The major void in the knowledge base consists of understanding how the trunk muscles and IAP behave under asymmetric trunk motion conditions. Therefore, the objectives of this study consisted of: 1) determining the influence of workplace factors (trunk work position, concentric and eccentric motion) upon the response of the internal trunk loading structures (muscles and IAP); 2) evaluating trunk muscle loading associated with motion; and 3) quantitatively predicting trunk muscle response to work factors.

### METHODS

**Approach.** To achieve the objectives of this study it was necessary to preserve the relationship between muscle force and EMG.<sup>5,18</sup> A highly controlled experiment was designed that required the subjects to exert a constant force with the back throughout a 45° range of motion while moving at constant velocities. It was assumed that the point of bend about the spine was located at L5-S1, and that this motion would relate to torques experienced about the spine during lifting.

**Subjects.** The 44 subjects in this study consisted of 34 male and 10 female volunteers. Their ages ranged from 17 to 40 years. None of the subjects had experienced a significant low-back disorder, and all were

considered in good health. Subject occupations covered a wide range, from professionals to those experienced in MMH. The anthropometric characteristics of the subject population are presented in Table 1.

**Design.** The experimental design for this study consisted of 4 independent variables and 11 dependent variables. The independent variables consisted of 1) trunk asymmetry (A), 2) forward trunk angle (T), 3) trunk concentric and eccentric isokinetic velocity (V), and 4) constant trunk torque (F).

Together, trunk asymmetry and trunk angle defined trunk position. Trunk asymmetry was set at three levels consisting of 0°, 15°, and 30° from the sagittally symmetric position. Only deviations where the subject's trunk was rotated clockwise with respect to the pelvis were used as the asymmetric positions. It was assumed that the exact opposite pattern (left-right muscle activation) of the muscles would occur if the trunk were rotated in the opposite direction. Trunk angle was set at three forward bending postures of the trunk, consisting of 5°, 22.5°, and 40° angles from vertical.

The trunk concentric and eccentric angular isokinetic velocity was set at four levels, consisting of 0 (static), 10, 20, and 30 degrees/second. The levels were chosen to fall within MMH back velocity ranges reported by Kim and Marras.<sup>17</sup> Finally, torque about L5-S1 was set at 20 and 40 ft-lbs.

The dependent variables in this experiment consisted of the internal forces that may influence the loading of the spine. Schultz and Andersson<sup>35</sup> have identified these forces by predicting the forces present in an imaginary transverse plane passed through the lumbar level of a person's trunk. This approach has identified 10 trunk muscles and IAP as influencing the loading of the spine along this plane. These 10 trunk muscles consist of latissimus dorsi right (LATR) and left (LATL), the erector spinae right (ERSR) and left (ERSL), the external oblique right (EXOR) and left (EXOL), the internal oblique right (INOR) and left (INOL), and the rectus abdominus right (RCAR) and left (RCAL). Lippold,<sup>17</sup> and Bigland and Lippold<sup>5</sup> have shown that the integrated EMG activities of a muscle operating under isometric or constant velocity conditions are related to the amount of force the muscle is producing. Hence, the integrated EMG activities of these muscles were used as dependent measures in this experiment. They represent the amount of relative muscle force within a particular velocity condition as the trunk is passing through specific positions. Intra-abdominal pressure also served as a dependent measure, and was identified by Schultz and Andersson as an internally generated force in their analysis.

**Apparatus.** The configuration of the equipment used in this experiment is shown in Figure 1. Concentric and eccentric velocity was controlled by a KIN/COM isokinetic dynamometer (Chattecx Corp.,

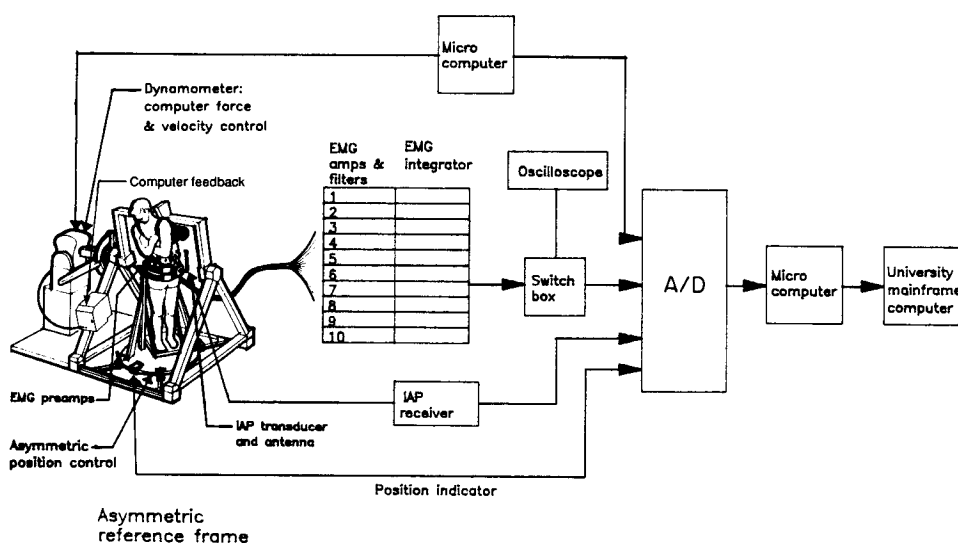


Fig 1. Configuration of experimental apparatus.

Chattanooga, TN). This device was aligned with the L5-S1 junction of the back through an asymmetric reference frame (ARF). This ARF positioned the subject relative to the dynamometer so that both symmetric and asymmetric back exertions could be tested.

Trunk torque about L5-S1 was controlled by the subject. The subjects viewed a computer monitor that graphically displayed their current level of torque production on-line. A target torque was shown on the computer screen, as was a tolerance of  $\pm 10\%$  about the target torque. Therefore, the subjects were able continuously to monitor their torque production and use this feedback to maintain the specified torque level. EMG variation due to this torque tolerance was at most 3%.

Electromyographic activities of the trunk muscles were monitored using small surface electrodes attached to small, lightweight preamplifiers. These preamplifiers were mounted on a belt that was fit around the subject's waist. This configuration minimized the amount of noise in the recorded signal. The preamplifiers were connected to EMG amplifiers, filters, and integrators. A switchbox was connected to the EMG amplifiers that permitted the signal quality of each EMG signal to be monitored. The EMG signal was low-pass filtered at 1,000 Hz and high-pass filtered at 80 Hz. The signal was rectified and averaged with a time constant window of 20 msec. This served as the integrated signal. Intra-abdominal pressure was monitored with a pressure transducer radio pill inserted rectally. An antenna worn around the subject's trunk received the IAP signal.

The dynamometer signals, ARF position, EMG signals, and the IAP signal were all digitized with an analog-to-digital (A/D) converter. This multichannel A/D system interfaced with a 386-based microcomputer to collect, display, and store the data on-line. Further processing was performed on the University mainframe computer system.

**Procedure.** A practice session was permitted to familiarize the subject with the experimental task of controlling torque by interfacing with the computer feedback system. When the subjects became proficient at the task, an appointment was made for the experimental session on a different day. During the experimental session the subjects were hooked up to the EMG system through standard preparation procedures and were given an IAP pill to insert. Once all signal qualities were verified, the experiment was begun. Maximum and minimum activities of each muscle in each trunk position were also collected for EMG normalization purposes. A minimum of 2 minutes of rest was allowed between exertions.<sup>6</sup>

The experimental task required the subjects to control their trunk torque between the tolerance limits of the exertion (defined on the computer screen) under each condition. If the subject failed to maintain exertions within the tolerance limits, the trial was rerun.

**Data Analysis.** Each dependent measure was evaluated as the trunk moved through a "trunk position window." These windows consisted of the forward trunk angle ( $5^\circ$ ,  $22.5^\circ$ , and  $40^\circ$ ) plus or minus  $1.25^\circ$  of motion at the various asymmetric trunk positions. Each value represented the mean activity as the trunk passed through a  $2.5^\circ$  range of motion. All data were compared and normalized with respect to the static maximum and minimum activity of the muscle as the subject assumed the various trunk angle and asymmetry positions. This ensured that comparable portions of the EMG signals were evaluated, and provided a means of controlling the length-tension effects on the integrated EMG signal.

Statistical significance was determined by using both multivariate and univariate analysis techniques. Multivariate analysis of variance (MANOVA) was used to determine if all dependent variables, as a set, responded in a significantly different manner to the various experimental conditions. Univariate analysis of variance (ANOVA) and discriminate function analysis procedures were used to determine how the individual muscles and IAP responded to each experimental factor. Post-hoc analyses were then used to identify the exact nature of these significant differences.

## RESULTS

### Significant Responses

Table 2 represents a summary of those muscles, IAP, and the overall combination of those variables that responded differently to the various workplace factors and interactions of workplace factors. The first column of this table (MANOVA) indicates that all experimental conditions and their interactions, except for the V $\times$ F interaction, had a significant multivariate effect upon the muscles and IAP.

The remaining columns of Table 2 show the univariate response of each variable to the experimental conditions. This analysis indicates that most muscles responded to changes in velocity, torque, the T $\times$ V interaction, and the A $\times$ T interaction. The A $\times$ T interaction indicates that trunk position plays a significant role in the activity of most trunk-supporting structures. When asymmetry was considered alone, most of the muscles on the right side of the body were affected. Generally, all muscles except for the oblique muscles responded to trunk angle changes. It is also interesting to note that of the individual workplace factors, IAP responded in a significantly different manner only to changes in trunk angle and the A $\times$ T interaction. This indicates that it was only sensitive to trunk position changes. The remaining significant reactions were fairly selective in terms of the muscles that were affected.

Table 2. Summary of Significant MANOVA, ANOVA, and Discriminant Function Analyses

	ANOVA											
	MANOVA	IAP	LATR	LATL	ERSR	ERSL	RCAR	RCAL	EXOR	EXOL	INOR	INOL
Asymmetry (A)	.0001		<b>.0001</b>		<b>.0002</b>	<b>.0001</b>	.066		<b>.009</b>			<b>.0001</b>
Velocity (V)	.0001		<b>.0004</b>	<b>.0001</b>	<b>.0001</b>	<b>.0001</b>	<b>.0001</b>	<b>.0001</b>	.0005	<b>.0001</b>	.0001	.0001
Torque (F)	.0001		.0001	<b>.0001</b>	<b>.0001</b>	<b>.0001</b>	<b>.0001</b>	.0001	.0001	.0001	<b>.0001</b>	.0001
Trunk (T)	.0001	.0174	<b>.0001</b>	<b>.0066</b>	<b>.0001</b>	<b>.0001</b>	<b>.0081</b>	<b>.0283</b>				<b>.0001</b>
A $\times$ F	.05		.0283									
V $\times$ F	.1273											
T $\times$ F	.0001				.0001	.0001		.0105	.0534		.0698	.0001
T $\times$ V	.0001		.0001	.0001	.0001	.0001	.0021	.0001	.0001	.0001	.0001	.0001
A $\times$ V	.0002					.0925				.0001		.0014
A $\times$ T	.0001	.0738	.0172	.0575	.0001		.0553	.0225	.0478	.0011	.0002	
T $\times$ V $\times$ F	.0001		.0001	.0001	.0001	.0001				.0004	.0001	.0001
A $\times$ T $\times$ F	.0097		.0989	.0041						.0069	.0673	
A $\times$ T $\times$ V	.0155									.0001		

ANOVA = analysis of variance; ERSR = erector spinae right; ERSL = erector spinae left; EXOL = external oblique left; EXOR = external oblique right; IAP = intra-abdominal pressure; INOL = internal oblique left; INOR = internal oblique right; LATL = latissimus dorsi left; LATR = latissimus dorsi right; MANOVA = multivariate analysis of variance; RCAL = rectus abdominus left; RCAR = rectus abdominus right.

Note: Bold numbers indicate discriminate function significance.

Discriminant function evaluations were also performed to determine how much each response variable contributed to the multivariate significance. The results of this analysis are also summarized in Table 2 for the main workplace factors (no interactions). The bold cells in this Table indicate that the erector spinae and latissimus dorsi muscles were always identified by the discriminant function analysis as contributing significantly to the multivariate significance.

**Trunk Position**

Trunk position is defined as the various combinations of trunk angle and asymmetry. This can best be evaluated by observing the A×T interaction. This interaction was significant for many of the trunk muscles in this experiment. Figure 2A and 2B shows the nature of this interaction for the back muscles. Figure 2 shows that the LATL does not have to generate as much activity as the LATR during the exertions. This indicates that as the trunk becomes more asymmetric, the contralateral latissimus dorsi muscle reduces its activity. This may be due to the muscle length-tension relationship or a sharing of load by another muscle. The erector spinae muscles reacted differently. As the trunk angle increases the asymmetry becomes less of a factor in the muscle response. A similar pattern of response was noted for LATL. ESRL, on the other hand, only responded to position changes in trunk angle.

The significant A\*T interaction effect in the antagonist muscles (RCAR, RCAL, EXOR and EXOL) result from a large increase in activity when the posture assumed was that of 40 degrees of forward bend and 30 degrees of axial rotation. It was this specific position that created large increases in antagonist muscle forces.

Position also influenced the activity level between muscle pairs. As the trunk becomes more asymmetric, the difference between the right and left erector spinae muscles becomes more pronounced. The left

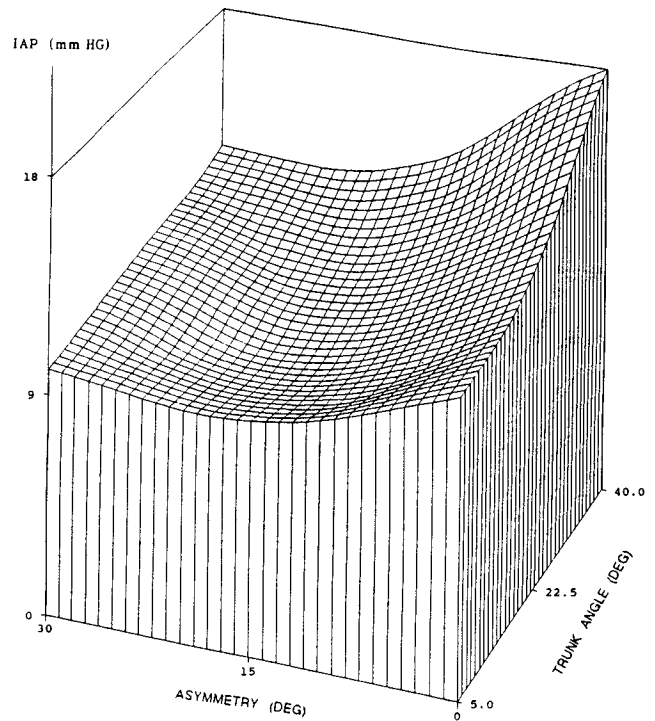


Fig 3. Effects of trunk position on IAP.

muscle increases its activity and the right muscle decreases its activity as the trunk becomes more asymmetric. Since the subjects were turning to the right, this was expected. However, the trends can now be quantified. The difference between these muscle activity levels is only about 1% under sagittally symmetric conditions. However, as the trunk becomes more asymmetric, the difference grows to nearly 10% at 30° of asymmetry. Some of the decrease in ERSR activity is compensated for by increases in the LATR and EXOR muscles. Since these muscles have both a vertical as well as horizontal force vector contribution, it is expected that the shear forces experienced by the spine would increase. Troup and Edwards<sup>40</sup> have shown that disc tolerance is decreased in asymmetric postures. This may help explain why LBD risk increases with asymmetric trunk loading.

Intra-abdominal pressure responded primarily to changes in trunk position. As shown in Figure 3, IAP decreased as a function of decreasing trunk angle. However, it also decreased as a function of trunk asymmetry. This indicates that any load-relieving properties supplied by IAP during MMH would be reduced during asymmetric lifting. It is not known if IAP would respond in a similar fashion at higher exertion levels.

**Trunk Force**

Table 2 indicated that all muscles responded in a significantly different manner to changes in torque levels. All muscles increased their activities when trunk torque increased. Figure 4 shows the relative increase in activity of the trunk muscles. These findings indicate that as trunk torque increases, the agonist and antagonist muscles increase their activities dramatically. It appears that as trunk torque increases, muscles other than the erector spinae muscles increase their activities to a large extent. This increase in coactivation of antagonist muscles is important. Their distances from the spine give them significant mechanical advantage. Thus, one would expect additional spinal loading, as well as a change in the nature of the loading (shear vs. compression),

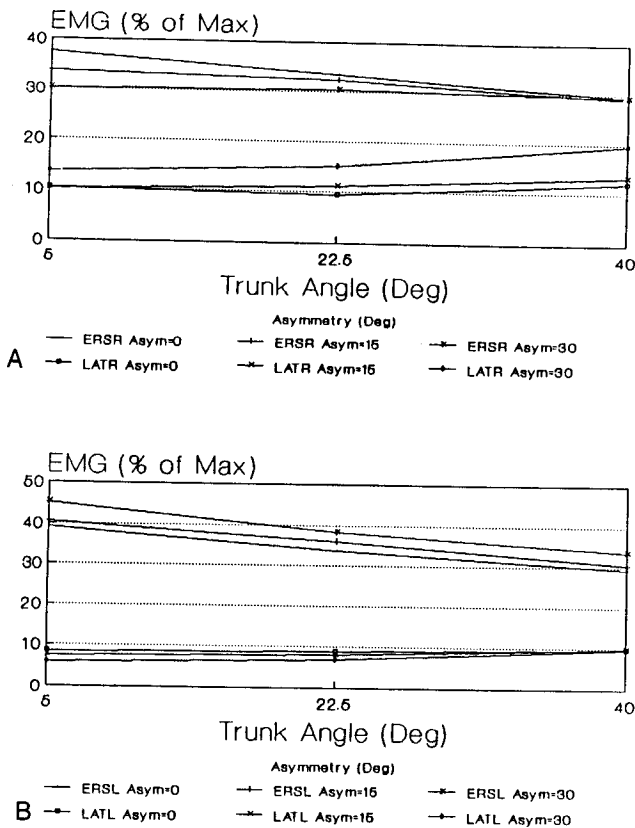


Fig 2. Position effects (trunk angle and asymmetry) on the (A) right and (B) left erector spinae and latissimus dorsi muscles.

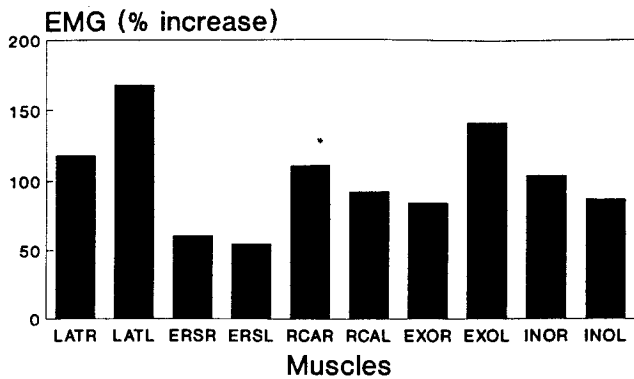
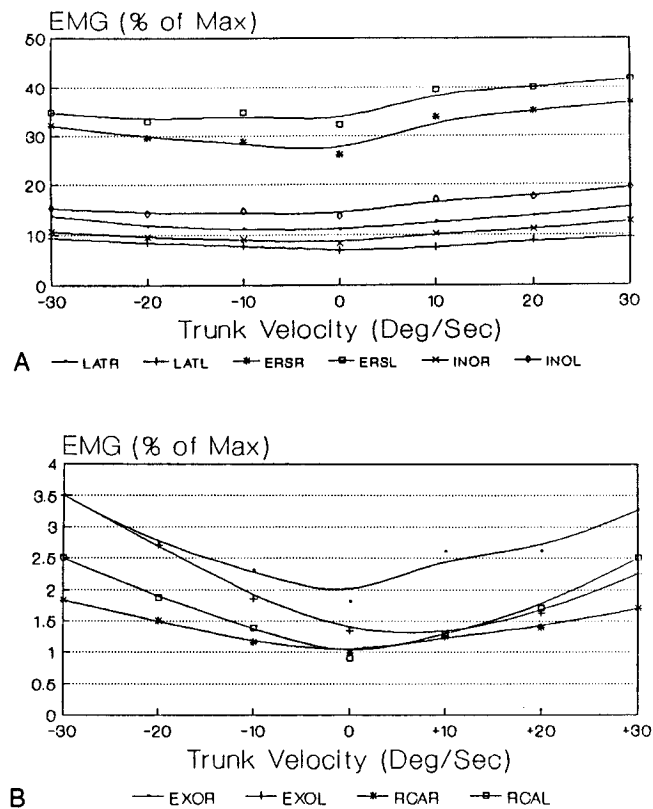


Fig 4. Percent increase in muscle activity necessary for the trunk to increase torque by 20 ft-lbs.

due to the activities of these muscles. Previous studies have ignored the significance of this coactivation.

**Velocity**

The response of the trunk muscles to changes in velocity are shown in Figure 5 (A,B). Several points are apparent from this Figure. First, in every muscle the EMG activity level is lowest under the isometric condition and becomes greater as velocity increases. However, this fact alone does not necessarily mean that the muscles are producing more force as velocity increases. Second, the erector spinae, latissimus dorsi, and internal oblique muscles are the most active under all the velocity conditions. Third, all muscles are active to some degree, even under



--eccentric, +=concentric, 0=isometric

Fig 5. Influence of trunk velocity on (A) extensor muscles and (B) flexor muscles.

isometric conditions. However, trunk motion greatly increases this activity. This coactivation may have fatigue implications as well as the trunk-loading implications. Fourth, the erector spinae and internal oblique muscles are far more active under concentric conditions than under eccentric conditions. This is consistent with other concentric/eccentric comparisons.<sup>33,39</sup> The other muscles (latissimus dorsi, external oblique, and rectus abdominus) respond to the absolute level of velocity regardless of whether it is concentric or eccentric.

**Interactions with Velocity and Force**

The combined effects or interactions represent those unique response trends that deviate from trends due to individual workplace factors. In other words, these interactions identify responses that would occur only when the workplace variables occur in combination. Selected significant interactions that influence the trunk muscle activities are discussed here.

Table 2 indicates that the T×F interaction affects six of the trunk muscles. An example of how this affected the erector spinae muscles is shown in Figure 6 for the ERSL. The surface of the Figure shows the muscle response as a function of two workplace factors. Electromyographic activity increases with increasing trunk torque. However, as the trunk angle increases the activity level decreases more at the 40 ft-lb level than at the 20 ft-lb level. This trend is interesting, since previous studies<sup>25</sup> have shown that the greatest trunk strength occurs with the trunk in the 22.5° position, yet there is no significant departure from linearity in this part of the curve. Thus, the increased torque must be due to other muscle groups. The internal oblique muscles may provide part of this needed torque. This muscle exhibited a complimentary pattern to that shown for the ERSL. In other words, under the conditions where ERSL is low the INOL activity is high. This demonstrates the cooperative nature of the trunk system.

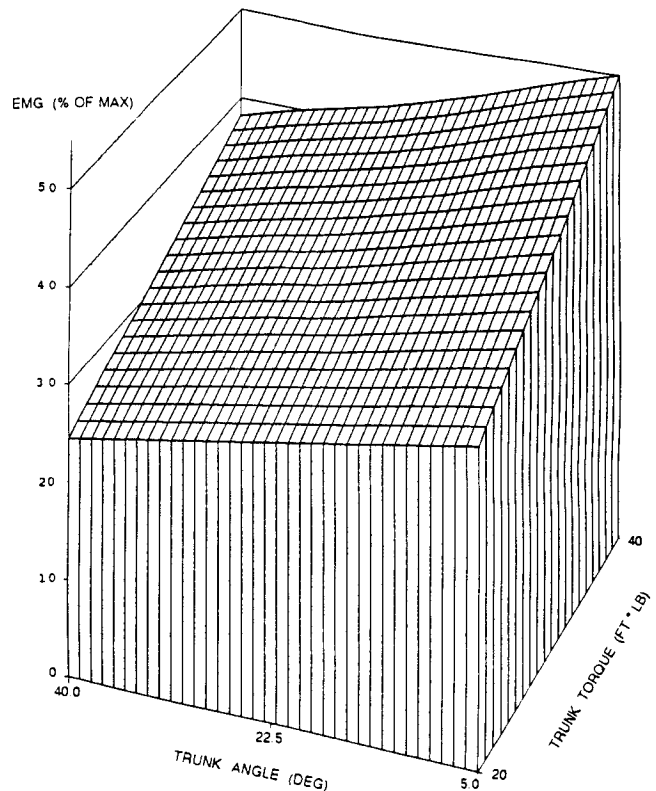


Fig 6. Reaction of erector spinae left muscle to combinations of trunk angle and trunk torque.

The  $T \times V$  interaction affected all trunk muscles, and is important because it provides information about how velocity affects muscle activity while controlling for changes in muscle length that would affect EMG activity. Figures 7 and 8 show examples of how the extensor muscles (LATL and ERSR) were affected by this interaction. Within each trunk angle level, activity was always greater under velocity conditions than under isometric conditions. Thus, when muscle length is controlled we still see increases in muscle activity that may indicate increased internal muscle force due to motion (since the external force is constant). It is interesting to note that the overall trend for the latissimus dorsi muscles was to complement the erector spinae muscles, in that when activity of one increased the activity of the other decreased. This should emphasize the importance of velocity and position during load assessment.

Figure 9 (A-C) shows the velocity-force interaction at each trunk angle ( $V \times F \times T$ ) for the LATR muscle. This Figure shows that within a specific trunk angle, the shape of the EMG responses are similar at each velocity condition in response to each torque level. Only the magnitudes of the signals change. Figure 9C also indicates that at the  $40^\circ$  trunk angle, the lowest EMG activity occurs under the eccentric activities as opposed to the isometric activities, as was the case at other trunk angles. The dramatic change in shape of this surface across the three trunk angles indicates a trunk angle-dependent use pattern.

### Velocity and Muscle Loading

Perhaps the most significant findings in this research can be appreciated by examining the significant  $T \times V \times F$  interactions. We could take advantage of the relationship between EMG activity and muscle force during constant velocity of motion to interpret muscle loading during motion.

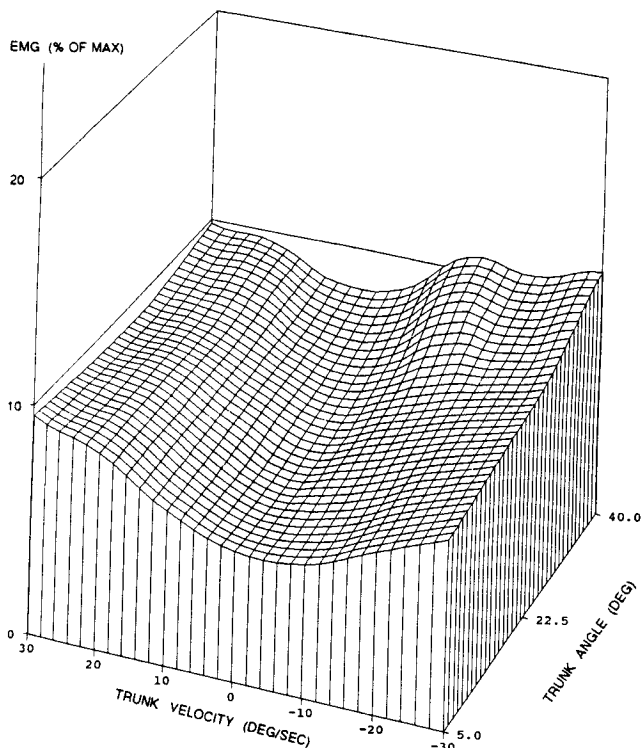


Fig 7. Effects of trunk velocity and trunk position (angle) on the response of the left latissimus dorsi muscle (- = eccentric, 0 = isometric).

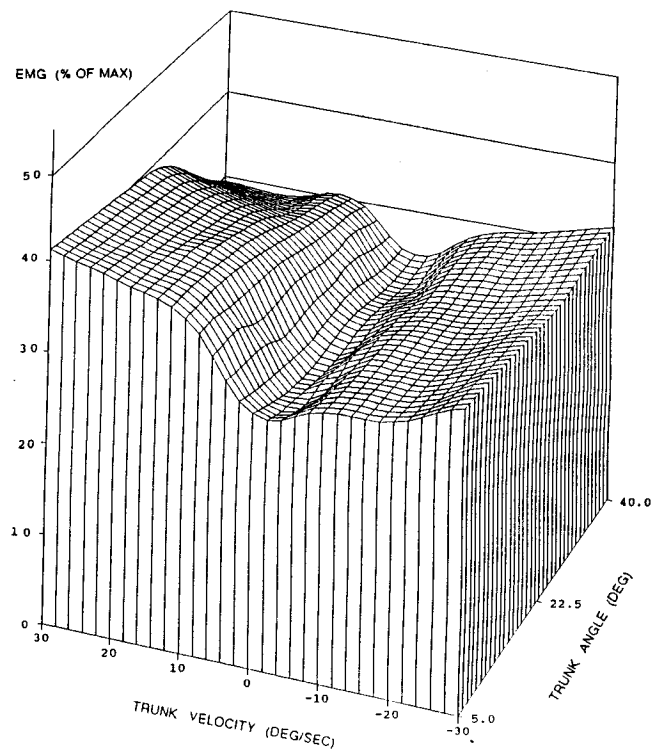


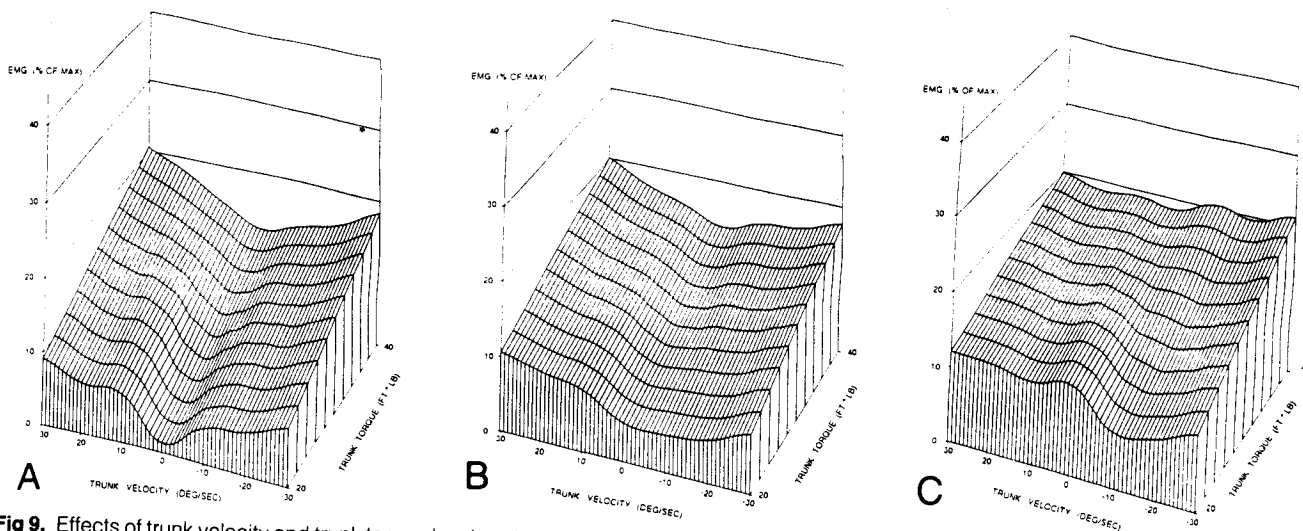
Fig 8. Effects of trunk velocity and trunk position (angle) on the response of the right erector spinae muscle (- = eccentric, 0 = isometric).

At this level of analysis, neither trunk velocity nor trunk position should influence muscle force estimates because these factors are controlled in the experimental design. By observing the difference in EMG required to produce the 20 and 40 ft-lb torques under these conditions we could determine the effect of velocity increases on EMG. If there was no muscle loading cost associated with velocity, this difference in EMG (associated with the different torque levels) should be constant across velocity conditions. If there is a muscle-loading cost to motion, then it should be reflected by the change between these EMG differences across velocity conditions.

The relative LATR muscle force cost required to increase trunk torque production by 20 ft-lbs is shown in Figure 10. The Figure shows that under isometric conditions an average difference of 7% to 9% of maximum EMG is required to increase trunk torque (depending on trunk angle). However, as trunk velocity increases, the relative difference in EMG required to produce a 20 ft-lb increase in trunk torque changes relative to trunk angle. As concentric velocity increases, the change in EMG increases (up to 11.5%) at the  $5^\circ$  and  $22.5^\circ$  trunk angles, yet remains relatively constant for the  $40^\circ$  trunk angle. However, when eccentric activities are explored the opposite pattern appears. The  $40^\circ$  trunk angle solicits the largest change in EMG and decreases with increases in eccentric velocity. The  $5^\circ$  and  $22.5^\circ$  trunk angles change EMG more moderately. A similar pattern was noted for LATL.

The velocity-muscle-loading cost of the erector spinae muscles was quite different. The cost of increasing trunk torque is rather constant for static or concentric velocity conditions. Thus, there was little muscle-loading change between velocities and hence little motion cost.

Both oblique muscle groups behaved much like the latissimus dorsi in response to trunk torque increases, indicating a muscle-loading cost of motion. However, the relative increase in activity was fairly low (less than 8%).



**Fig 9.** Effects of trunk velocity and trunk torque level on the right latissimus dorsi muscle when trunk is in the (A) 5°, (B) 22.5°, and (C) 40° trunk angle position (- = eccentric, 0 = isometric).

These results indicate that there is a muscle-loading cost of velocity in the muscles featured in this study, with the exception of the erector spinae. However, this cost also appears to be trunk angle-dependent. Force increases in the latissimus muscles could be as high as 2% of maximum force for every 10 degree/second increase in velocity at high trunk angles, whereas the cost of motion to the erector spinae muscles is negligible.

**Quantitative Description of Trends**

The previous results indicated that there are many interrelated trends that occurred in the EMG activity of the trunk muscles. Knowledge of such trends is valuable for biomechanical assessment and modeling of the lumbar spine for occupational as well as rehabilitation purposes. However, for this information to be useful for future research, these trends must be quantitatively predictable. The effects of the various trends and interactions are quantitatively described by the regression coefficients in Table 3. These coefficients can be fit into a regression model to describe a muscle response to any combination of physical conditions (ie, velocity, trunk angle, asymmetry, force level, etc). The R<sup>2</sup> statistic in the first column indicates the degree of variability

(between subjects) that can be explained using each formula. This statistic indicates that it is possible to describe accurately the EMG activity of the trunk extensor muscles if some basic subject, trunk motion, and workplace factors are known. However, predictions of the abdominal and external oblique muscles are fairly weak. These equations characterize the complete response of the various muscles to the workplace variables examined in this study.

**DISCUSSION**

This study has accomplished several goals. First, it has identified those workplace factors and combinations of factors that influence the activity of the trunk muscles and IAP. The exact nature of these effects is described in the Figures that appear in this paper. Generally, it has been found that the erector spinae and latissimus dorsi muscles are the most active and reactive across the various workplace conditions. The antagonist muscles also play an important role, in that they become more active as trunk velocity increases, trunk torque increases, or trunk position deviates from a sagittally symmetric orientation. The consequences of this coactivation range from increased risk of overexertion to increased spine loading. This degree of coactivation was not seen in

**Table 3.** Table of Regression Coefficients Used to Predict Trunk Muscle Activities Using Workplace Variables and Worker Strength

Muscles	R <sup>2</sup>	A	T	V	F	M1	F <sup>2</sup>	F <sup>3</sup>	V <sup>2</sup>
LATR	.756	.00293			.0109	-.00124	-.0000190	-.00000004	.0000348
LATL	.778		.000937	-.000662	.00813	-.000982		-.00000007	.0000213
ERSR	.916			.00187	.0161	-.000645	-.0000935	.00000019	.0000752
ERSL	.923		-.00238	.00231	.0198	-.000383	-.000137	.00000031	
RCAR	.525	.000253			.000491	-.0000568	.00000539	-.00000002	.00000693
RCAL	.454	.000228			.000830	-.000103	.00000373	-.00000002	.0000161
EXOR	.590	.00106		-.000290	.00113	-.000148	.0000113	-.00000005	
EXOL	.619	.000819	-.000545	-.000446	.00206	-.000187		-.00000001	
INOR	.810		.000294		.00911	-.000938	-.0000163	-.00000003	.0000425
INOL	.863	.00160		.000698	.0108	-.000758	-.0000287		

A = axial rotation of the shoulders relative to the pelvis (in degrees); F<sup>3</sup> = exerted trunk torque cubed (in foot-pounds cubed); F<sup>2</sup> = exerted trunk torque squared (in foot-pounds squared); F = exerted trunk torque (in foot-pounds); M1 = maximum extension torque capacity of the subject when standing with trunk angle 5° and asymmetry 0 (in foot-pounds); T = forward flexion angle of the trunk (in degrees); V = angular trunk extension velocity (in degrees per second).

Sample calculation: Subject maximum torque 180 ft-lb; exerting 15 ft-lb of torque while moving at 20°/sec in asymmetric posture 10° counter-clockwise (shoulders relative to pelvis as viewed from above): ERSR = (.00187)\*20 + (.0161)\*15 - (.000645)\*180 - (.0000935)\*15\*15 + (.00000019)\*15\*15\*15 + (.0000752)\*20\*20 = 17.25% of maximum.

Note: See Table 2 for a list of other abbreviations.

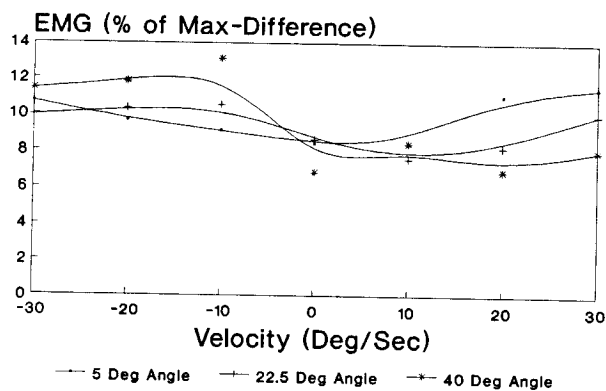
previous studies. This may be due to the fact that previous studies investigated either isometric maximal or submaximal exertions, both of which would decrease the amount of coactivation of the muscles. This study, on the other hand, investigated controlled motions that would be closer to real MMH conditions. Thus, coactivation must be considered in future analyses and models if they are to be realistic.

This analysis has also shown that the general effect of increases in coactivation due to trunk velocity and asymmetry is to either shift the load to, or increase the loading on, muscles other than the erector spinae. These findings indicate that the internal muscle loadings are shifted to muscles that are smaller in cross-sectional area and are therefore more likely to suffer an overexertion injury when supplying the force necessary to perform the task. It is expected that these events would be magnified at greater force exertion levels. Additionally, the nature of the loading forces (compression vs. shear) on the spine would change, as discussed earlier. Collectively, these findings may help explain why many epidemiologic studies have identified asymmetric postures as a risk factor in occupationally related LBDs.

The results of this experiment also helped define the role of IAP during trunk motion. It has been found that, at these trunk exertion levels, IAP reacts primarily to trunk position, becoming greater as trunk angle increases. It has also been found that IAP decreases when the trunk orientation becomes asymmetric. Thus, if there are any load-relieving properties associated with IAP, they are minimal during most nonsagittally symmetric lifts.

The second goal of this study was to help understand how velocity affects the muscle loading within the trunk. Through a careful experimental design, we have been able to evaluate, for the first time, the influence of trunk velocity on trunk muscle loading. We have demonstrated that there is indeed a muscle force cost associated with trunk motion in muscles other than the erector spinae group. This increased muscle force due to motion can be quantified by examining the trends shown in Figure 10 for the latissimus dorsi muscle. Further studies examining a wider range of velocities and trunk torques could use similar methods to quantify these trends.

The source of the motion loading component may be due to two possible sources. First, increased coactivation would create increased resistance, stability, or stiffness of the trunk. Winters et al<sup>41</sup> have identified coactivation as a source of muscle impedance. Thus, the trunk musculature would have to produce more force to overcome this resistance. Second, the increased muscle loading during motion may be a response to trunk inertial forces. Even though this experiment was



--eccentric

**Fig 10.** Difference in right latissimus dorsi EMG (percent of Max) required to increase trunk torque by 20 ft-lbs. Change across velocities indicate differences in muscle loading.

performed under isokinetic conditions, variations in actual trunk dynamics may have occurred.

This added muscle force due to motion is fairly small throughout the range of trunk loadings and velocities examined in this study. However, since the affected muscles generally have a greater moment arm with which to act on the spine, the effects of these increases on spine loading could be significant. Additionally, these muscle-loading effects may be more profound at greater trunk torque exertion levels, greater velocities, or nonisokinetic velocities. Future studies need to examine a larger range of trunk torque and trunk velocities so that these trends can be further quantified and used for workplace design. Also, the muscle-loading effects of other trunk motion components, such as acceleration, need to be explored.

As mentioned earlier, velocity also increases the degree of coactivation of the antagonist muscles. This finding is particularly important when considered in conjunction with the muscle sequence changes that occur with trunk velocity.<sup>24</sup> The net result of this increased coactivity is an increase in spine loading during motion. Thus, models must begin to account for trunk motion when attempting to predict the loading on the spine due to MMH.

Loading on the spine due to concentric and eccentric motion varies considerably. Most occupational lifts involve a concentric component as well as an eccentric component. The current results have shown that in some muscles the EMG response to concentric and eccentric motion is very similar. In other muscles, a concentric motion causes much greater activity as compared to an eccentric exertion. This is probably due to the passive muscle components that help produce tension within the muscle during an eccentric exertion. In summary, there is a significant and powerful biomechanical cost of motion to the muscles. The effects of this motion and the type of motion on muscle and spine loading must also be considered in future modeling attempts.

The final goal of this study was to describe mathematically the expected response of the trunk musculature to workplace factors. The information provided in Table 3 satisfies this goal to a large extent. This Table incorporates those workplace factors and combinations of factors, along with individual subject factors, to predict trunk muscle activity. Generally, Table 3 shows that this could be accomplished fairly well for the extensor muscles, where up to 90% of the variance in muscle activity could be explained. Predictions for the flexor muscles were also less accurate than those of the extensors. This information could be used in conjunction with dynamic biomechanical models wherein EMG activity levels can be associated with muscle force by means of proper scaling of the muscle force-EMG signal.

Several qualifying remarks are also in order for this experiment. First, this study represents a first step in understanding the trunk-loading effects of highly controlled workplace trunk motions. Further research is needed before the state of knowledge is adequate to understand trunk loading under free dynamic MMH conditions.

Second, the trends identified in this study are only valid within the range of variables investigated. The study was designed to investigate several different variables collectively, as opposed to a few variables in great detail. This was necessary due to the large number of conditions involved in this experiment and the need to minimize the effects of fatigue on the experimental data.

Third, the EMG data reflect only the added activity required to perform the task variables. If the data are to be used for biomechanical modeling purposes, the resting muscle force or the activity necessary for a particular subject to maintain a particular posture must be added to the analysis.

Finally, the results from the internal oblique muscles should be treated with caution. Electromyographic signals from these muscles were recorded with electrodes placed over the lumbar triangle, where the muscle is superficial. Quality control checks were performed to



ensure that cross-talk was minimized. However, since the recording site was posterior, it may not reflect the general behavior of the muscle especially at the more lateral or anterior sites.

### SUMMARY

Generally, these results should help us to understand and appreciate how the trunk functions under more realistic MMH situations. The important findings of this study are summarized below:

1. Through a controlled experiment, we have been able to isolate the reactions of the trunk muscles and IAP to trunk motion, trunk asymmetric position, exertion level, and combinations of these factors. Most reactions resulted in increased coactivation between muscle groups.
2. This study has been able to quantify the added trunk muscle force (cost) associated with trunk concentric and eccentric motions. This added cost occurs primarily in the muscles other than the erector spinae group.
3. Intra-abdominal pressure activity decreased as trunk asymmetry increased, and was not affected by velocity level or load level.
4. The reactions of the muscles to workplace factors and motions have been mathematically described.
5. The results of this study can be used to facilitate understanding of spine loading during MMH movements.

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