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Muscle Activities During Asymmetric Trunk Angular Accelerations

W. S. Marras and G. A. Mirka

Department of Industrial and Systems Engineering, The Ohio State University, Columbus, Ohio, U.S.A.

Summary: The objective of this study was to characterize trunk muscle and intra-abdominal pressure behavior during extensions of the trunk when angular trunk acceleration levels and trunk twist were varied during lifting exertions. Since force is related to acceleration, it was believed that changes in trunk acceleration would cause activity changes in the muscles and abdominal cavity pressurization mechanics that load the spine during manual materials handling tasks. The electromyographic activity of 10 trunk muscles and intra-abdominal pressure were studied in 39 subjects as they moved their trunks under high, medium, and low constant angular acceleration conditions. The results indicated that almost all the muscles were affected by acceleration and asymmetry. Muscle activities of up to 50% of maximum were observed even though a minimal amount of torque was being produced by the back. Coactivation of muscles was also apparent. Muscles located at the greatest distances from the spine, such as the latissimus dorsi and oblique groups, increased their activities the most as trunk acceleration increased. Muscles located farthest from the spine also played an important role as the trunk became more asymmetric. Intra-abdominal pressure changed minimally over the test conditions. The nature of these responses and their impact on spine loading are discussed. **Key Words:** Low back disorder—Trunk acceleration—Electromyography—Biomechanics—Intra-abdominal pressure.

Assessments of spine loading during the performance of occupational tasks, such as manual materials handling, usually consider the contribution of both internal and external forces acting on the spine. External forces are generated by external objects that create an external moment about the spine. Internal forces consist of reactions or countermoments supplied by the trunk muscles. In this case, the musculature is at a severe biomechanical disadvantage relative to externally generated forces or moments. Therefore, the muscles must create large forces to keep the trunk in equilibrium, and the internal forces are the primary loaders of the spine during a lifting task. It is important to determine how these muscles behave so that accurate assessments of trunk loadings may be determined.

Traditional analyses of these internal forces primarily have focused on the action of these internal forces under isometric and sagittally symmetric spine loading conditions (2,15). However, most manual materials handling tasks are dynamic and involve lifts outside the sagittal plane of the body. These asymmetric motions are generated by complex activities of the trunk musculature that are not well understood. Marras et al. (4–11) and Gallagher et al. (3) have characterized the response of the trunk muscles and intra-abdominal pressure under

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Address correspondence and reprint requests to W. S. Marras, Department of Industrial and Systems Engineering, The Ohio State University, 1971 Neil Avenue, Columbus, OH 43210, U.S.A.

controlled isokinetic trunk velocity conditions during both symmetric and asymmetric exertions. These studies have shown that there are patterns of trunk muscle and intra-abdominal pressure usage that affect both the sequence of muscle activation and spine loading. Other than these studies, we have been unable to find any other research that has attempted to understand how the internal trunk forces respond to dynamic components of a lift. It is particularly important to understand how the muscles cause angular trunk acceleration because we know that acceleration is closely related to force production. Thus, the goal of this study was to investigate how the internal spine loading forces (muscles and intra-abdominal pressure) behave in order to create angular trunk accelerations while the trunk is moving through typical manual materials handling postures.

METHOD

The experimental task required subjects to extend their trunks starting from a standing flexed position (with the thorax at a 45° forward angle from vertical relative to the pelvis) and ending in an upright standing position (thorax and pelvis angle of 0°). This task was performed with the trunk extending in the sagittal plane as well as with the trunk extending while twisted 15 and 30° in the transverse plane. The latter positions resemble asymmetric industrial lifts. These experimental positions of the trunk are shown in Fig. 1. This experiment required the subjects to exert a constant minimal force with the back throughout the exertion while moving the trunk at different constant angular accelerations. Acceleration was generated about the lumbrosacral junction.

Subjects

The 39 subjects in this study consisted of 31 male and eight female volunteers. Their ages ranged from 17 to 40 years. None of the subjects had experienced a low back disorder and all were considered in good health. Subject occupations ranged from students to professionals to those with experience in manual materials handling. Mean height of the subjects was 1.79 m (SD = 0.31) and mean weight was 797.5 N (SD = 42.1).

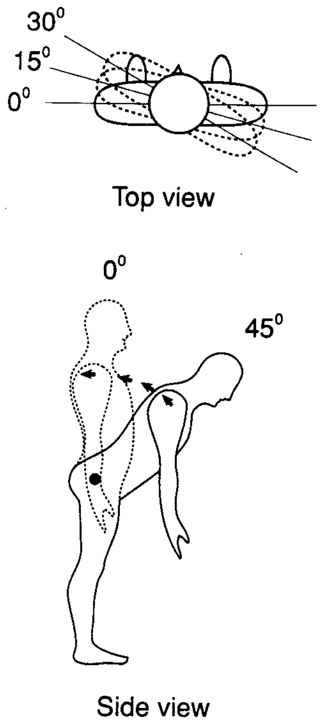

FIG. 1. Experimental task trunk positions.

Design

The experimental design consisted of two independent variables and 11 dependent variables. The independent variables consisted of trunk asymmetry and trunk acceleration. Trunk asymmetry was set at three twisting positions consisting of 0, 15, and 30° deviations from the sagittally symmetric position. Only deviations where the subject's trunk was rotated clockwise with respect to the feet were used as the asymmetric positions. It was assumed that the exact opposite pattern (with respect to the left–right activation muscle usage) of the muscles would occur if the trunk were rotated in the opposite direction.

Trunk acceleration was controlled by the subjects. They were asked to accelerate the trunk at subjectively determined high, medium, and low constant accelerations while exerting a constant minimum torque of approximately 4.1 Nm (±1.25 Nm) about L5/S1. While performing the task, the subject was asked to view a computer monitor that displayed instantaneous trunk velocity and torque. The subject was asked to increase the velocity in a linear manner (within a ±8.5°/s/s tolerance) to produce constant acceleration while maintaining a constant torque. The task average acceleration was determined by differentiation of the velocity signal (generated by the dynamometer) over the range of motion.

The dependent variables were the internal forces that influence spine loading. Schultz and Andersson (14) modeled these forces as being generated by 10 trunk muscles and intra-abdominal pressure.

Apparatus

The configuration of the equipment used in this experiment is shown in Fig. 2. Acceleration was controlled with a KIN/COM isokinetic dynamometer. This device was aligned with the lumbro-sacral junction of the back via an asymmetric reference frame. This reference frame positioned the subject relative to the dynamometer so that both symmetric and asymmetric back exertions could be tested.

Electromyographic activities of the trunk muscles were monitored using small surface electrodes. The muscles were isolated so that cross-talk could be minimized. The trunk muscles monitored consisted of the latissimus dorsi, the erector spinae, the external oblique, the internal oblique, and the rectus abdominus muscles. All muscles were monitored on both the right and left sides of the body. The internal oblique muscle activities were monitored at the lumbar triangle. The electrodes were attached to small lightweight preamplifiers. These preamplifiers were mounted on a belt that was fit around the waist. This configuration minimized the amount of noise in the recorded signal. The preamplifiers were connected to electromyographic amplifiers, filters, and integrators. A switchbox was connected to the amplifiers that permitted the signal quality from each muscle to be monitored. The signal was low pass filtered at 1,000 Hz and high pass filtered at 80 Hz. The signal was then rectified and averaged with a time constant window of 20 ms. This served as the processed or integrated signal.

Intra-abdominal pressure was monitored with a pressure transducer radio pill inserted rectally (13). An antenna was worn around the waist of the subject. This antenna picked up the signal, which was amplified by a receiver. The pill was sterilized and calibrated before each subject was tested.

The dynamometer signals, asymmetric reference frame position signals, processed electromyographic signals, and the intra-abdominal pressure signal were all digitized with an analog-to-digital (A/D) data acquisition system. This system contained

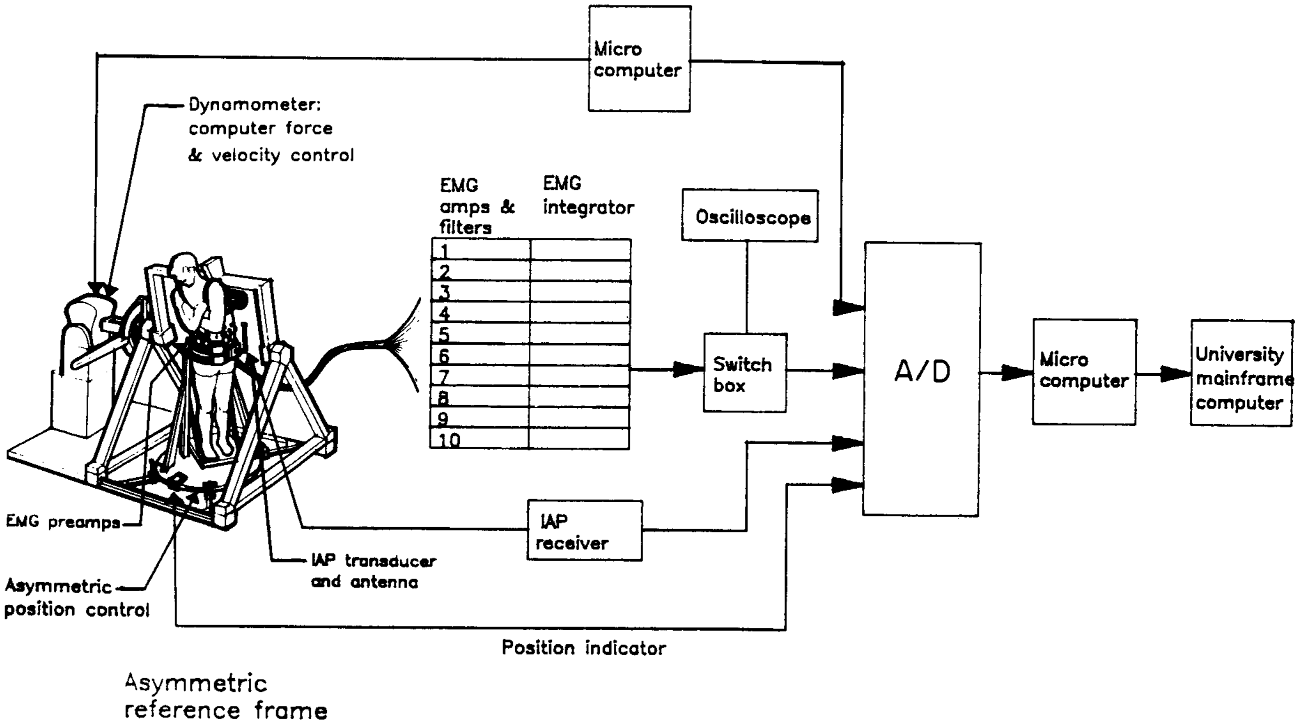

FIG. 2. Equipment configuration.

multichannel A/D capabilities and permitted a 386 based microcomputer to collect, display, and store the data online. Data were collected at 100 Hz. Further processing was performed on an IBM 4341 mainframe computer.

Procedure

Initially, background and anthropometric information was collected from the subjects. Next, they were trained in the use of the asymmetric reference frame system and permitted to practice the experimental task using the computer feedback. Once the subjects became proficient at the experimental task, an appointment for the experimental session was made. This session always occurred on a day subsequent to the training session. During the experimental session, maximum activities of each muscle in each trunk position were also collected so that the electromyographic signals could be normalized. Normalization was necessary so that the relative electromyographic activity caused by acceleration could be differentiated from the change in electromyographic activity caused by the muscle length–tension changes throughout the motion. At least 2 minutes of rest were allowed between each exertion in accordance with standard strength testing protocols (1).

Data Analysis

Each dependent variable value was evaluated as the trunk moved through a "trunk position window." These windows consisted of the forward trunk angle (5, 22.5, and 40°) ±1.25° of motion evaluated at each asymmetric trunk angle. Thus, each value represented the mean activity as the trunk passed through a 2.5° range of motion. All data were compared with respect to the maximum activity and resting level of the muscle or intra-abdominal pressure as the subject passed through the specific angles. This normalization procedure ensured that comparable portions of the muscle electromyographic signals were evaluated.

RESULTS

Acceleration Performance

The data were first analyzed to determine how intended acceleration rate and asymmetry affected the observed angular trunk acceleration level. This information is summarized in Fig. 3. In this study, mean low acceleration levels were measured at between 35.8 and 39.5°/s/s. Mean medium acceleration levels ranged between 65.4 and 67.5°/s/s. Finally, the mean high acceleration levels varied between 125.2 and 136.0°/s/s with some accelerations reaching as high as 335°/s/s. Differences between asymmetry conditions within each acceleration condition were not statistically different from each other. However, under the high acceleration condition, increased asymmetry resulted in reduced trunk acceleration.

Internal Force Behavior

Statistically significant multivariate analyses and individual analyses of muscle and intra-abdominal pressure reactions to the various experimental conditions are summarized in Table 1. Multivariate analyses indicated that, collectively, the variables responded differently to acceleration and asymmetry. This analysis also showed that the variables responded uniquely to the combination of acceleration and asymmetry conditions when considered collectively. The evaluations of the individual muscles and intra-abdominal pressure show that most muscles responded in a significantly different manner to changes in acceleration and changes in combinations of asymmetry and acceleration. Intra-abdominal pressure did not respond in a significantly different manner to asymmetry or acceleration. However, an additional analysis did show that it responded differently to changes in the trunk angle and acceleration combinations.

Of the muscles examined, the erector spinae muscles displayed the greatest amount of electromyographic activity. The mean activity of this muscle group varied from 24 to 36% of maximum activity

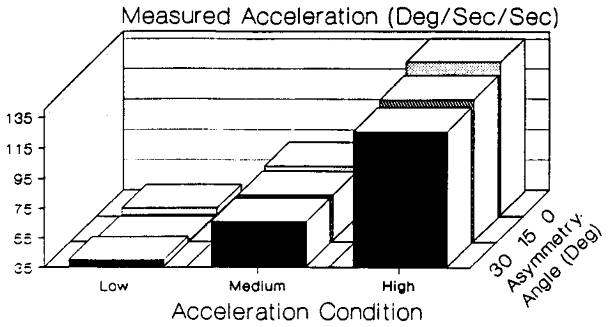

FIG. 3. Mean angular accelerations of the trunk observed in this study as a function of intended acceleration level and trunk asymmetry.

TABLE 1. *MANOVA and ANOVA significance summary for acceleration and asymmetry effects*

		ANOVA										
	MANOVA	IAP	LATR	LATL	ERSR	ERSL	RCAR	RCAL	EXOR	EXOL	INOR	INOL
Asymmetry	.0001		.0206					.0514	.0622			.0107
Acceleration	.0001		.0001	.0001	.0226	.0001	.0407	.0002	.0351		.0001	.0001
Asymmetry × acceleration	.0001			.0001	.0600	.0001	.0374	.0001	.0001	.0001		.0001

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

under the various conditions. However, individual activities of this muscle group were as high as 50% of maximum under certain conditions. The next most active muscle groups were the latissimus dorsi and internal oblique groups. Mean activities of these muscles varied from 3 to 19% of maximum, depending on the condition. Finally, the mean trunk flexor muscle activities varied between 1.5 and 6% of maximum.

Acceleration

Relative changes in electromyographic activity of the trunk extensor and flexor muscles to acceleration conditions are shown in Fig. 4A and B. This figure shows the relative increase in electromyographic activity in the medium and high acceleration conditions compared with the low acceleration condition. This figure indicates that as angular trunk acceleration increases the relative increase in electromyographic activity is much greater in the latissimus dorsi and internal oblique muscles than in the erector spinae muscles. This figure also indicates that the relative rate of increase between conditions is more rapid for the latissimus dorsi and internal oblique muscles and appears linear for the erector spinae muscles. It is also apparent that the degree of coactivation between muscles increases significantly with increased trunk acceleration.

Asymmetry

The effects of asymmetry for the muscles that responded in a significantly different fashion are shown in Fig. 5. This analysis shows that as the trunk becomes more asymmetric, muscles other than the erector spinae muscles are affected. The asymmetric position required the subject to turn clockwise to the right; therefore it appears that the left internal oblique muscle is the contralateral muscle that compensates for asymmetry on the left side of the body by increasing its activity and bearing more of the load.

Acceleration and Asymmetry

The interaction of acceleration and asymmetry significantly affected the erector spinae, rectus ab-

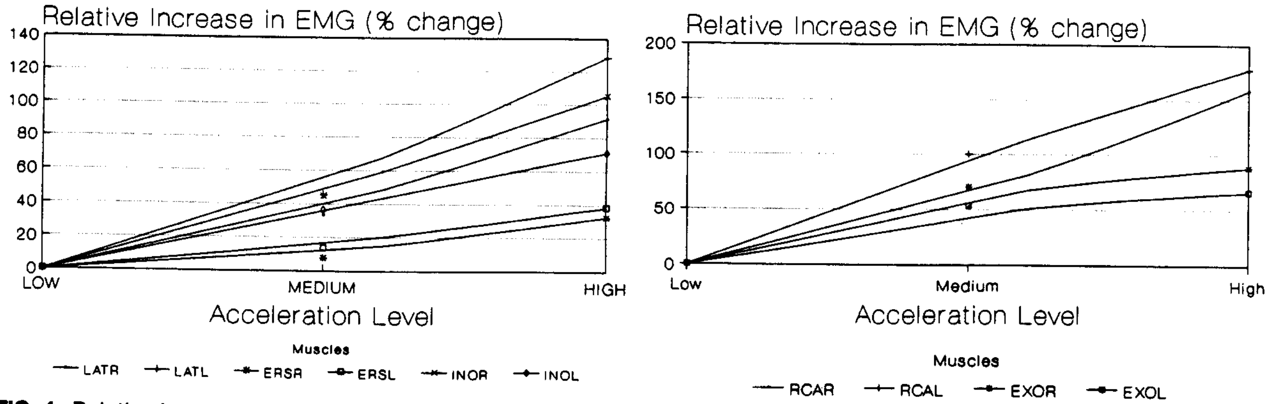

FIG. 4. Relative increases in electromyographic activity as a function of trunk angular acceleration condition for **(A)** the trunk extensor muscles and **(B)** the trunk flexor muscles. LATR, latissimus dorsi right; LATL, latissimus dorsi left; ERSR, erector spinae right; ERSL, erector spinae left; INOR, internal oblique right; INOL, internal oblique left; RCAR, rectus abdominus left; RCAL, rectus abdominus left; EXOR, external oblique right; EXOL, external oblique left.

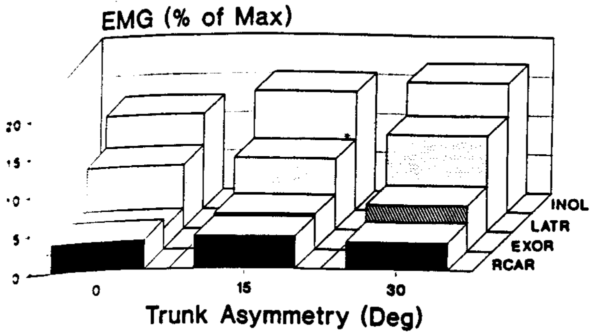

FIG. 5. Effects of trunk asymmetry on mean trunk muscle activity. RCAR, rectus abdominus right; EXOR, external oblique right; LATR, latissimus dorsi right; INOL, internal oblique left.

dominus and external oblique muscle pairs. Examples of these reactions for the right erector spinae muscle is shown in Fig. 6. Figure 6 shows that as acceleration increases, the electromyographic activity of the muscle increases substantially. However, this increase in activity increases at different rates depending on the asymmetric angle. The lowest activity occurs with the trunk in a 15° asymmetric angle at the low acceleration level. A similar pattern occurred for the left erector spinae muscle except that the activity level does not decrease appreciably under the high acceleration condition when greater asymmetry is present.

Both acceleration and asymmetry influence the external oblique right and rectus abdominus left muscles. The general trend for both of these muscles is for increased activity as asymmetry increases and as trunk acceleration increases. However, the trend is much more pronounced at high acceleration levels. This trend is shown in Fig. 7 for the right external oblique muscle. These increases occur at the point where activity declines in the erector spinae muscle. These patterns show the cooperative affect of the coactivation between muscle groups.

As mentioned earlier, intra-abdominal pressure responded significantly to changes in acceleration only when trunk angle also changed. This trend is shown in Fig. 8. It appears from this figure that intra-abdominal pressure activity peaks under medium accelerations at greater trunk angles, low accelerations at middle trunk angles, and high accelerations at upright trunk angles.

DISCUSSION

The results of this study have several implications for the biomechanical function of the trunk

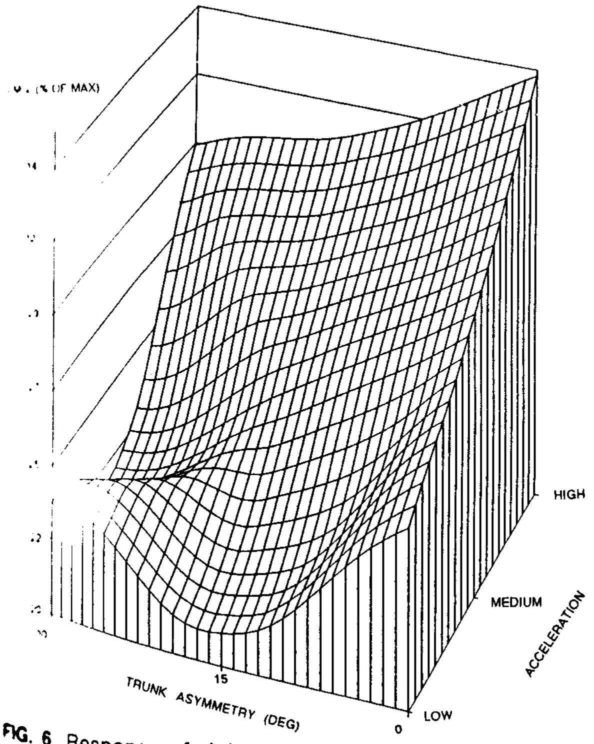

FIG. 6. Response of right erector spinae muscle to trunk asymmetry and trunk acceleration.

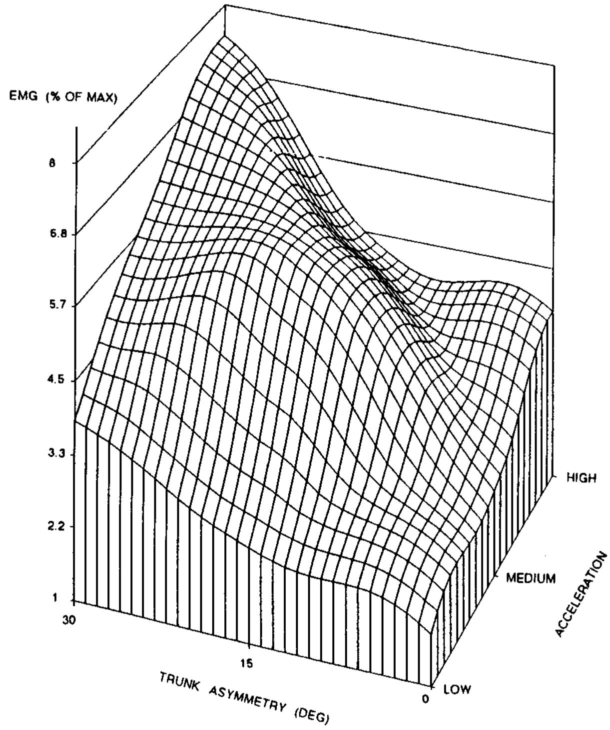

FIG. 7. Response of right external oblique muscle to trunk asymmetry and trunk acceleration.

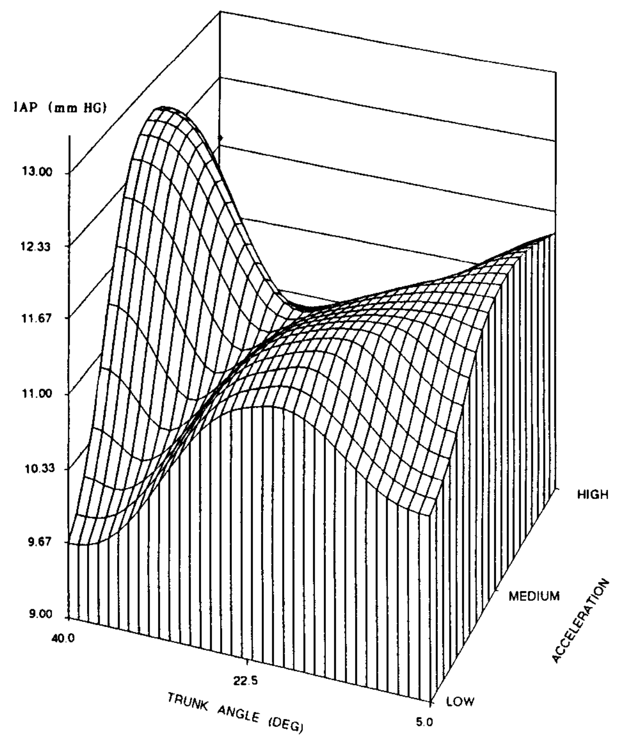

FIG. 8. Response of intra-abdominal pressure to trunk angle and trunk acceleration.

during manual materials handling and may improve our understanding of how low back disorders occur during lifting tasks. We have shown that subjects can produce significant constant accelerations throughout the lifting range of motion. However, such activities appear to place a significant toll on the trunk musculature. Muscle activities of up to 50% of maximum were observed to produce angular trunk accelerations even though a very minor external torque was produced by the trunk.

It is also interesting that a significant amount of coactivation occurs with increases in trunk acceleration. Much of this increase in muscle activity occurs in the antagonist muscles. These coactivations were small in magnitude; however, this may be an indication that significant increases in spine loading may occur when greater trunk torques are generated. Even though the measured acceleration of the trunk did not differ significantly as a function of trunk asymmetric angle, the activity of the internal trunk forces did change significantly as trunk asymmetry changed. When the relative activity levels of the various muscle groups are compared with the responses of the same muscles in reaction to asymmetric isokinetic velocity conditions (11), it is apparent that much more coactivity occurs under acceleration conditions even though the torque exertion level is minimal. Also apparent from a comparison of these two studies is the fact that in both studies the erector spinae muscles always produced the greatest amount of activity and the rectus abdominus always produced the least amount of activity. However, the velocity study showed that the latissimus dorsi muscles and internal oblique muscles both contributed equally to the production of velocity. In this study, the internal oblique and external oblique muscles were far more active during the generation of trunk acceleration than were the latissimus dorsi muscles. This study has also shown that the latissimus dorsi, internal oblique, and rectus abdominus muscles are the muscles that change their activity the most in response to changes in acceleration level. Thus, these findings indicate that there appears to be a specificity of muscle function. Some muscles appear to contribute more to the production of acceleration or asymmetry than do others. Therefore, if one wishes to understand the activity of the internal load supporting structures and the relative contribution of these structures to spine loading, one cannot consider a dynamic activity as simply a series of static postures.

The concept of specificity of muscle function is also reinforced by the pattern of relative muscle activity increase over the various acceleration conditions. In this study we have shown that most trunk muscles increase their activities at a rate much greater than that of the erector spinae muscles as acceleration increases. In fact, it appears that the muscles with the greatest mechanical advantage increase their activities the most as the acceleration conditions increase. Thus, muscles that are the farthest from the spine and provide the most efficient internal moment (i.e., oblique muscles) increase their activities the most as trunk acceleration is increased. The sum of these increased trunk muscle forces influence spine loading.

Trunk asymmetry appeared to affect muscles other than the erector spinae muscles. This indicates that during the production of acceleration of the trunk under asymmetric conditions, the internal countermoment is assisted by the small, thin oblique muscles. Since muscle force generation is a function of the cross-sectional area of the muscle, this indicates that the oblique muscles could be easily stressed. Several researchers have hypothesized that these small muscles of the trunk may be responsible for many low back disorders (12). This could explain why industrial epidemiology studies have shown that asymmetric lifting increases the risk of suffering a low back disorder.

There also appears to be strong interactive effects of those variables associated with acceleration. For example, in this study the interaction of acceleration and asymmetry indicated some unique responses of the muscles that could not be explained by any of the variables individually. The musculoskeletal system of the trunk is very complex and general models that do not describe the dynamic components of trunk motion during materials handling tasks may not provide an accurate representation of trunk loading during work.

Collectively, this information indicates that even though large postural muscles such as the erector spinae group are important for the major supporting function of the trunk, the smaller surrounding musculature play an important role during motion generation and trunk control.

Intra-abdominal pressure only responded in a significantly different manner to changes in the forward trunk angle as trunk acceleration changed. Previous studies (4,5) have shown that intra-abdominal pressure is primarily a function of forward trunk angle. We also hypothesized that intra-abdominal pressure may play a preparatory role in trunk force exertion. This study does not disprove this theory, because a preparatory response would occur prior to trunk motion. Thus, the role of intra-abdominal pressure in the biomechanical support and loading of the spine must still be investigated in experiments that are designed to explore this issue in particular.

In this study we have described the manner in which the activity of the various muscles responds to the various experimental components. However, it should be emphasized that an increase in electromyographic activity does not necessarily indicate that an increase in muscle force has occurred. Therefore, one should be cautious in relating the results of this study to spine loading. Further research is needed to clarify this issue. If a dynamometer were available that could control acceleration levels as opposed to the subject controlling acceleration, then specific accelerations at specific torque levels could be tested. The portion of the electromyographic signal responsible for increased muscle force could be partitioned from the portion of the signal caused by muscle motion (11). However, an increase in muscle activity does indicate that the worker may be exposed to greater fatigue, and thus, a greater risk of suffering an overexertion injury.

Future studies could build on this study and should investigate several additional aspects of acceleration. First, this study used a relatively minor torque about the spine during acceleration exertions. During a manual materials handling task, however, much greater moments are imposed about the spine. Hence, future studies should investigate the reactions of trunk musculature and intra-abdominal pressure to accelerations performed under different torque exertion conditions. Next, some of the muscle responses, such as those of the internal oblique muscles, resembled the responses of other muscle groups under some conditions. This may indicate cross-talk between internal oblique and erector spinae electrodes. On the other hand, the internal oblique muscles did show unique responses to several conditions that did not solicit a unique response from the erector spinae muscles. Therefore, future studies should use intramuscular electrodes to minimize the chance of cross-talk and attempt to verify the results of this study. Finally, attempts to explore the role of intra-abdominal pressure in trunk acceleration should investigate the intra-abdominal pressure activity prior to the motion of the trunk in order to determine whether this pressure acts in a preparatory manner.

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