

Trunk Strength during Asymmetric Trunk Motion

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It is important to understand how trunk strength varies as a function of workplace factors so that the work environment can be designed to minimize the risk of low back injury. In this study maximal trunk torque production around the lumbosacral junction was measured in 44 subjects as trunk concentric and eccentric isokinetic velocity and trunk asymmetric line of action were varied. Trunk torque decreased by approximately 8.5% of maximum for every 15 deg of asymmetric trunk angle. Increases in concentric velocity decreased trunk strength, whereas increases in eccentric trunk velocity increased strength. Significant interactions were also found, and it was determined that the common finding that eccentric strength exceeds concentric strength is true only for forward trunk angles at all asymmetric angles. These results should have significant implications for the design of manual materials handling tasks.

INTRODUCTION

Occupationally related low back disorders (LBDs) have become a problem of epidemic proportion in the industrialized world in recent years. It is estimated that in most industries between 20% and 25% of workers' compensation claims involve LBDs. However, these injuries are responsible for nearly 40% of workers' compensation costs (Industrial Commission of Ohio, 1987). Epidemiological studies have also shown that the risk of suffering an LBD can be related to the lifting tasks required of the workers (Andersson, 1981). Thus occupationally related LBD has been recognized as a major problem in the industrial environment.

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It is widely known that the majority of LBD incidents associated with the workplace involve muscular overexertion injuries (Industrial Commission of Ohio, 1987). These injuries occur frequently and are quite acute initially but may progress to a more chronic state with repetitive strains. One of the basic concepts in the ergonomic control of the workplace is to design manual materials handling tasks so that the strength required by the task does not exceed most workers' capabilities. Worker strength has traditionally been evaluated using isometric strength tests of workers in sagittally symmetric postures (i.e., NIOSH, 1981). However, a review of most industrial work environments indicates that these conditions are extremely rare (Marras, Sudhakar, and Lavender, 1989). Trunk motions are asymmetric in most manual materials handling tasks and typically in-

volve significant concentric as well as eccentric velocity profiles. *Concentric exertions* involve shortening of the muscle during the exertion of force, whereas *eccentric exertions* refer to force exerted while the muscle is lengthening. Concentric exertions are involved during the lifting portion of a manual materials handling task, whereas eccentric exertions are prevalent during the lowering portion of the task. Most previous studies have evaluated only concentric strength, but many high-LBD-risk occupations (e.g., nursing) involve an extensive amount of eccentric exertions. Therefore, the objective of this study was to investigate how trunk strength, defined as torque production around the lumbosacral (L5/S1) junction, is influenced by asymmetric trunk position and changes in concentric and eccentric velocity.

PREVIOUS STUDIES

Garg and Badger (1986), in an investigation of whole-body lifting strengths, asked subjects to lift weights at three asymmetric lifting angles (with a foot position of 30, 60, or 90 deg to the object lifted). Reductions of 6% to 9% in maximum acceptable weight were observed for each 30-deg increase in asymmetry. They also found that maximum isometric strength decreased by 12%, 21%, and 31% for asymmetric lift angles of 30, 60, and 90 deg, respectively. Mital and Fard (1986) compared lifting in a 90-deg asymmetric position with that in a sagittally symmetric position and found that subjects were willing to lift 8.5% less weight asymmetrically.

Several studies have investigated the manner in which velocity affects trunk strength around L5/S1 in the sagittal plane of the body. Marras, Joynt, and King (1985) and Marras, King, and Joynt (1984) originally investigated subjects' ability to exert torque

around L5/S1 while moving under concentric isokinetic velocity conditions. They found that trunk extensor torque was greatly affected by increases in velocity. Mean torque production decreased by 78.5% of maximum as subjects' trunk velocities increased from isometric to the maximum trunk velocity. Later studies by Marras, Wongsam, and Rangarajulu (1986) and Marras, Rangarajulu, and Wongsam (1987) investigated trunk extensor torque in the sagittal plane under absolute (as opposed to relative) isokinetic velocity conditions for velocities ranging from 0 deg/s to 90 deg/s. They found that trunk torque capability was reduced by 0.55% of maximum for each deg/s increase in trunk concentric velocity.

Few studies of trunk torque as a function of concentric and eccentric trunk exertions appear in the literature. One of the first studies of concentric and eccentric back extension strength was performed by Smidt, Amundsen, and Dostal (1980), who tested 11 subjects lying on their sides while an isokinetic velocity was set at 13 deg/s. They found that eccentric strength exceeded concentric strength by 70 to 150 newtons, depending on the trunk angle. Reid and Costigan (1987) also tested subject L5/S1 strength and found that for trunk extension the ratio of eccentric divided by concentric work had a mean value of 1.20. Thus subjects were able to do about 20% more eccentric work over a velocity range of 25 deg/s.

Very few studies have investigated trunk strength under either asymmetric trunk position conditions or sagittally symmetric trunk velocity conditions. However, there is nothing in the literature that collectively investigates trunk strength as a function of both asymmetry and trunk velocity under more realistic lifting motion conditions. This study was designed to investigate such a relationship.

METHOD

In this experiment trunk position and angular motion were defined around L5/S1. *Trunk position* refers to the position of the thorax relative to the pelvis. Maximum voluntary trunk extension strength was investigated in subjects exposed to changes in trunk asymmetry and velocity under isometric, concentric, and eccentric conditions. This was accomplished by placing subjects in a device that oriented them with respect to a dynamometer so that trunk exertion was controlled and isolated around L5/S1 exclusively. The concentric experimental task required the subject to begin the exertion with the trunk flexed at a 45-deg angle forward from upright. From this position the subject performed a maximal extension of the trunk until the trunk was in an upright position. Eccentric exertions were performed beginning with the trunk in an upright standing position and resisting flexion of the trunk until the trunk was flexed at 45-deg forward bend. These positions resemble those in lifting and lowering tasks. Asymmetric exertions were performed in exactly the same manner except that the thorax was rotated relative to the pelvis prior to exertion. Asymmetric exertions consisted of forward trunk extensions (and resisting flexion) while the trunk was prerotated at a given angle. Thus no additional twisting occurred during the exertion.

Subjects

Serving as subjects were 44 healthy adults. Of these, 36 were male and eight were female. The ages of this population ranged from 17 to 40 years. No subject had ever experienced a back disorder. The mean height and weight of the subject population (males and females combined) was 178.9 cm ($SD = 9.3$) and 75.54 kg ($SD = 13.77$), respectively.

Design

Three factors served as independent variables in this experiment: angular trunk extension velocity, trunk asymmetry, and trunk angle. The trunk velocity variable incorporated isometric, concentric, and eccentric exertions into seven different levels. *Trunk velocity* refers to the extension velocity of the thorax relative to the pelvis and does not involve rotational actions of the spine. Concentric trunk velocity was tested at 10, 20, and 30 deg/s. Eccentric trunk velocity was also tested at 10, 20, and 30 deg/s. These velocity levels were selected based on the work of Kim and Marras (1987), who found that under dynamic lifting conditions subjects' lifting velocities generally did not exceed 30 deg/s. An isometric velocity condition (0 deg/s) was also included in the experimental design.

Trunk asymmetry was defined in terms of the rotational position of the thorax around L5/S1—specifically, the position of the shoulders relative to the hips defined the asymmetric angle. The trunk asymmetry variable had three levels: a sagittally symmetric condition (0 deg) and deviations of the trunk from the sagittal plane toward the coronal plane of the body of 15 and 30 deg. All deviations from the sagittal plane occurred with the subject rotating his or her shoulders clockwise (viewed from above). The trunk asymmetry planes used in this experiment are shown in Figure 1.

Finally, a variable of forward trunk angle was incorporated into the design so that asymmetric angle could be better defined and velocity conditions compared at set points. In this experiment upright standing was defined as 0 deg of trunk angle. The experimental trunk angles consisted of forward angles of the trunk of 5, 22, and 40 deg.

The dependent variable in this study was the maximum voluntary trunk torque exerted

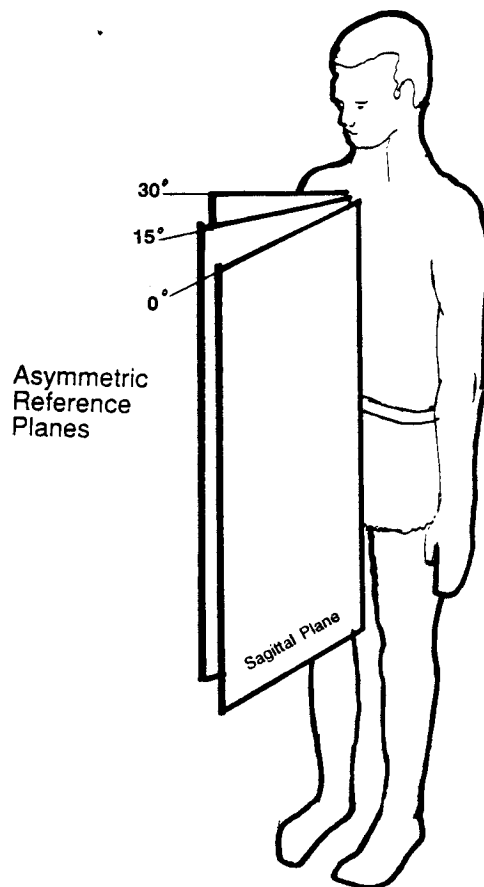


Figure 1. Definition of asymmetric trunk angles.

around L5/S1 against an isokinetic dynamometer as the trunk passed through a 2.5-deg window centered at the designated trunk angles. This window was defined at each forward trunk angle for all asymmetric angles of the trunk, permitting the torque to be compared at each of nine positions (three asymmetric angles \times three trunk angles) for each velocity. The torque axis center of rotation in this experiment was aligned with L5/S1 and the point of force application was at approximately 30.5 cm (1 ft) superior to that point. This corresponded to a point on the back just below the scapula on most subjects.

Apparatus

Subjects were placed in an asymmetric reference frame (ARF) for this experiment. The ARF interfaced with a KIN/COM dynamometer capable of controlling both concentric and eccentric exertions. The rotating axis arm of the KIN/COM was interfaced with the ARF so that it controlled the motion around L5/S1. The subject was strapped into the ARF so that only trunk motion was permitted. Subjects' legs were straight.

Subjects exerted force against rollers that contacted the upper back. These rollers were attached to a load cell at that point so that only trunk torque and not the mass of the ARF was measured. This arrangement allowed for elongation of the spine during trunk motion. KIN/COM velocity and trunk angle were controlled with a microcomputer. Trunk asymmetry was controlled by rotating the subject on a platter relative to the dynamometer. The ARF is shown in Figure 2. The output of the ARF and KIN/COM was monitored on-line with an analog-to-digital (A/D) converter interfaced with a Compaq 386 microcomputer. Data were collected at a 100-Hz sampling rate. Customized data acquisition and analysis software were used to evaluate the data.

Task

The experimental task required the subject to exert maximum voluntary extension torque with the back under the various experimental conditions. If the subject did not feel that he or she produced a maximum exertion on any trial, the condition was repeated. Rest periods of at least two minutes were permitted between trials.

Analysis

The experimental data were analyzed via a three-way ($3 \times 3 \times 7$) analysis of variance

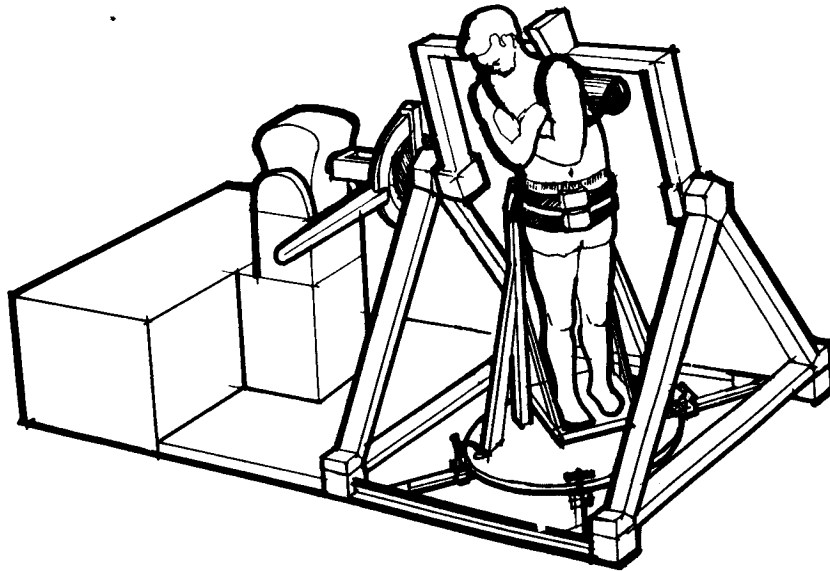


Figure 2. The asymmetric reference frame used to control trunk motion and trunk position.

(ANOVA) procedure so that both the main effects as well as interactive effects could be evaluated. Significant effects were further evaluated using post hoc analysis procedures. Regression analysis was also employed to predict torque output as a function of the various experimental variables. This facilitated the quantification of experimental results.

RESULTS

Significant Effects

A significance summary of the experimental factors is shown in Table 1. As shown, all variables and interactions, except for the Asymmetry \times Trunk Angle interaction, influence the ability of the trunk to exert torque around L5/S1.

Descriptive results of the study are summarized in Table 2. This table shows trunk strength normalized relative to the strongest position of the trunk and the relative changes that occur as velocity, trunk angle, and trunk asymmetry are changed.

Asymmetry

This study indicated that as trunk asymmetry increases, overall strength (isometric, concentric, and eccentric) decreases at the rate of between 8% and 9% of maximum for every 15 deg of asymmetry increase. Variability in strength was also evident, particularly under the sagittally symmetric condition. This variability probably arose from the inherent differences in capability of this varied subject population.

TABLE 1

ANOVA Significance Summary of Maximum Trunk Torque

<i>Variable</i>	<i>df</i>	<i>F</i>	<i>p > F</i>
Asymmetry (As)	2	70.21	0.0001*
Trunk angle (Tr)	2	15.89	0.0001*
Velocity (V)	6	6.44	0.0001*
As \times Tr	4	1.31	0.2690
As \times V	12	2.76	0.0012*
Tr \times V	12	32.33	0.0001*
As \times Tr \times V	24	2.61	0.0001*

* Significant at 0.001 level.

TABLE 2

Normalized Torque, in Percentage of Maximum at a Standard Position, Produced during Maximal Exertions

	<i>Asymmetry (deg)</i>								
	<i>0</i>			<i>15</i>			<i>30</i>		
	<i>5</i>	<i>22</i>	<i>40</i>	<i>5</i>	<i>22</i>	<i>40</i>	<i>5</i>	<i>22</i>	<i>40</i>
<i>Trunk (deg):</i>									
Angular velocity (deg/s)									
Eccentric									
30	0.78 (0.19)	0.84 (0.21)	0.81 (0.26)	0.69 (0.19)	0.74 (0.21)	0.72 (0.22)	0.61 (0.17)	0.67 (0.21)	0.64 (0.24)
20	0.75 (0.19)	0.82 (0.22)	0.80 (0.24)	0.68 (0.17)	0.74 (0.22)	0.71 (0.24)	0.60 (0.17)	0.64 (0.18)	0.62 (0.23)
10	0.75 (0.21)	0.78 (0.22)	0.74 (0.25)	0.66 (0.16)	0.68 (0.20)	0.63 (0.24)	0.58 (0.17)	0.60 (0.21)	0.55 (0.25)
Isometric									
0	0.63 (0.18)	0.88 (0.24)	1.00 (0.29)	0.67 (0.16)	0.86 (0.20)	0.94 (0.23)	0.59 (0.14)	0.75 (0.20)	0.82 (0.22)
Concentric									
10	0.79 (0.23)	0.86 (0.29)	0.69 (0.30)	0.71 (0.17)	0.80 (0.21)	0.70 (0.22)	0.67 (0.21)	0.75 (0.25)	0.66 (0.24)
20	0.79 (0.22)	0.86 (0.25)	0.69 (0.27)	0.73 (0.19)	0.78 (0.22)	0.65 (0.19)	0.67 (0.19)	0.72 (0.22)	0.62 (0.22)
30	0.75 (0.21)	0.79 (0.23)	0.65 (0.24)	0.71 (0.20)	0.72 (0.20)	0.60 (0.19)	0.66 (0.19)	0.69 (0.20)	0.55 (0.18)

Standard deviations in parentheses.

Trunk Angle

The effect of trunk angle on strength was similar to that seen in previous studies. Generally, of the experimental trunk angles tested, trunk strength was greatest when the trunk was flexed at a 22.5-deg angle and decreased by 7% to 10% as the trunk became more upright or more flexed.

Trunk Velocity

The main effect of trunk velocity was overshadowed by its interaction with other variables. However, several general trends can be gleaned from these data. First, static exertions result in the greatest trunk strength. Second, eccentric strength is not greater than

concentric strength except under the 30-deg/s conditions. In this case the increase in eccentric strength compared with concentric strength is only 2.0%. Third, concentric strength decreases by about 0.33% of maximum for every degree-per-second increase in trunk velocity. Finally, eccentric strength increases as trunk velocity increases. It should be kept in mind that these findings may be influenced by the various interactions. Therefore, these interactions must be examined before differences between this and previous studies can be assessed.

Trunk Angle × Velocity

A significant Trunk Angle × Velocity interaction was identified by the ANOVA evalua-

tion. The nature of this interaction is shown in Figure 3. As indicated in the trunk angle analysis, the maximum trunk torque is produced when the trunk is in a 22.5-deg flexed position. However, Figure 3 shows that this is a complex relationship. Maximum torque is generated at the 22.5-deg trunk angle only for dynamic exertions. The peak torque is generated at the 40.0-deg trunk angle for the isometric conditions. A significant decrease in isometric torque production is also evident at the more upright trunk angles compared with dynamic exertions at the same trunk angle.

Asymmetry × Velocity

The Asymmetry × Velocity interaction is shown in Figure 4. This interaction indicates that at all velocities, trunk strength decreases as asymmetry increases. However, this rate of decrease is greater for eccentric velocities than it is for isometric and concentric velocities. A significant drop in trunk strength is

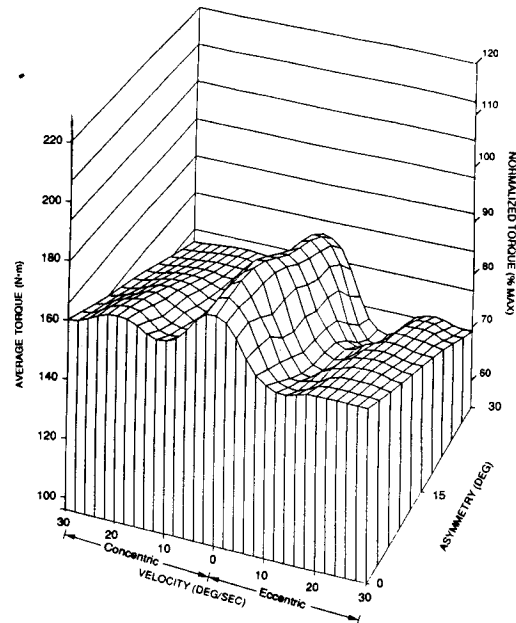


Figure 4. *Trunk Velocity × Trunk Asymmetry interaction effect on trunk strength.*

also apparent for slow (10-deg/s) eccentric velocities.

Asymmetry × Velocity × Trunk Angle

A significant Asymmetry × Velocity × Trunk Angle interaction was also found in this study. This can be interpreted as a decomposition of Figure 4 at the various trunk angles. These interactions are shown in Figures 5, 6, and 7. The nature of this relationship is such that at the 5.0-deg trunk angle (Figure 5) a significant decrease in trunk strength is seen at the isometric sagittally symmetric trunk position relative to the dynamic conditions. As the trunk moves through the 22.5-deg trunk angle (Figure 6), the isometric conditions result in trunk torque productions that are at least as great as the concentric torques and in many asymmetric positions exceed concentric exertions. Finally, as the trunk passes through the 40.0-deg trunk position (Figure 7), it is clear that

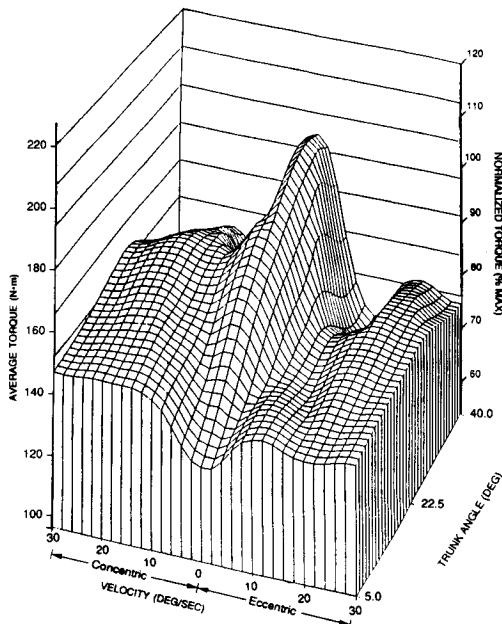


Figure 3. *Trunk Velocity × Trunk Angle interaction effect on trunk strength.*

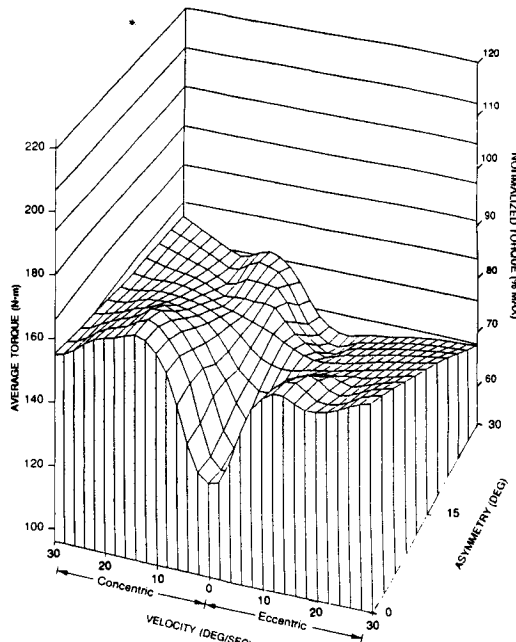


Figure 5. *Trunk Velocity* × *Trunk Asymmetry* interaction effect on trunk strength at a trunk angle of 5.0 deg.

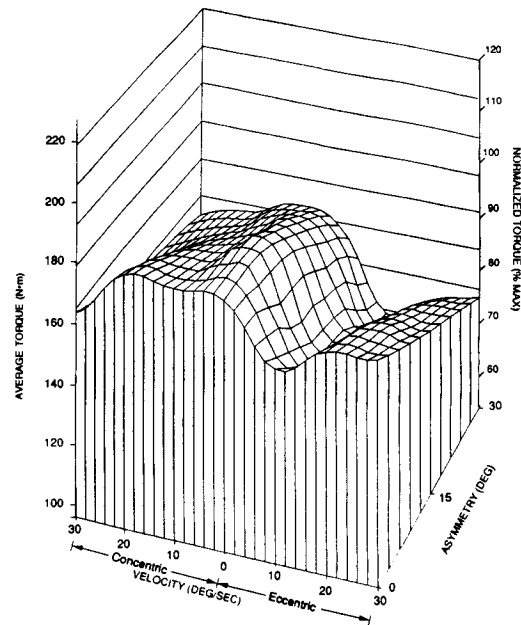


Figure 6. *Trunk Velocity* × *Trunk Asymmetry* interaction effect on trunk strength at a trunk angle of 22.5 deg.

the isometric trunk exertions result in trunk torques that are 20% to 30% greater than the dynamic exertions. In this specific position it can also be seen that eccentric exertions exceed concentric exertions, and the magnitude of this relationship is similar to that reported in the previous literature. This interaction shows the importance of the specific trunk angle positions to the capacity to generate strength with the trunk.

Predictions of Strength

The experimental results were used to create regression models that predict trunk torque exertion levels as a function of the various experimental variables investigated in this study. The coefficients of these models are presented in Table 3 for isometric, eccentric, and concentric exertions. This table indicates that by knowing the positions of the trunk, the subject's maximum static trunk

torque capability (MAX) in a standard position (sagittally symmetric, static exertion with a 40-deg trunk angle), and the task velocity characteristics, maximum trunk torque could be predicted. This model explains between 37% and 70% of the variability in trunk strength. The table indicates that the best predictability is possible for the isometric exertions and the least predictability is possible when attempting to predict eccentric exertions.

DISCUSSION

These results have shown that the factors that affect trunk strength are related in a rather complex manner. Factors such as trunk asymmetry, trunk angle, and trunk velocity each affect trunk strength in a manner that has been described generally in the literature. However, when the combination of these variables is considered, as is the case in

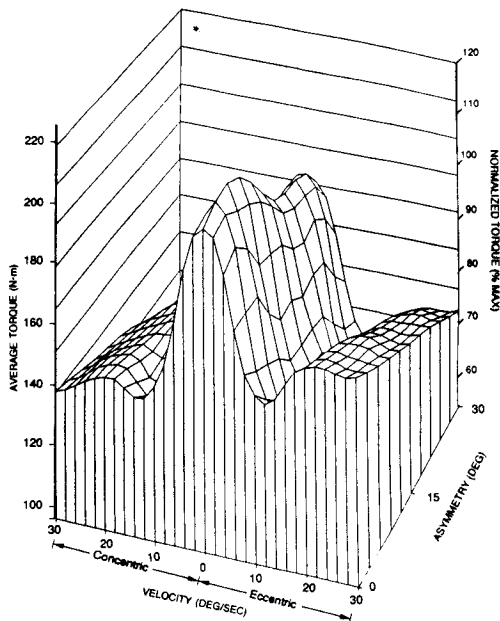


Figure 7. *Trunk Velocity × Trunk Asymmetry interaction effect on trunk strength at a trunk angle of 40.0 deg.*

most industrial manual materials handling conditions, the relationship with trunk strength changes significantly.

Perhaps one of the more significant findings of this study is the capacity to produce trunk torque as a function of trunk angular velocity and trunk angle. It was concluded that the maximum trunk torque capacity changes dramatically as a function of velocity and trunk angle. Of the angles studied, the peak torque for dynamic exertions occurred at the 22.5-deg trunk angle, whereas peak torque under isometric exertions occurred at the 40.0-deg trunk angle. This interaction indicates that dynamic strength of the back can not be interpreted in quasi-static terms as is the current practice in workplace design. The difference in these situations probably relates to the fact that under dynamic conditions much of the trunk strength is used to support and move the trunk at greater trunk angles when a greater trunk moment of inertia is

present. Therefore, there is less trunk strength available to apply to the object that is to be moved. This is also consistent with our knowledge of the length-tension relationship of the back muscles and epidemiologic studies. Thus when workers are lifting an object with their trunks greatly flexed, the risk of suffering an LBD is increased because of the increase in trunk moment and the decrease in available strength at this position.

The relationships among trunk asymmetry, trunk velocity, and trunk angle also have important implications for manual materials handling situations. Both Smidt et al. (1980) and Reid and Costigan (1987) indicated that eccentric trunk strength always exceeds concentric trunk strength. However, our results have shown that this is the case only when the trunk is in a flexed position. Several factors may explain these differences. First, the aforementioned studies positioned the subjects with their hips and knees flexed. This could put subjects in a position that would be equivalent to a forward flexed posture in our study. Next, Smidt et al. and Reid and Costigan did not measure trunk torque at a constant distance from L5/S1, as was the case here. Those studies used a cable arrangement attached to a strap around the chest that would indicate that the distance between L5/S1 and the point of force application would change as the trunk moved through its range of motion.

If one examines the types of high-risk jobs that involve a high degree of eccentric exertion, one can see how the findings of this study may help to explain the increased risk. For example, one of the greatest risks of LBD involves the nursing profession. When nurses or nurses' aids lift and lower a patient, a high degree of eccentric strength is required. The position of the worker in these circumstances is fairly similar to the experimental position seen in this study; the knees are straight. The worker must carefully lower the patient, usu-

TABLE 3

Regression Coefficients for Prediction of Maximum Torque Production Using Workplace Factors

<i>Exertion</i>	<i>Intercept (Nm)</i>	<i>Max</i>	<i>Asym</i>	<i>Tr</i>	<i>Vel</i>	<i>R²</i>
Eccentric	84.8	0.3144	-1.1890	0.0485	-0.5346	0.37
Isometric	11.2	0.6031	-0.7632	1.6680	—	0.70
Concentric	87.6	0.4456	-0.7000	-0.3609	-0.5439	0.50

Max = maximum torque in Nm exerted by this subject at 0 deg asymmetry, 40 deg trunk, and 0 deg/s velocity. Asym = the asymmetric posture (in degrees) for this trial. Tr = the trunk angle (in degrees) for this trial. Vel = the angular velocity of the trunk (in degrees per second) for this trial.

ally at a slow velocity. This study has identified significant reductions in eccentric strength capability at these slow velocities. Thus the worker would be at an increased risk of suffering an overexertion injury. Furthermore, given that eccentric strength is much lower than concentric strength at more upright trunk angles, the risk of an overexertion injury is also increased at the beginning of the lowering task. The increased moment imposed on the spine at the end of the lowering task identifies another point at which an LBD may occur. Finally, in most patient handling tasks, the job entails some asymmetric handling of the patient. This as well as several previous studies have shown that trunk strength decreases as asymmetry of the trunk increases. This would also place the worker at a greater risk of injury.

Most of the changes in strength associated with this study can be explained, theoretically, by changes in length of the trunk musculature during the exertion task. Strength is reduced when the trunk musculature operates at the nonoptimal regions of the length-tension relationship curve. There is also some biomechanical reasoning indicating that the risk of suffering an LBD increases because of factors other than overexertion of the muscles. Some work (Troup and Edwards, 1985) has shown that the disc tolerance to compression is greatly reduced when the disc is loaded under asymmetric motion conditions.

Thus the relative loading on the disc (compared with static exertions) would be increased because of motion, given that motion increases the force on the disc ($F = m \times a$) and the tolerance to compression forces would be reduced. Hence under asymmetric motion conditions not only is the trunk strength reduced, resulting in a greater risk of an overexertion injury, but the risk of increasing the relative loading on the disc also increases.

The quantitative information gained from this study could be used to assist the ergonomist in designing manual materials handling work stations. If the positions of the worker's back and motion characteristics (i.e., velocity of motion and nature of motion) can be documented throughout a repetitive manual materials handling task, and an indication of maximum trunk strength can be measured (MAX), then the strength throughout the range of motion can be predicted using the regression model coefficients shown in Table 2. If the available strength throughout the exertion is exceeded by the moment imposed around the spine by the lifting task, then the task elements (lifting heights, distances of travel, etc.) that impose motion and asymmetry around the spine can be changed until the trunk motions are such that they can be performed by the majority of workers. This procedure would help to minimize the risk of LBD in the workplace.

CONCLUSIONS

This study has investigated the effects of trunk motion and asymmetric position of the trunk on the ability to generate trunk strength. Significant effects of asymmetry, trunk angle, and trunk motion have been quantified. This study has also shown that the relationships among these variables are rather complex and that static or quasi-static trunk strength capabilities cannot be extrapolated to dynamic trunk strength conditions. These results have also helped to clarify some of the existing literature concerning the relationship between concentric and eccentric trunk strength. Previous findings that eccentric strength exceeds concentric trunk strength have been shown to be valid only at specific trunk angles; furthermore, this is not a general relationship for the trunk. The implications of these findings for the risk of overexertion and disc tolerance in LBD risk have also been discussed.

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