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Spine Loading and Probability of Low Back Disorder Risk as a Function of Box Location on a Pallet

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ABSTRACT

It is widely believed that depalletizing operations in manufacturing and service environments substantially increase the risk of occupationally related low back disorders (LBDs). It has been established that the weight of the box lifted off a pallet can affect the risk of occupationally related LBD but few have considered the influence of the location of the box on the pallet (region) when assessing risk. Thus, the objective of this study was to assess spinal loading characteristics and the probability of high LBD risk as a function of box weight and its location on the pallet. Ten experienced order selectors were recruited from a local distribution center and were evaluated as they transferred boxes of different weights (40, 50, and 60 lb) from six different locations (regions) of a pallet to a pallet jack. Workers were monitored for their trunk motion characteristics as well as the electromyographic (EMG) activity of ten trunk muscles as they performed the task. Workplace factors as well as trunk kinematic and EMG information were used as inputs to: (1) a risk assessment model, and (2) an EMG-assisted model that was used to predict the three-dimensional spine loadings that occurred during the task. The results indicated that conditions where a worker must reach to a low level of the pallet increased spinal load and risk probability far more than changes in the weight of the box. Thus, spinal loads were significantly large in magnitude and would be expected to lead to an increase in low back disorders when workers lifted form the lowest layer of the pallet. The load moment was found to be strongly influenced by pallet region, which resulted in increased spinal loading and risk probability as the moment increased. This effort has also facilitated our understanding as to why spine loading increases under the various conditions studied in this experiment. Nearly all differences in spinal loading can be explained by a corresponding difference in coactivation of the trunk musculature. This in turn significantly increases the synergistic forces supplied by each muscle to the spine and results in an increase in spinal loading. © 1997 John Wiley & Sons, Inc.

1. INTRODUCTION

Depalletizing or "picking" orders from a pallet is an extremely common operation in many manufacturing and service sector operations. With the increase in "just-in-time" delivery systems for parts and products many items are stored in a warehouse facility until they are needed by a customer or manufacturing facility. In many warehouse facilities it is not uncommon for order selectors to spend their entire work day simply picking items from thousands of pallets and stacking them on a pallet jack to form an order that is then shipped to the customer or to a retail sales facility. In these types of situations it is often not feasible to automate the selection of items because of efficiency and cost concerns. Yet these environments represent work situations where occupationally related low

back disorders (LBDs) are common and costly. For example, order selection in the food industry has been associated with one of the greatest LBD rates in the United States. The National Association of Wholesale Grocers of America (NAWGA) and the International Foodservice Distribution Association (IFDA) disclosed that 30% of the injuries reported by food distribution warehouse workers were attributable to back sprains/strains (Waters, 1993). In addition, over a 5-year period, it was found that back injuries could account for nearly 60% of lost work days (National Institute for Occupational Safety and Health [NIOSH], 1993, 1995).

Depalletizing operations represent about one half of the manual materials handling tasks in such operations. Depalletizing is most often performed with no mechanical aids and can involve extended reaches to low as well as high vertical heights. The pallets may be palletized or stacked by an automated stacking system or by a worker using a lift table at a manufacturing facility and then delivered to the distribution facility. Thus, the contents of the pallet may be handled or moved by a human from various positions on the pallet for the first time at the distribution facility. Therefore, many materials handling problems may be avoided at the manufacturing facility but may present a substantial risk of LBD at the distribution facility.

Because workers must often lift with the body in extended reach positions (both horizontally as well as vertically) in these situations, it is suspected that the location of the object on the pallet as well as the weight of the object may be major determinants of the risk of injury to the worker. It has been known for some time that the initial height of a lift as well as the horizontal location of the object to be lifted both have a major influence on the loading of the spine and the risk of an occupationally related LBD. For example, the 1981 *Work Practices Guide for Manual Lifting* (NIOSH, 1981) as well as the 1991 *Revised Lifting Equation* (Waters et al., 1993) incorporate as major factors in their assessments vertical as well as horizontal load location indices (relative to the spine) to assess the acceptability of a manual materials handling situation. Thus, we suspect that spine loading as well as the risk of occupationally related LBD for depalletizing operations may vary widely as a function of where a load is located on a pallet. However, we have been unable to find assessments in the literature that describe quantitatively how the risk of LBD varies in workers as they lift from different pallet locations. Hence, the objective of this study was to observe spine loading and risk of occupationally related LBD as professional workers lifted objects of different weights from different locations on a pallet.

2. METHOD

2.1. Subjects

Ten experienced order selectors ages 19 to 49 years of age were recruited from a local food distribution center and were evaluated as they selected boxes from a slot (bin) on to a pallet jack. The average (SD) weight and stature of the workers was 176.3 lb (18.5 lb) and 71 in. (2.8), respectively. Their work experience in warehouse settings ranged from 0.25 to 23 years.

2.2. Experimental Design

The experimental design consisted of a two-way, within subject design. The *independent variables* included box weight and pallet region. Subjects served as a random effect. The

weights of the boxes in this study were 40, 50, and 60 lb. (18.2, 22.7, and 27.3 kg). These weights were at the upper percentiles of typical box weights in a common warehouse setting. Therefore, these weights were chosen to evaluate the effects of heavier loads on the low back and the subsequent changes in LBD risk parameters.

Each of the pallets were divided into six regions or locations corresponding to front-top, back-top, front-middle, back-middle, front-bottom, and back-bottom areas. Figure 1 shows a schematic view of these six regions on a standard pallet. The upper portion of the boxes in each of the regions remained at a set level corresponding approximately to: regions A and B at a height of 52.7 in. (133.8 cm) from the floor, regions C and D at a height of 37.5 in. (95.3 cm) from the floor, and E and F at a height of 18.75 in. (47.6 cm) from the floor. Regions B, D, and F were located approximately 22 in. (56 cm) away from the front of the pallet. The size of the box was held constant at 11 by 19.5 by 12 in. (H × W × D) with a corresponding volume of 2681 in^3. This box represents a typical "large" box found in a food distribution center. The number of boxes in each region consisted of either three or four boxes depending on the stacking pattern, which was alternated at each level (for pallet stability purposes).

Dependent variables consisted of probability of increased occupationally related LBD risk and spine loading characteristics. Probability of increased occupationally related LBD risk was assessed by the risk model developed by Marras et al. (1993, 1995). This is a multiple logistic regression model that observes five key trunk motion and workplace factors associated with a lifting task. The five key factors consist of: (1) external load moment, (2) lifting frequency, (3) trunk lateral velocity, (4) trunk twisting velocity, and (5) trunk sagittal flexion angle. The model compares these values to a data base of over 400 high-risk and low-risk industrial manual materials handling jobs and assesses the probability that the *combination* of these factors resembles a high-risk job situation. Thus, the model predicts the probability of high LBD risk group membership for a particular job and *will be referred to throughout this article as "risk probability."* The low-risk jobs

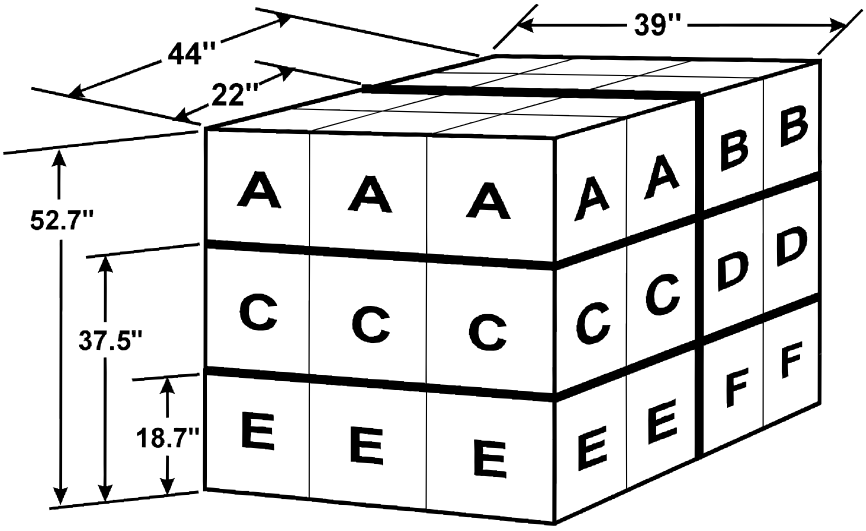

Figure 1 A schematic view of the six regions of the pallet.

in this data base are those jobs that have been observed over 3 years to have no LBD incidences. The high-risk jobs consisted of jobs that had at least 12 incidences of LBD per 200,000 h of exposure (mean of 26.4 incidences). The model results in an odds ratio of 10.7 (CI = 4.9–23.6) and is currently undergoing a prospective validation study.

The assessment of spine loading focused on the forces imposed on the lumbosacral junction (L5/S1) during the materials handling task. This low back location is where most back injuries occur. Spine loading variables of interest included maximum compression, lateral shear, and anterior-posterior (A-P) shear forces. These forces were predicted via the Biodynamic electromyography (EMG)-assisted model developed at the Ohio State University over the past decade (Granata and Marras, 1993, 1995a, 1995b; Marras and Granata, 1995, 1996; Marras and Reilly, 1988; Marras and Sommerich, 1991a, 1991b; Mirka and Marras, 1993; Reilly and Marras, 1989). The model uses kinematic information about the trunk along with electromyographic information about the trunk musculature to estimate spinal loads as well as predict the moments imposed on the spine in three-dimensional space. The maximum values of sagittal bending, lateral bending, and axial twisting moments were also assessed in this study.

2.3. Experimental Task

Workers were instructed to pick the entire compliment of boxes from the pallet so that they could be observed picking from all locations on a pallet. While the workers were lifting boxes they were being continuously monitored so that trunk motion and loading characteristics could be assessed.

In order to simulate a "realistic" warehousing depalletizing task, subjects transferred boxes from one pallet to another. The depalletizing task started when the subject grasped the box and ended when he crossed an imaginary line that coincided with the point at which the subject was upright and facing the "palletizing" pallet. Data were collected for only this interval of time, although subjects completed the task. The lifting rate for all subjects was set at 166 boxes handled per hour, which was determined from the minimum loading rate required at a local warehouse where the subjects were employed. The actual lifting cycle was one box lifted every 10 s (360 per hour), which was signaled by a computer tone; however, the actual lifting rate was adjusted to 166 lifts/h by including any down time (e.g., moving pallets, lunch, and additional rest breaks).

The boxes were stacked on a standard pallet generally found in a warehouse. The pallet was constructed of wood with a width of 40 in. (101.5 cm) and a depth of 44 in. (112 cm).

2.4. Apparatus

The Lumbar Motion Monitor (LMM) was used to collect kinematic information about the trunk for use by the EMG-assisted model as well as the risk model. The LMM is essentially an exoskeleton of the spine in the form of a triaxial electro-goniometer that measured instantaneous position, velocity, and acceleration of the trunk in three-dimensional space. The lightweight design of the LMM allowed the data be collected with minimal obstruction to the subject's movements. For more information on the design, accuracy, and application of the LMM, refer to Marras et al. (1993). Load moment information was collected (for use in the risk model) by measuring the horizontal distance between the load center of mass and L5/S1 and multiplying this value by the weight of the box lifted.

Electromyographic (EMG) activity was monitored via bipolar surface electrodes spaced approximately 3 cm apart at the ten major trunk muscle sites (Mirka and Marras, 1993). The ten muscles of interest were: right and left erector spinae; right and left latissimus dorsi; right and left internal obliques; right and left external obliques; and right and left rectus abdominis.

A force plate (Bertec 4060A) and a set of electro-goniometers measured the external loads and moments relative to L5/S1 during the various calibration exertions that permitted one to "tune" the model for the individual subject. The electro-goniometers measured the relative position of L5/S1 with respect to the center of the force plate, along with the subject's pelvic angle. The forces and moments were translated and rotated from the center of the force plate to L5/S1 in this manner (Fathallah, 1995).

All signals from the above equipment were collected simultaneously through customized Windows™-based software developed in the Biodynamics Laboratory. The signals were collected at 100 Hz and recorded on a 486 portable computer via an analog-to-digital board.

2.5. Statistical Analyses

Univariate analysis of variance (ANOVA) procedures were used to identify the statistically significant effects in this study. Significance was judged relative to an α level of 0.05. Post hoc analyses consisted of Tukey multiple pairwise comparisons.

3. RESULTS

3.1. LMM Risk

A summary of the risk analyses are shown in Table 1. The table indicates that overall risk as well as the behavior of four of the five risk factors that compose the risk model. The fifth risk factor component (lift frequency) was controlled in this experiment; thus, the variable was not assessed. The table indicates that overall probability of increased risk changed significantly as a function of box weight, box location (region), and weight and region interaction. Table 1 also indicates that the risk factors of trunk sagittal flexion angle, maximum lateral velocity, and load moment were significantly affected by both box weight and location. In addition, load moment was also affected by the box weight and location interaction.

The magnitude of the affected risk factors increased with increases in trunk moment. Figure 2 shows how imposed trunk moment was influenced by the combination of box

TABLE 1. LBD Risk Analysis—Significance Summary

	Maximum Sagittal Flexion	Average Twisting Velocity	Maximum Lateral Velocity	Maximum Moment	LBD Risk
Weight	0.005	0.245	0.001	0.000	0.0000
Location	0.000	0.052	0.000	0.000	0.0000
Weight × Location	0.953	0.288	0.542	0.000	0.0000

Note: Shaded cells represent effects significant at $\alpha = 0.05$.

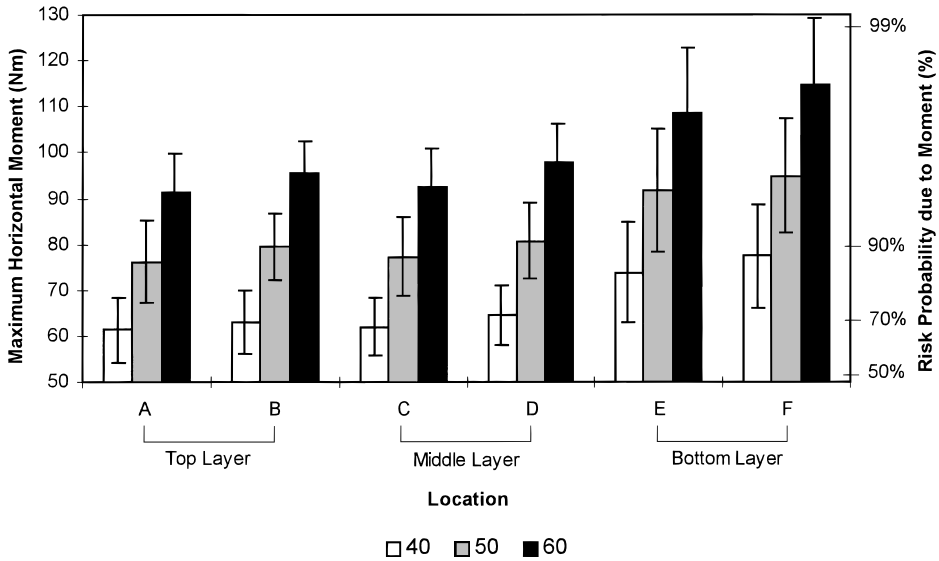

Figure 2 Maximum horizontal moment as a function of weight and location.

weight and region on the pallet. Overall, the load moment (defined as the box weight multiplied by the distance from the spine) was similar in regions A and C with the average moment in these regions between 76 and 77 Nm. Region B resulted in the next greatest moment (average 79 Nm) followed by region D (average moment of 81 Nm). However, the greatest average moments occurred in regions E (average 91 Nm) and region F (average 95 Nm). This analysis indicated that the greatest differences in moments imposed upon the spine was between regions A and F. For a given box weight the moment imposed upon the spine was on average over 25% greater when subjects lifted boxes from region F compared to region A. By contrast, increasing box weight by 10 lb within regions A or F increased moment by an average of just over 21%. It should also be noted that most of the moments, regardless of location, were on the upper end of the LBD risk factor probability scale. However, the moment associated with region F resulted in a risk factor value that maximally contributed to overall LBD increased risk probability.

Figure 3 shows how maximum sagittal trunk flexion angle varied as a function of the region of the box on the pallet. This figure indicates that a very significant and dramatic change in trunk sagittal position occurs as subjects lift from the different regions. Regions E and F resulted in the greatest trunk flexion angles. Maximum sagittal trunk flexion angles increased monotonically between regions A and F and increased by a total of over 31°. The risk probability scale in this figure indicates that the changes in the magnitude of this factor contributed greatly to the overall changes in risk probability estimates among the regions.

The maximum lateral trunk velocity risk factor behavior among the regions is shown in Figure 4. In general, the lateral trunk velocity observed in this study contributed moderately to the overall LBD risk because the values of the risk factor were generally between 20% and 40% of this component's risk value. The greatest values of this variable were observed in regions B and F, whereas the lowest values occurred in region C.

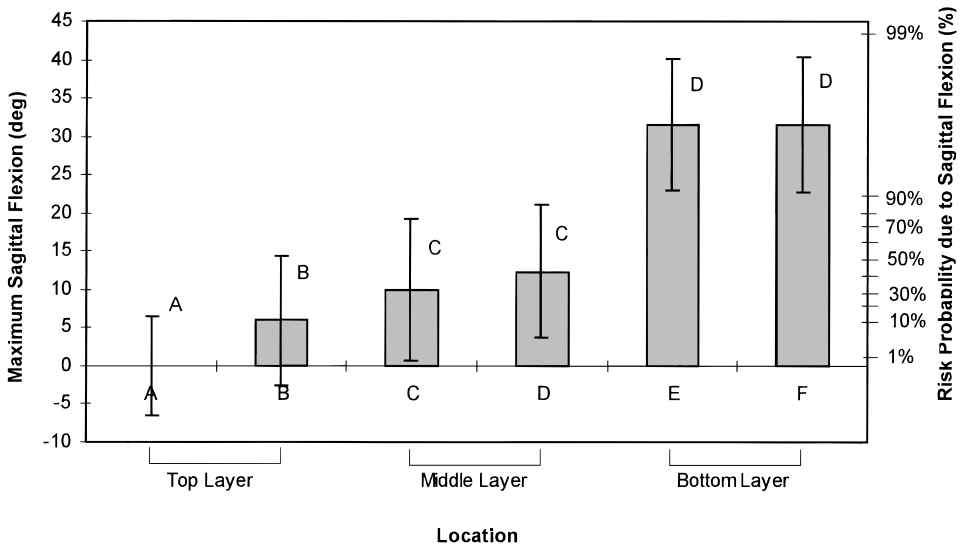

Figure 3 Maximum sagittal flexion as a function of location.

The overall probability of increased LBD risk, which considers the contribution of all the risk factor components to the increased probability of LBD risk, is shown in Figure 5. This figure indicates that overall risk probability increases significantly as one lifts from lower regions and more distant horizontal regions on the pallet. Within the 40-lb box weight, risk probability can increase from 0.4 in region A to 0.72 in region F. Similarly,

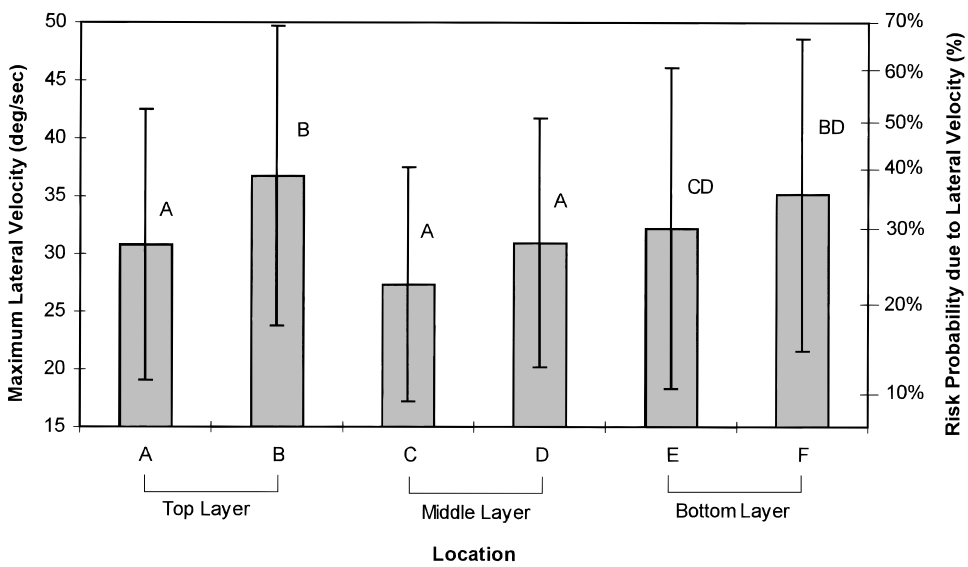

Figure 4 Maximum lateral velocity as a function of location.

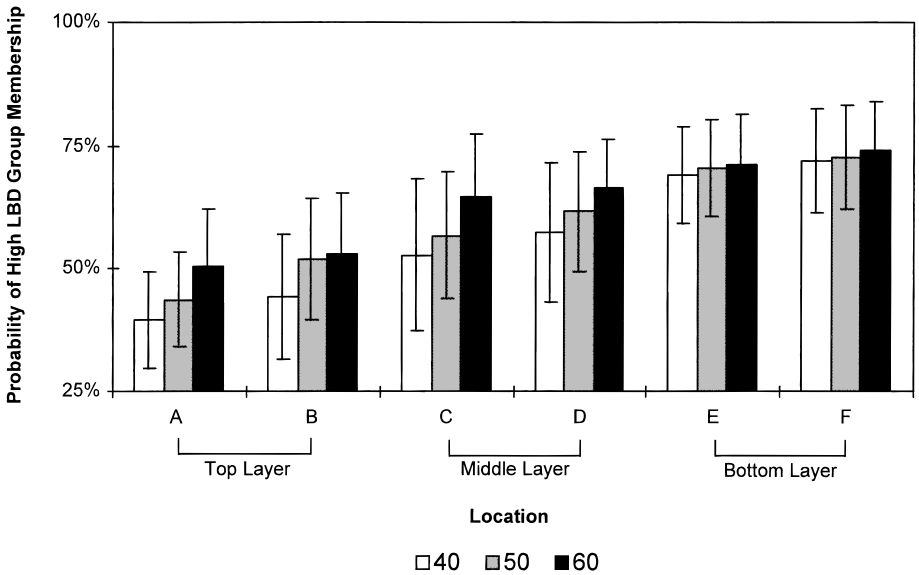

Figure 5 Overall LBD risk as a function of weight and location.

for a 60-lb box probability increases from 0.51 in region A to 0.74 in region F. This analysis indicates that the vertical component of the pallet region as well as the horizontal distance component of the pallet region play a role in defining risk. However, the horizontal distance contributes more to the probability of increased risk in regions A through D than it does in regions E and F because the effects of moment tend to saturate risk probability in regions E and F. In addition, the vertical component of region significantly increases risk probability as one lifts from lower vertical location levels.

3.2. Spinal Loads

The results of the ANOVA, which evaluates the influence of the box characteristics and box location upon spinal loading, are shown in Table 2. The analysis indicated that spinal loading responded in a statistically significant manner to changes in box weight as well as changes in position of the box on the pallet (region). Specifically, spine compression, anterior shear, and lateral shear were significantly affected by box weight as well as the

TABLE 2. Spinal Loading—Significance Summary

	Maximum Lateral Shear Force	Maximum A-P Shear Force	Maximum Compression Force
Weight	0.003	0.006	0.001
Location	0.016	0.000	0.000
Weight × Location	0.738	0.095	0.000

Note: Shaded cells represent effects significant at $\alpha = 0.05$.

region of the pallet from which the box was lifted. Only compression was affected by the interaction of these two variables.

As with LBD risk probability, the relationship between box weight and spine loading behaved as expected. Increasing the box weight by 10 lb increased spinal compression by an average of 446 N, and lateral and anterior shear by an average of 74 and 86 N, respectively. Figure 6 shows that lateral shear increased as subjects lifted from lower regions with the largest difference in shear occurring between regions A and the lower two regions (E and F). The anterior shear behavior was a bit more complex. Figure 6 also shows that anterior shear was greater in regions E and F with the average anterior shear force approaching the spine tolerance of 1000N for shear force (McGill, 1996).

Spinal compression increased linearly with box weight and monotonically (except for region B) with region. A slight increase in average compression (149 N) was observed when lifting from region B compared to region C. Because subjects lifted layer by layer, a greater horizontal moment was necessary, which typically involved a lateral reach when lifting from this location. The interaction of region with box weight on spine compression is shown in Figure 7. Compressive loads vary from an average of 1225 N when lifting 40-lb boxes in region A to an average of 5453 N when lifting 60-lb boxes in region F. Within a box weight, region had a profound influence on compressive load. The average increase in compressive load between regions A and F was 3325 N, representing a 126% increase in compressive loading for the same box weight. These differences can be explained, in part, by the increase in the moment supported by the spine. Figure 8 shows the resultant spinal moment predicted by the model as a function of box weight and region. This moment varies from the moment described in Figure 2 in that this moment includes the effects of box dynamics (inertial effects), whereas the moments described in Figure 2 are static moments.

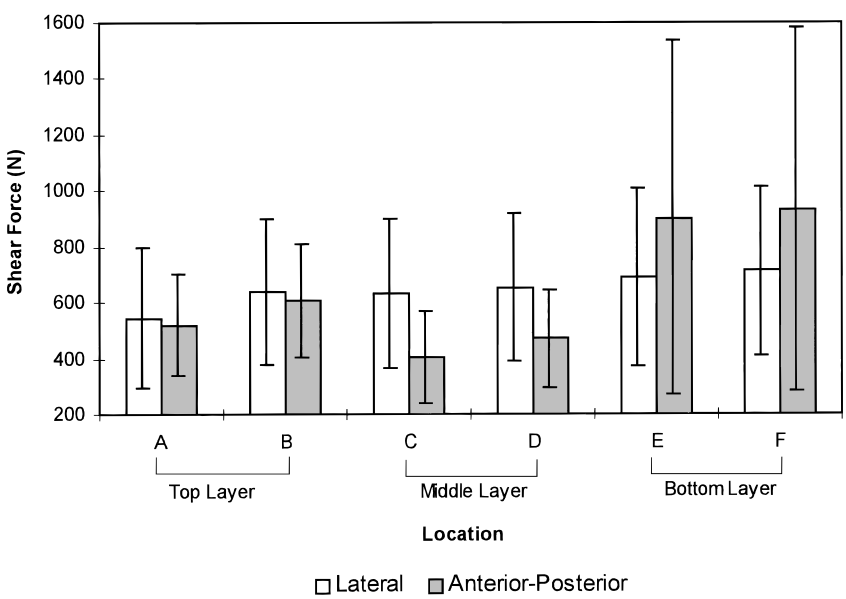

Figure 6 Maximum lateral and anterior-posterior shear forces as a function of location.

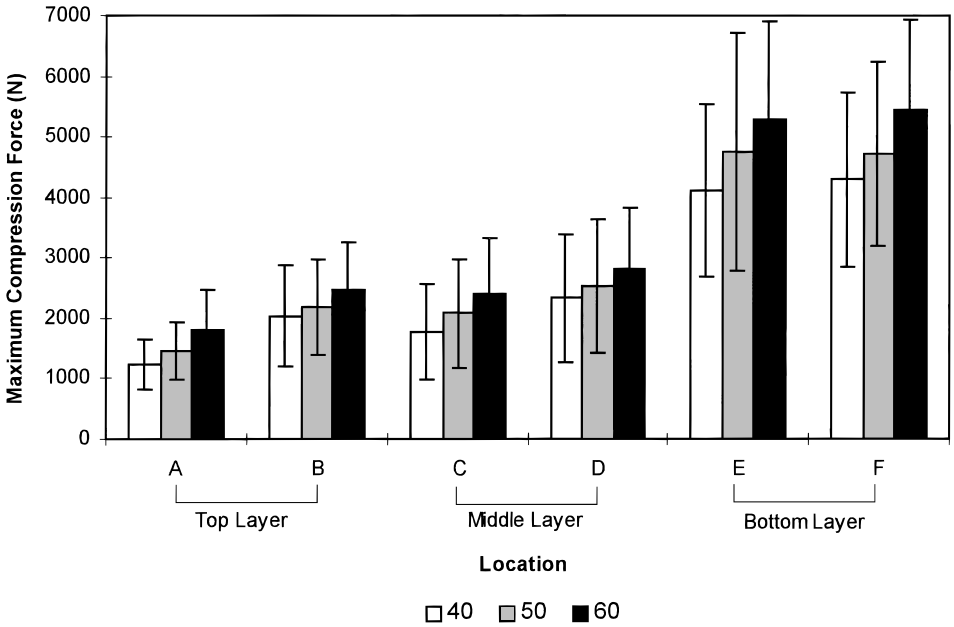

Figure 7 Maximum compression force as a function of weight and location.

4. DISCUSSION

This work has facilitated our understating of which specific conditions in a depalletizing operation contribute to increased spinal loading and increased probability of LBD risk. This analysis has shown that the location of the box on the pallet is a far greater determinant of spine loading and risk than the weight of the box alone. The LBD risk analysis has indicated that lifting a box from low and distant locations (regions E and F) imposes nearly twice the risk probability as lifting the same weight box from a more desirable location (region A or C). In addition, few lifts resulting in compression forces over 3400 N (typically less than 30% of the observations regardless of box weight) were observed at the top or middle layer lifts. However, 97% of the lifts from the lower layer of the pallet resulted in spine compression values above 3400 N and would be expected to increase the risk of an occupationally related low back disorder (NIOSH, 1981).

As expected, as box weight increases, spine loading increases on average by about 470 N for every 10-lb increase in box weight. However, the increase in loading was far more dramatic when one considers the relative increase in loading as a function of box weight increases at the lower levels of the pallet (weight $\times$ region interaction). For example, the average increase in compression for each 10-lb increase in box weight in region F (bottom layer) was greater than 655 N or a 130% increase in spine compression per 10-lb increase in box weight over what was seen in region A (top layer). Thus, the position from which one lifts appears to be of more importance to spine loading than the mere weight of the box alone.

Distant locations on a pallet typically require the worker to reach farther, thereby increasing the mechanical moment arm of the worker-environment system. This empha-

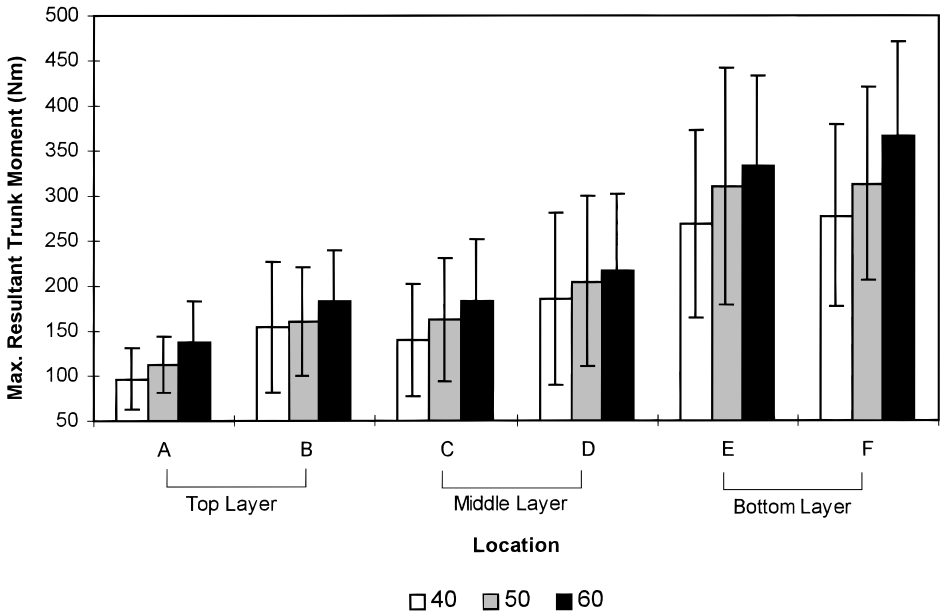

Figure 8 Maximum resultant trunk moment as a function of weight and location.

sizes the importance of considering moment as opposed to object weight alone when assessing the risk of LBD as a function of the job. The significance of this load moment effect was also apparent when subjects lifted from region B (Figures 2 and 8). Lifts from this location also required a significant horizontal reach. Previous studies have also indicated that moment is an important indicator of job risk (Chaffin and Page, 1994; Marras et al., 1993). In general, conditions where a worker must reach to a low level also increase the moment arm significantly and, thus, increases spinal load significantly. This fact in itself is not new. However, we have now been able to document that within these box weight ranges the lowest level of the pallet is the level that primarily presents substantial risk. Lifting the same load from a higher location imposes lower risk probability on the worker. In addition, we have now been able to quantitatively assess the degree or magnitude of spine loading that occurs once one bends down to the lowest level of a pallet. These findings also imply that current lifting guides should reevaluate the dramatic influence of this vertical factor upon safe lifting limits.

This study has facilitated our understanding of how LBD risk probability might be associated with spine loading. Traditionally, spine compression has been of interest in most biomechanical assessments of lifting. However, this study has shown that spine anterior/posterior shear as well as lateral shear change dramatically as risk probability changes. Even though the magnitude of these shear related changes are not great compared to changes in compression, one must consider the fact that the tolerance of the spine to shear is typically much lower than the tolerance of the spine to compression. Thus, the relative changes in shear may approach spine tolerance limits much more rapidly than with changes in compression. These observations imply that true biomechanical risk may be more a function of a combination of spine loading (compression combined with shear) as opposed to just compression alone.

This effort has also facilitated our basic understanding as to why spine loading increases under the various conditions studied in this experiment. Further analyses of these data indicated that nearly all differences in spinal loading were explained by a corresponding difference in coactivation of the trunk musculature. When workers bend to the lower levels of the pallet they must cocontract their muscles in order to increase trunk stability. This increase in cocontraction implies that the muscles within the trunk contract simultaneously, thereby opposing each other and decreasing their efficiency. This process, in turn, increases the loading of the spine. This finding adds an additional mechanism of loading to the long-held belief that forward bending was hazardous because of the reduction in muscle strength that occurs with trunk flexion due to the length-strength relationship of the trunk musculature. A combination of these two effects may explain why LBD risk probability increases at these low levels of lifting.

These findings have several implications for the design of the distribution workplace. First, distribution facilities would benefit most from raising the pallets off the floor so that the lowest lift performed would correspond to region C (about 48 cm off the floor). However, given the number of pallets in a distribution center and the value of floor space solutions such as lift tables may be unfeasable. Future efforts might explore whether there is a range of pallet heights that would significantly reduce the risk that would be lower than 48 cm.

Second, this study has shown that solutions such as turntables would be of limited value. They would help in region B but they would help little in region F (since load and risk are similar in regions E and F) where the most significant risk and loading resides.

Third, a practical alternative may be the inclusion of handles on the boxes. The strong influence of region also implies that handles may have a profound effect on reducing spinal loading and risk of LBD because they can have the effect of raising the location of the box on the pallet. This might be especially beneficial if handles are combined with double pallets, which would also effectively raise the height of the lift. This implication is supported by the work of Davis, Marras, and Waters (1996), who have shown that spine loading can be greatly reduced by the introduction of handles in a lift.

This study also has implications for the design of manufacturing facility workplaces. It is common in manufacturing facilitates for workers to reach into bins located on the floor. This study has helped us understand the risk of LBD and loading that occurs on the spine when workers reach to far and low regions of the bin.

Several limitations of this study should also be acknowledged. First, this study only observed box handling. In many distribution environments bags and other containers are handled. Even though we would expect the general trend to be similar to that found here, we are unable to estimate how the magnitudes of the loading and risk probability might change with variations in container design.

Second, this study has shown that raising the pallet off the floor would be beneficial in terms of lifting from the lower regions of the pallet. However, we did not explore the effects of lifting from levels higher than those of levels A and B (133.8 cm off the floor). We expect that reaching to levels above this level would also increase the risk and spine loading because this situation would also increase coactivation as well as tax the trunk muscles length-strength relationship. Thus, one must not generalize the results of this study to regions not explored in this study.

Third, in this study we observed workers lifting from a “full slot.” In other words, the vertical clearance in the slot was 72 in. so that subjects would step into the slot. Many slot locations in distribution centers are only 40 in. tall. Thus, in these situations the worker

would be expected to bend and reach even more than observed in this study. This would be expected to increase spine loading and LBD risk even further.

Finally, subjects were instructed to lift the boxes on a pallet layer by layer as recommended in most distribution centers. However, when unsupervised workers in distribution facilitates often depalletize in a "pyramid" fashion, selecting whatever box is closest to them. This would probably reduce the risk and spine loading observed in regions B and D because workers would be stepping closer to the box and would not be required to reach as far, thereby reducing the external moment imposed upon the spine.

5. CONCLUSIONS

This study has observed the effect of box weight and box location on a pallet in the assessment of LBD risk probability and spine loading of workers in distribution center environments. This study has shown that the location of the box on the pallet is a more important indicator of LBD risk probability and spinal loading than the weight of the box. The lower regions of the pallet were identified as most problematic areas for lifting. In addition, when box weight increases at these low regions the risk of LBD and spinal loading increases substantially, whereas, increases in box weight at the higher regions of the pallet are associated with little increases in LBD risk and loading. This study has been able to quantify the changes in risk and spine loading as a function of these parameters. Based upon these findings some practical solutions for the design of distribution centers have been suggested.

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REFERENCES

Chaffin, D.B. and Page G.B., 1994, Postural effects on biomechanical and psychophysical weight-lifting limits, *Ergonomics*, **37**(4), 663–676.

Davis, K.G., Marras, W.S., and Waters, T.R., 1996, Reduction of spinal loading through the use of handles, *Ergonomics*, (in review).

Fathallah, F.F., 1995, Coupling spinal motion and spinal loading in industrial tasks. Unpublished doctoral dissertation, The Ohio State University, Columbus, OH.

Granata, K.P. and Marras, W.S., 1993, An EMG-assisted model of loads on the lumbar spine during asymmetric trunk extensions, *Journal of Biomechanics*, **26**(12), 1429–1438.

Granata, G.P. and Marras, W.S., 1995a, An EMG-assisted model of trunk loading during free-dynamic lifting, *Journal of Biomechanics*, **28**(11), 1309–1317.

Granata, G.P. and Marras, W.S., 1995b, The influence of trunk muscle coactivity upon dynamic spinal loads, *Spine*, **20**(8), 913–919.

Marras, W.S. and Granata, K.P., 1995b, A biomechanical assessment and model of axial twisting in the thoraco-lumbar spine, *Spine*, **20**(13), 1440–1451.

Marras, W.S. and Granata, K.P., 1996, An assessment of spinal loading during lateral trunk motions, *Journal of Biomechanics*, (in review).

Marras, W.S., Lavender, S.A., Leurgans, S., Rajulu, S., Allread, W.G., Fathallah F. and Ferguson, S.A., 1993, The role of dynamic three dimensional trunk motion in occupationally-related low back disorders: the effects of workplace factors, trunk position and trunk motion characteristics on injury, *Spine*, **18**(5), 617–628.

Marras, W.S., Lavender, S.A., Leurgans, S., Fathallah, F., Allread, W.G., Ferguson, S.A., and Rajulu, S., 1995, Biomechanical risk factors for occupationally related low back disorder risk, *Ergonomics*, **38**(2), 377–410.

Marras, W.S. and Reilly, C.H., 1988, Networks of internal trunk loading activities under controlled trunk motion conditions, *Spine*, **13**(6), 661–667.

Marras, W.S. and Sommerich, C.M., 1991a, A three dimensional motion model of loads on the lumbar ppine: I. Model structure, *Human Factors*, **33**(2), 129–137.

Marras, W.S. and Sommerich, C.M., 1991b, A three dimensional motion model of loads on the lumbar spine: I. Model validation, *Human Factors*, **33**(2), 139–149.

McGill, S.M., 1996, Searching for the safe biomechanical envelope for maintaining healthy tissue, Pre-Meeting Workshop, International Society for the Study of the Lumbar Spine (ISSLS): The Contribution of Biomechanics to the Prevention and Treatment of Low Back Pain, University of Vermont, June 25.

Mirka, G.A. and Marras, W.S., 1993, A stochastic model of trunk muscle coactivation during trunk bending, *Spine*, **18**(11), 1396–1409.

National Institute for Occupational Safety and Health (NIOSH), 1981, Work practices guide for manual lifting. Department of Health and Human Services (DHHS), National Institute for Occupational Safety and Health (NIOSH), Publication No. 81–122.

National Institute for Occupational Safety and Health (NIOSH), 1993, Interim Report, HETA 91–405, March 1992.

National Institute for Occupational Safety and Health (NIOSH), 1995, HETA 93–0920–2548.

NAWGA and IFTA (1992) Voluntary Ergonomics Program management Guidelines, National American Wholesale Grocers' Association and International Foodservice Distribution Association.

Reilly, C.H., and Marras, W.S., 1989, SIMULIFT: a simulation model of human trunk motion during lifting, *Spine*, **14**(1), 5–11.

Waters, T.R., Putz-Anderson, V., Garg, A., and Fine, L.J., 1993, Revised NIOSH equation for the design and evaluation of manual lifting tasks, *Ergonomics*, **36**(7): 749–776.

Waters, T.R., 1993, Workplace factors and trunk motion in grocery selector tasks. In *Proceedings of the Human Factors and Ergonomics Society 37th Annual Meeting*, October 11–15, 1993, Seattle, WA, pp. 654–658.