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Effects of box features on spine loading during warehouse order selecting

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Low back disorders in distribution centres or warehouses have been identified as an area of elevated risk in many industries. The task of an order selector requires workers manually to lift boxes from storage bins to a mobile pallet. This study explored the effect of box features and box location when lifting from a pallet in a storage bin upon spine loading. Ten experienced warehouse workers were asked to lift boxes from a pallet while the size, weight, handle features and location of the box on a pallet were changed. An EMG-assisted model was employed to assess spine compression, lateral shear and anterior-posterior shear during the lifts. The position from which the worker lifted a box on a pallet had the most profound effect on spine loading while the lower level of the pallet represented the greatest loadings on the spine. Box weight did not appear to be a feasible means of controlling spine loading unless its position on the pallet could also be controlled. The inclusion of handles had an effect similar to reducing the box weight by 4.5 kg, whereas box size did not effectively affect spine loading. The mechanisms by which these factors affect spine loading are discussed.

1. Introduction

Low back disorders (LBD) continue to represent the most common and most costly musculoskeletal disorder experienced in the workplace (Hales and Bernard 1996). Many of these LBDs are associated with occupational factors (Spengler *et al.* 1986) and significantly increase workers' compensations costs. For example, LBDs account for approximately 16 – 19% of all workers' compensation claims, but 33 – 41% of the total cost of all work compensation costs (Spengler *et al.* 1986, Webster and Snook 1994).

Manual material handling (MMH) tasks have been associated with the majority of lower back injuries (Snook *et al.* 1978, Bigos *et al.* 1986). These tasks often require the worker to be exposed to several known risk factors including lifting, bending, twisting motions, lateral bending motions, maintenance of static postures, carrying heavy loads, and combinations of these (Bigos *et al.* 1986, Snook *et al.* 1978, Kelsey *et al.* 1984, Keyserling *et al.* 1991, Marras *et al.* 1993). One of the most common MMH tasks, especially in warehouses or distribution centres, consists of palletizing and depalletizing, which can be defined as the transferring and stacking of material (boxes and bags) onto pallets. These tasks continue to employ manual labour because it remains a cost-effective method of material transfer (Drury *et al.* 1989).

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The National Association of Wholesale Grocers of America (NAWGA) and the International Foodservice Distribution Association (IFDA) report that 30% of the injuries reported by food distribution warehouse workers were attributable to back sprains/strains (Waters 1993). Hence, grocery item selectors have an incidence of LBD at least as high as other MMH jobs. Thousands of workers are employed in the food distribution industry, with most being male (Waters 1993). The job of the grocery item selector requires lifting and lowering during the transferring of various containers (boxes and bags) from pallets located in storage bins throughout the warehouse to a pallet which is generally positioned on the front of a motorized fork truck along the storage bins.

The boxes handled in food distribution centres vary in size and weight. Drury *et al.* (1982) evaluated box characteristics and found the median box size to be 28.0 cm long, 20.5 cm wide and 21.5 cm high. The effects of box size on the maximum acceptable weight of lift (MAWL) have been evaluated by several researchers (Garg and Saxena 1980, Snook and Ciriello 1991). These studies have shown that as the depth of the box increases, MAWL decreases. In theory, the larger the depth (in the sagittal plane) of the box, the larger the moment arm about lumbosacral joint (L_5/S_1).

Additionally, the weights of the boxes vary drastically depending upon the material contained inside, with about 6% of the boxes > 23 kg (50 lb) (Marras *et al.* 1996). Numerous studies have indicated that box weight is an important factor in LBD risk (Herrin *et al.* 1986, Marras *et al.* 1993, 1995). However, a more significant consideration might be the moment imposed about the spine during the lift as opposed to box weight alone. An increase in moment arm or weight would result in an increase in external moment, which has been directly linked to increases in muscle activity, and, ultimately, increases in spinal loading (compression and shear forces) (Chaffin and Baker 1970, Chaffin and Park 1973, Andersson *et al.* 1976, NIOSH 1981, Schultz and Andersson 1981, Seroussi and Pope 1987, Marras and Mirka 1990, Marras and Sommerich 1991b, Waters *et al.* 1993).

While the majority of the boxes transferred have no handles, those boxes that do have handles are usually cutouts in the two ends of the box (Drury *et al.* 1982). In 1991, NIOSH developed a lifting equation that incorporated new factors for handle coupling and task asymmetry. A wide range of research investigating the effects of

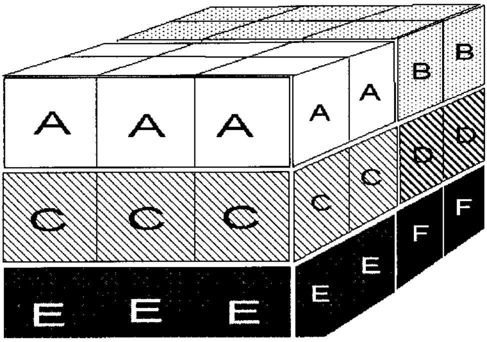

Figure 1. Schematic view of the six regions of the pallet (A, front-top; B, back-top; C, front-middle; D, back-middle; E, front-buttom; F, back-bottom).

handles during lifting has been conducted using psychophysical methodology (Garg and Saxena 1980, Smith and Jiang 1984). However, this method has not been validated by correlating MAWL values to actual incidence rates (Leamon 1994). Few studies have investigated the effects of handles on loading of the spine. Freivalds *et al.* (1984) employed a biomechanical model to estimate the effects of spine loading due to handle use. They found loading increased with handles. However, the model only evaluated the effects of loading due to one muscle in the back and the investigation was performed under conditions that do not match those seen in industry.

Another factor that might significantly affect spine loading and risk of injury is position of the box on the pallet. The position of the box on the pallet might affect the external moment arm distance and corresponding trunk moments. Boxes at the back of the pallet might require larger moment arms about L_5/S_1, resulting in larger trunk moments. This could especially be the case when the worker cannot step on the pallet. Although the effects of external moment on spinal loading have been well documented, the trade-offs associated with changes in moment arm resulting from variations in box size, weight, handle presence and position on a pallet during warehouse order selecting have not been investigated. Thus, it is hypothesized that box features may affect the moment arm, trunk moment, and ultimately, spine loading.

The assessment of spinal loading has evolved from very simple two dimensional static models to complete three-dimensional dynamic models with numerous trunk muscle inputs. We have developed an electromyographic (EMG)-assisted model that is well suited to evaluate dynamic lifting under realistic work conditions (Marras and Reilly 1988, Reilly and Marras 1989, Marras and Sommerich 1991a,b, Granata and Marras 1993, 1995, Marras and Granata 1995, 1997, Davis *et al.* 1997). Therefore, the objective of the current study was to employ biomechanical load assessment measures to evaluate the effect of transferring boxes (depalletizing) of different size, weight, and handle conditions from different positions on a pallet.

2. Methods

2.1. *Subjects*

Ten male subjects who worked as item selectors at a local warehouse volunteered to depalletize/palletize boxes with various features. The subjects' ages ranged from 19 to 49 years (average 27.2 years), with a work experience range of 0.25 – 23 years in a warehouse setting. The average (SD) height of the selectors was 180.3 (7.1) cm and the average weight was 89.1 (8.4) kg.

2.2. *Experimental design*

The experimental design used a four-way, within-subject design. The independent variables were: (1) box size; (2) box-handle coupling; (3) box weight; and (4) pallet region. Subjects served as a random effect. Two sizes of boxes were evaluated in this study – a 'small' box with dimensions of 20.3 × 40.6 × 30.5 cm (H × W × D) and a 'large' box with dimensions of 28 × 49.5 × 30.5 cm, which corresponded to volumes of 4023 and 6810 cm^3, respectively. Handle conditions consisted of (1) boxes with cut-out handles and (2) boxes without handles. The cut-out handles were 8.9 cm wide and 2.5 cm high, positioned at the centre of the longer sides of the boxes, 5.1 cm below the top of the box. The position and size of the handles were similar to those commonly found on boxes used in warehouse environments. The weights of the boxes in this study were 18.2, 22.7 and 27.3 kg respectively. These weights were at the upper percentiles of typical box weights found in a common warehouse setting. Therefore, these weights were chosen to evaluate the effects of heavier loads on the low back and the subsequent risk of LBD.

Each of the pallets were divided into six regions 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 handles of the boxes in each of the regions remained at a set level corresponding approximately to front-top and back-top regions at 133.8 cm from the floor; front-middle and back-middle regions at 95.3 cm from the floor; and front-bottom and back-bottom regions at 47.6 cm from the floor. The number of boxes in each region depended on the size of the box. A pallet of large boxes had four boxes in front-top region, three boxes in back-top region, and seven boxes in regions front-middle, back-middle, front-bottom, and back-bottom, while the pallets of small boxes had eight boxes in each of the six regions.

The boxes were stacked on a standard pallet generally found in a warehouse with a width of 101.5 cm and a depth of 112 cm. The small box conditions used a double-stacked pallet to allow the handles of the boxes in various regions to correspond to the heights of the large boxes which were stacked on a single pallet. The height of the fully loaded pallet was 138 cm. The small boxes contained boxes of salt while the large boxes contained plastic bottles of water. In order for the boxes to have the desired weight, specific amounts of material were removed from the inside containers (e.g. water was drained from the centre bottle). The pallets of small boxes contained six rows of ten boxes, while pallets of the large boxes comprised five rows of seven boxes.

The dependent variables associated with spinal loading were evaluated using an EMG-assisted biomechanical model (Marras and Reilly 1988, Reilly and Marras 1989, Marras and Sommerich 1991a,b, Granata and Marras 1993, 1995, Mirka and Marras 1993, Marras and Granata 1995, 1997, Davis *et al.* 1997). The spinal loads estimated in this study were the maximum values of compression force, anterior-posterior (A/P) shear and lateral shear forces on the lower back at the lumbosacral joint. The trunk moments included the maximum values of sagittal bending, lateral bending, and axial twisting moments.

2.3. *Task*

To simulate a ‘realistic’ warehousing depalletizing task, subjects transferred boxes from one pallet to another. The depalletizing task started when the participant grasped the box from the pallet in the storage bin and ended when he crossed an imaginary line that coincided with the point at which the participant was upright and facing the ‘palletizing’ pallet (pallet in the aisle where the boxes will be stacked). Data were collected for only this interval of time, although subjects completed the task. An overhead view of the arrangement is shown in figure 2.

The lifting rate for all subjects was set at 166 boxes handled per h and was determined from the minimum loading rate required at the local warehouse where the subjects were employed. The actual lifting cycle was one box lifted every 10 s (360 per h) which was signalled by a computer tone; however, the actual lifting rate was adjusted to 166 lifts/h by including any down time (e.g. moving pallets, filling out body part discomfort surveys by the subjects, lunch, and additional rest breaks).

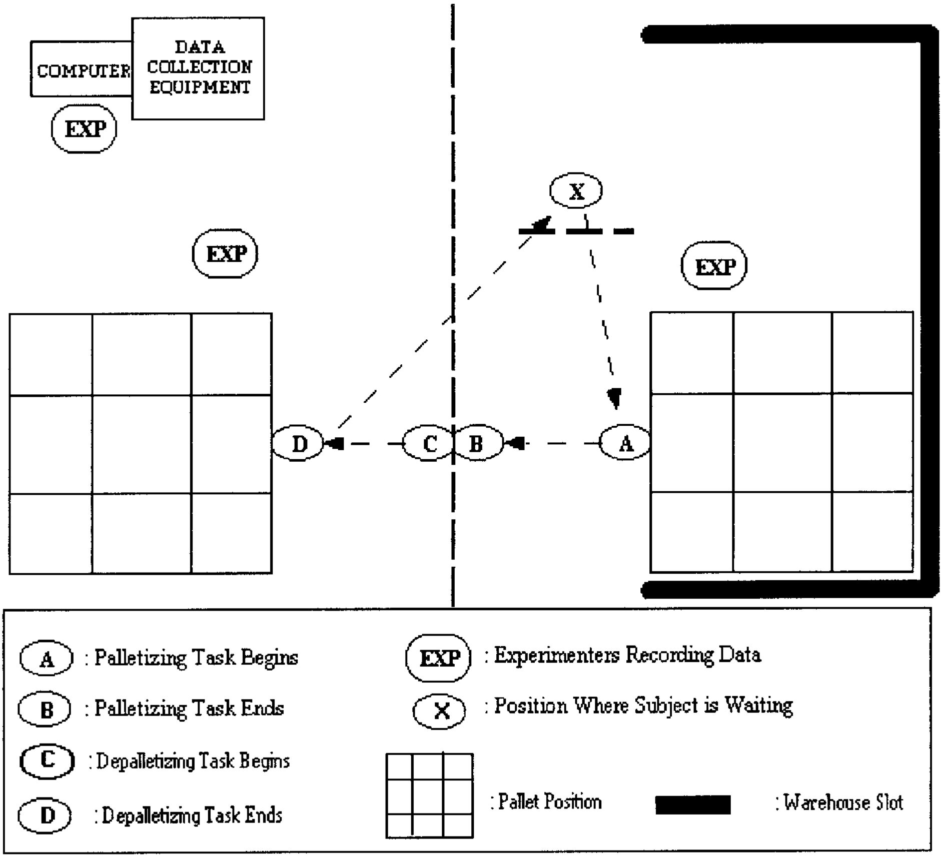

Figure 2. Schematic view of the experimental layout.

2.4. *Apparatus*

The lumbar motion monitor (LMM) was used to collect the trunk motion variables. It is essentially an exoskeleton of the spine in the form of a triaxial electrogoniometer that measured instantaneous three-dimensional position, velocity and acceleration of the trunk. The light-weight design of the LMM allowed the data to be collected with minimal obstruction to the subject's movements. For more information on the design, accuracy, and application of the LMM, see Marras *et al.* (1992).

Electromyographic (EMG) activity was monitored through the use of bipolar electrodes spaced approximately 3 cm apart at the ten major trunk muscle sites. The muscles 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 abdominus. For the standard locations of electrode placement for these muscles, see Mirka and Marras (1993).

A force plate (Bertec 4060A; Worthington, OH, USA) and a set of electrogoniometers measured the external loads and moments placed on L_5/S_1 during the various calibration exertions. The purpose of the calibration exertions was to determine the individual gain to be used in the 'open-loop' exertions. 'Open-loop' referred to exertions that use a predetermined gain (muscle gain represents the maximum force per unit area of muscle) to calculate internal moments and forces, rather than calculating a specific gain for each exertion. The electrogoniometers measured the relative position of L_5/S_1 with respect to the centre of the force plate, along with the subject's pelvic angle. The forces were translated and moments were rotated from the centre of the force plate to L_5/S_1 through the use of the electrogoniometers (Fathallah *et al.* 1997).

All signals from the aforementioned equipment were collected simultaneously through customized Windows$^{\mathrm{TM}}$-based software developed in the Biodynamics Laboratory. The signals were collected at 100 Hz and recorded on a 486 portable computer via a 16-bit analogue-to-digital board.

2.5. *Procedure*

Upon arriving at the Biodynamics Laboratory, subjects were given a brief description of the study and what they would be required to do. Subjects read and signed a consent form. Next, anthropometric measurements were taken. The surface electrodes then were applied using proper placement procedures to sample the muscles of interest. Skin impedances were kept $< 1\ \mathrm{M}\mu$. The participant was placed into a stable structure that allowed maximum exertions to be performed in six directions, while a constant resistance was held against the participant. These maxima were performed to allow all subsequent EMG data to be normalized. The six exertions consisted of: sagittal extension with the trunk at a 20° forward flexion angle; sagittal flexion at 0° flexion; right lateral flexion at 0° flexion; left lateral flexion at 0° flexion; right twist at 0° flexion; and left twist at 0° flexion. After each maximum exertion, 2 min of rest were given, in accordance with past research (Caldwell *et al.* 1974).

Before handling each pallet of boxes, the participant completed a set of calibration lifts to determine muscle gain. During the calibration exertions, the participant lifted a 22.7 kg box from a sagittally symmetric position at a slow, smooth pace (controlled by the participant). The lift started at the subject's knee height and ended in his upright position. The calibration lifts were run under 'closed-loop' conditions; that is, internal moments were validated with measured external moments. The model performed well with physiologically reasonable gains (average = 28.4 N/cm^2), high R^2 (average = 0.87) and low average absolute error (average = 21.9 Nm) for the calibration exertions. Before and after each set of calibrations, data were collected to determine the position of the LMM and the relative position of L_5/S_1 to the centre of the force plate measured by the electrogoniometers for each participant standing erect.

Subjects then were instructed as to how to transfer boxes from one pallet to another, that is, the order of the boxes to be lifted and not the style of lifting. In general, subjects unloaded boxes from left to right and from front to back. The participant was instructed not to begin depalletizing a new row until the current row was completely finished. A computer-generated tone sounded to indicate the participant was to begin lifting the next box. After one box was transferred, the participant returned to a designated spot marked on the floor to await the next tone. This procedure allowed the experimenters to control the lifting rate of each participant. The subjects were only allowed to step on the pallet for the bottom layer and were permitted to slide the boxes forward for the upper layers.

The pallets' positions corresponded to the positions commonly found in a grocery warehouse setting. Each participant transferred all boxes on a pallet for all the combinations of independent variables (e.g. 12 pallets total). The order in which these 12 pallets were handled was randomized for each participant, and each participant completed all 12 pallets on the same day.

2.6. *Data analyses*

The LMM voltages were converted into angles, velocities and accelerations through a customized conversion software. The kinematic data were used in the EMG-assisted spinal load model. The raw EMG signals were preamplified, high-passed filtered at 30 Hz, low-passed filtered at 1000 Hz, rectified, and integrated via a 20 ms sliding window hardware filter. The EMG data were normalized with respect to the maximum output of the muscles (obtained at the beginning of the testing) and muscle length – strength and force – velocity modulations by a customized software program (Granata and Marras 1993, Davis *et al*. 1998a). The EMG, kinematic, and 'closed loop' muscle gain data were imported into the EMG-assisted model to calculate spinal forces and moments on the lumbosacral joint.

Descriptive statistics were computed for all of the dependent variables. Analysis of variance (ANOVA) statistical analyses then were performed on all the dependent variables. For all significant independent variables, *post-hoc* analyses, in the form of Tukey multiple pairwise comparisons, were performed to determine the source of the significant effect(s).

3. Results

The ANOVA analysis indicated that compression as well as both shear forces (lateral and A/P) were significantly influenced by box weight and the position of the box on the pallet. The presence of handles was found to affect the level of A-P shear and compression force while box size only had an effect on the A-P shear force. In addition, interactions of box size and handle with region resulted in statistically significant differences for all three spine loading measures. A/P shear and compression both responded in a statistically different manner to the various handle conditions and the weight by region interaction. Finally, A/P shear responded differently to the size conditions. Table 1 summarizes the statistically significant differences that were observed.

As expected, as the box weight increased, spine loading in all three directions increased. Figure 3 shows that each loading measure increased by about 15% for each 4.5 kg increase in box weight (slightly more for A/P shear). However, this figure also indicates a large amount of variation associated with each loading parameter. In other words, because of the large distributions of forces, an 18.2 kg box often produces loads on the spine that are very similar to a 27.3 kg box. It appears that the spine loading distributions have a great deal of overlap (as evidenced by the standard deviation bars in figure 3) between the box weight conditions.

The position of the box on the pallet (its region) can explain much of the overlap in spine loadings observed as a function of box weight. Figure 4 shows how spine compression varies as a function of the box location. This figure indicates that there is a significant increase in spine compression in front-bottom and back-bottom regions of the pallet. Specifically, the spine loading distributions are significantly shifted upward at these lower levels of the pallet. Similar trends were observed for A/P shear and lateral shear, however, the magnitudes of the loads were smaller with lateral shear displaying the lowest magnitude of loading in all pallet positions.

The interaction of the box weight and region indicated that the weight of the box was more of a problem at the lower regions of the pallet than at the upper or middle layers of the pallet. Figure 4 shows that the greatest compression force occurred at the lowest level of the pallet and this is where the differences in weight resulted in the largest differences in spine loading. This figure indicates that even the lightest boxes

Table 1. Analysis of variance results for spinal loading.

	Maximum lateral shear force	Maximum anterior-posterior shear force	Maximum compression force
Size (S)	0.1144	0.0317*	0.3116
Handle (H)	0.1032	0.0094*	0.0001*
Weight (W)	0.0001*	0.0001*	0.0001*
Region (R)	0.0009*	0.0001*	0.0001*
S × H	0.3969	0.3989	0.3592
S × W	0.2148	0.5429	0.5779
S × R	0.0242*	0.0084*	0.0001*
H × W	0.6630	0.8528	0.8025
H × R	0.0120*	0.0001*	0.0001*
W × R	0.4048	0.0001*	0.0001*
S × H × W	0.3797	0.5480	0.4552

*Significant at $p \leqslant 0.05$.

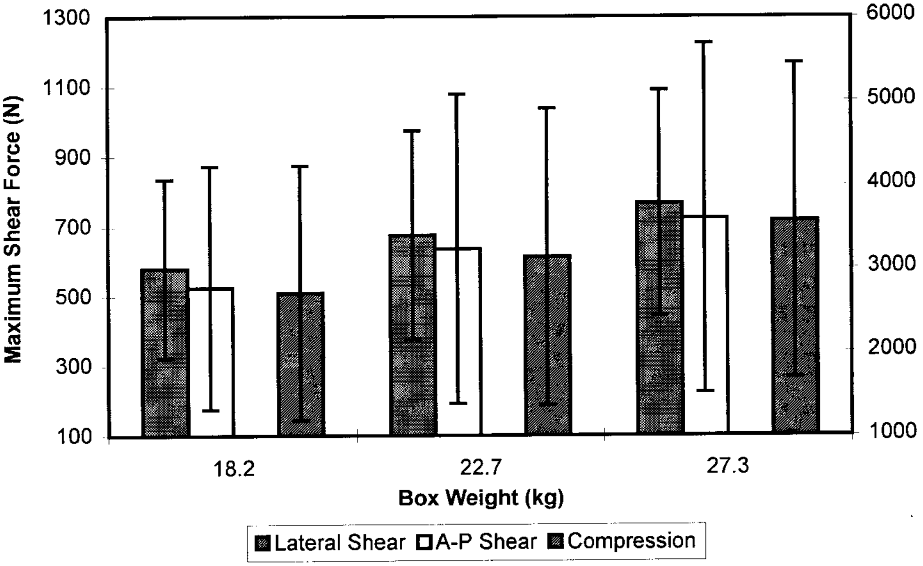

Figure 3. Three-dimensional spine loading as a function of case weight.

averaged peak compressive loads that were > 3400 N in front-bottom and back-bottom regions of the pallet. Similar trends were observed for the spinal A/P shear forces as shown in figure 5.

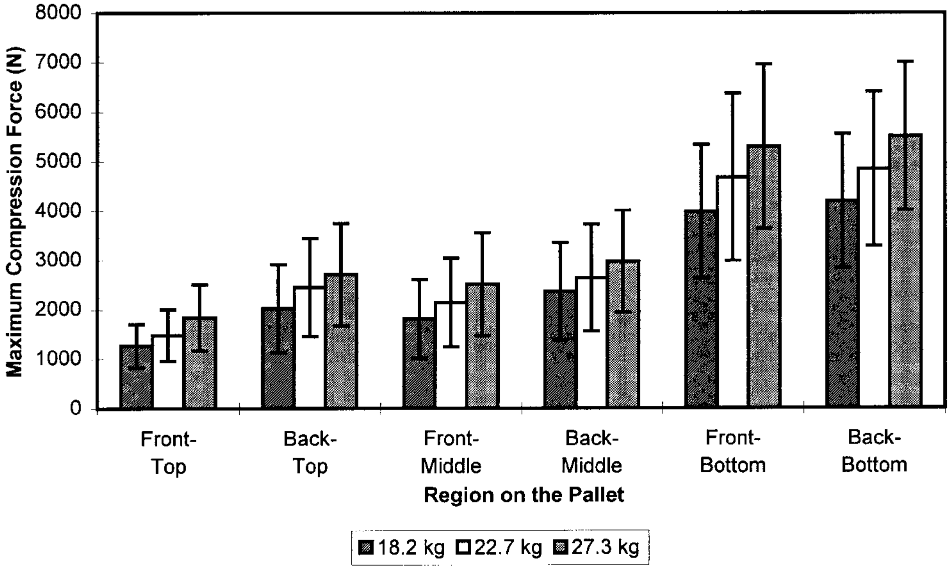

Figure 4. Maximum compression force as a function of box weight and box location of the pallet.

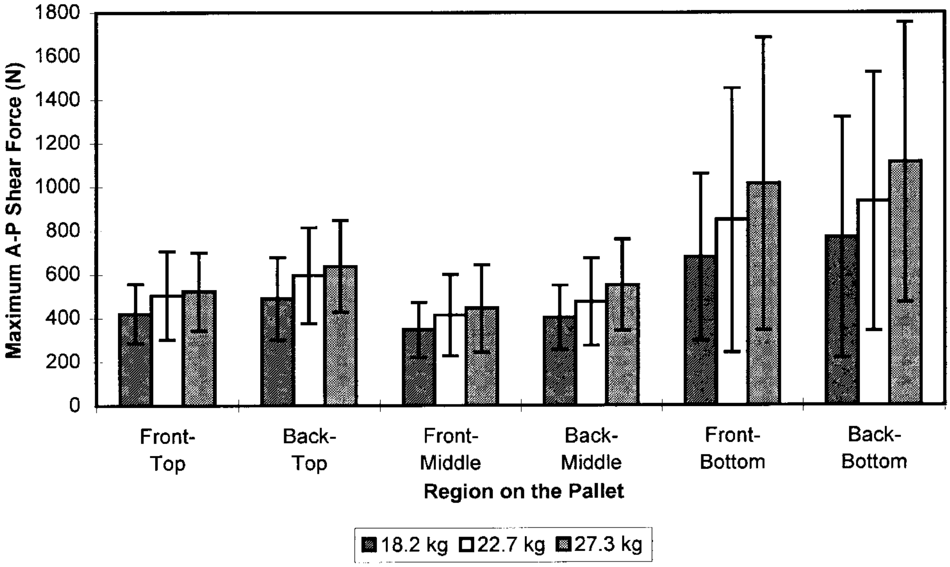

Figure 5. Maximum anterior-posterior shear force as a function of box weight and box location on the pallet.

Handles decreased the compression and A/P shear forces on the spine by about 10 – 15%. However, the A/P shear load relief was more prominent at the lower regions of the pallet as shown in figure 6. The trend shown in this figure was also representative of the compression and lateral shear loading profiles.

Finally, handling the smaller box reduced the average maximum A/P shear force by 50 N compared with the large box. The size by region interaction had a significant effect on all three spine loading measures. However, the trends among these measures was not consistent. The smaller box resulted in slightly lower A/P shear forces in the front-top, back-top, and front-bottom regions (figure 7), whereas, the larger box resulted in lowered lateral shear force in these same regions as well as in the back-bottom region. Although the effect of box size on compression was statistically significant the practical effect was negligible.

4. Discussion

To get an accurate interpretation of the results, they must be viewed as a function of the tolerance limits of the spine. The literature is rich with references to spine compression tolerance. This is an area of much debate and the range of compression tolerances is large (Chaffin and Andersson 1991). Many analyses employ the limits adopted by the NIOSH Work Practices Guide for Manual Lifting (1981). This document suggests that 3400 N is the point at which vertebral end plate microfractures begin to occur in those < 40 years of age. It is believed that the repair process of these microfractures facilitates the degeneration of the disc. Furthermore, as spine compression increases to 6400 N about half of workers will experience vertebral endplate microfractures. Shear tolerances are less prominent in the literature. However, McGill (1996) has recently suggested 1000 N as a tolerance

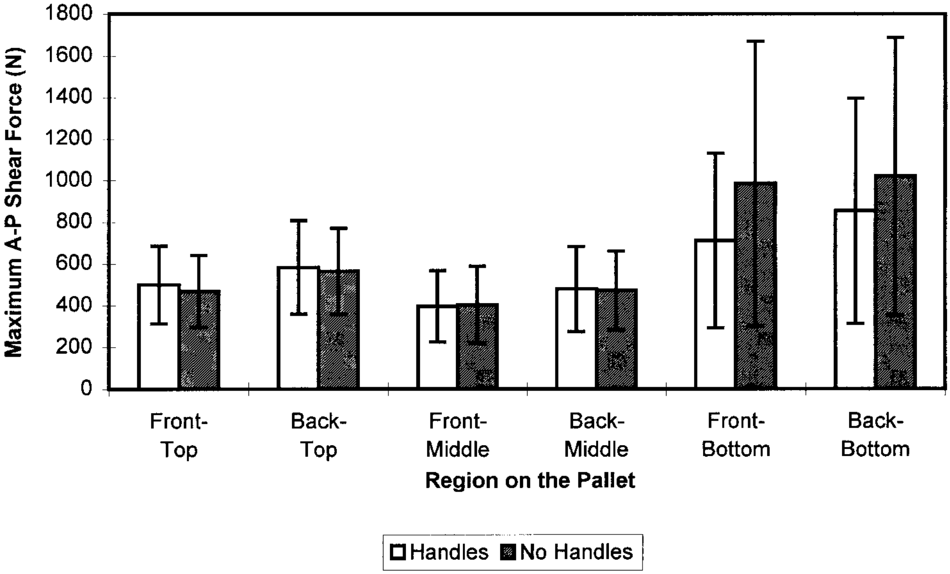

Figure 6. Maximum anterior-posterior shear force as a function of box handle coupling and box location on the pallet.

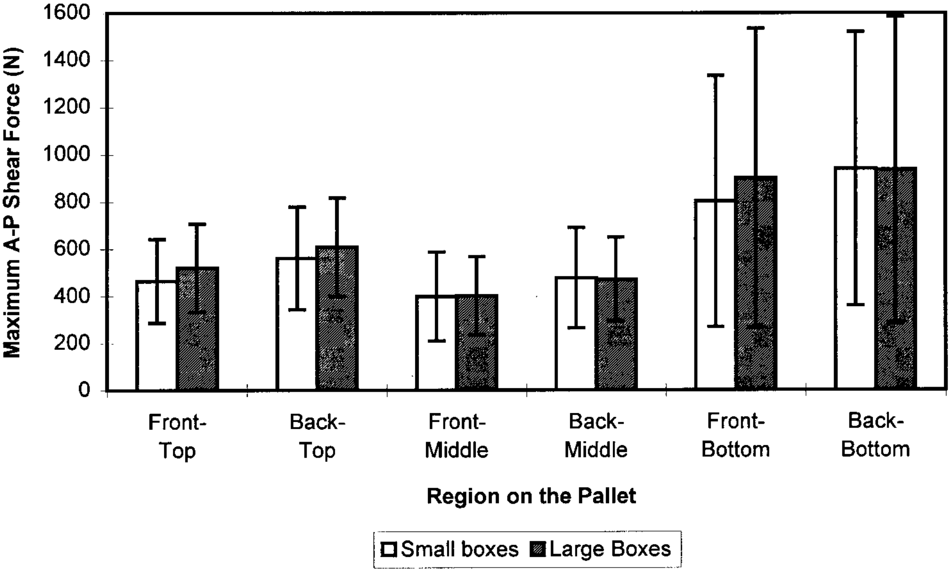

Figure 7. Maximum anterior-posterior shear force as a function of box size and box location on the pallet.

level for disc damage due to shear loading. Thus, we will assume these 'benchmarks' as values to consider when interpreting the significance of these results.

This analysis has shown quantitatively that the greatest influence on spine loading is the location from which the box is lifted from a pallet. Spine loading measures have shown that the lower regions of the pallet (front-bottom and back-bottom regions) contribute the most to spine loading. These regions also represent the conditions where most of the spine compression distribution and a large portion of the A/P shear forces exceed the spine tolerance limits (NIOSH 1981, McGill 1996). The compressive forces exceeded the tolerance limits of the spine more often (a greater portion of the distribution) than did the A/P shear forces. In fact, even the relatively light 18.2 kg box, without handles, resulted in $> 70\%$ of the lifts > 3400 N spine compression tolerance limit. Therefore, a large benefit can be derived by elevating the pallet so that boxes can be transferred off an elevated or adjustable platform such as a lift table. However, there are many situations where raising the load in a bin might be impractical. For example, a distribution centre with thousands of order-picking bins might find this solution to be cost-prohibitive. The influence of the position of the box relative to the spine has been described by many other studies (Andersson *et al.* 1976, Chaffin and Page 1984, Serousi and Pope 1987, Davis *et al.* 1998a). Similar to this study, these researchers found that the greater magnitudes of trunk flexion (due to lower box positions) resulted in higher muscle activity and spinal loads.

This study also has shown that the manipulation of box features also may affect the loading associated with a lift. Box size, weight and handle conditions all displayed significant influences on spine loading, especially when these factors were considered as a function of box region. It is not surprising that an increase in spinal loads was found as the box weight increased (Chaffin and Baker 1970, Chaffin and

Park 1973, Marras and Sommerich 1991b). Of these features, size, although often statistically significant, appeared to have little influence in moving the spine loading from above a tolerance benchmark to below the benchmark for either compression or shear. A/P shear increased slightly for the large boxes in about half of the pallet regions. This probably was due to an increase in the moment associated with a slightly large box since the box centre of gravity would be slightly farther from the body compared with a smaller box. In the same regions lateral shear decreased slightly with the large box. This probably was due to reduced lateral bending associated with large boxes, since subjects were not required to reach as far with a larger box as compared with a smaller box. For the sizes of boxes evaluated in this study, the effects of A/P and lateral shear were off-setting. Thus, manipulating box size appeared to have little practical value.

Box handles, across all regions, tended to reduce the loading on the spine for a given box weight. The 27.3 kg boxes with handles resulted in a mean maximum compression force of 3275 N. This was slightly less than the 22.7 kg boxes without handles (3399 N). When handles were added to the 22.7 kg boxes, the mean maximum compression force reduced to 2864 N, which was comparable with the mean maximum compression force from 18.2 kg boxes without handles (2925 N). *Therefore, the effect of including handles on boxes was approximately equivalent to reducing the box weight by 4.5 kg.*

The reduction of the spinal loads through the use of handles was contrary to Freivalds *et al.* (1984), who found that the peak compression forces were higher for the boxes with handles. Their assessment neglected multiple muscles by using a single equivalent muscle, rigid link model, and, thus, failed to account for the higher coactivity that occurred for the boxes without handles. On the other hand, similar results of lower forces when lifting boxes with handles was found by Kromodihardjo and Mital (1987) and Davis *et al.* (1998b).

Box weight and handle condition, together, did appear to have a great influence on spine loading. To appreciate how spine compression loading changed as a function of these features as well as the region factor, table 2 has been included to indicate the percentage of observations that exceed the two NIOSH compression force 'benchmarks' discussed earlier. It indicates how the inclusion of handles and boxes of different weights interact with pallet region to define loading, and therefore risk of LBD. Similar analyses for the shear forces indicated that, for the most part, spine compression was more problematic than the shear forces for the weight factor alone. Table 2 indicates that the practical benefit of handles is realized for the heavier boxes located at the lower levels of the pallet. *Specifically, regardless of box weight, the using of handles can reduce the percentage of observations that exceed the 6400 N limit by approximately 50%*. The effect of handles also interacts with the region factor. Compression forces often exceed the tolerance limit for all box weights at the lowest layer of the pallet. The decrease in compression force by the use of handles most likely resulted from the decrease in the external moments. This would be expected since the handles were located at the top of the boxes and subjects were not required to bend the torso to the same extent as when lifting was done without using handles. This would reduce the external moment generated by the torso mass.

Further evaluation of the model results confirmed that significant differences in maximum L_5/S_1 compression force were associated with differences in three of the four maximum moment measurements (e.g. sagittal, twisting, and resultant moment). The external moment associated with boxes containing handles was

Table 2. Summary of the percentage of data within the benchmark zones for spine compression.

		Box weight					
		18.2 kg		22.7 kg		27.3 kg	
Region on the pallet	Benchmarks (n)	Handles	No handles	Handles	No handles	Handles	No handles
Front-top	< 3400	100.0	100.0	100.0	99.2	99.2	100.0
	3400 to 6400	0.0	0.0	0.0	0.8	0.8	0.0
	> 6400	0.0	0.0	0.0	0.0	0.0	0.0
Back top	< 3400	98.2	89.1	84.5	76.4	83.6	67.3
	3400 to 6400	1.8	10.9	15.5	23.6	16.4	32.7
	> 6400	0.0	0.0	0.0	0.0	0.0	0.0
Front-middle	< 3400	98.7	91.3	94.7	82.7	92.6	76.0
	3400 to 6400	1.3	8.7	5.3	17.3	7.4	23.3
	> 6400	0.0	0.0	0.0	0.0	0.0	0.7
Back-middle	< 3400	88.7	82.0	80.7	75.3	76.7	64.7
	3400 to 6400	11.3	18.0	19.3	24.7	23.3	34.6
	> 6400	0.0	0.0	0.0	0.0	0.0	0.7
Front-bottom	< 3400	45.3	30.0	29.3	14.0	16.0	3.3
	3400 to 6400	52.0	62.0	62.7	65.3	72.0	66.0
	> 6400	2.7	8.0	8.0	20.7	12.0	30.7
Back bottom	< 3400	35.3	24.0	30.0	10.7	9.3	2.0
	3400 to 6400	60.7	67.3	56.7	65.3	71.3	62.0
	> 6400	4.0	8.7	13.3	24.0	19.3	36.0

significantly less than the moment for boxes without handles. The most pronounced reduction of maximum moment was for the sagittal moment, which reduced to 151.8 Nm from 176.4 Nm (a 13.9% decrease) by the inclusion of handles on the boxes. Examination of the results also shows that the effect of including handles is to raise the lift point of the box. This affects the length – strength relationship of the trunk muscles, moving the load position to a location where this relationship becomes more optimal. Thus, including handles is analogous to slightly changing the position of the box on the pallet.

A large portion of the A/P shear distribution also exceeded the 1000 N tolerance at the bottom regions when no handles were present on the box. Specifically, A/P shear was found to be problematic for the 27.3 kg boxes in the front-bottom and back-bottom regions. Handles were also found to reduce this average peak shear to well below the 1000 N tolerance (figure 6). Observations of the subjects indicated that this reduction in shear associated with handles was due to the fact that subjects could grab the handle and slide the load toward them as opposed to reaching to the far end of the box to lift, as was observed when lifting was done without using handles.

These results based upon spine loading also were compared to an analysis of the same features evaluated with a LBD risk model (Marras *et al.* 1993). This analysis resulted in very similar results (Allread *et al.* 1996). Thus, the spinal loading profiles were for the most part similar to trunk motion and workplace factor measures that match trunk motions and workplace factors historically associated with jobs placing workers at an increased risk of LBD.

Several potential limitations of this study should also be acknowledged. First, the work performed by the warehouse order selectors was performed in a laboratory environment. Every effort was made to simulate a distribution centre; however, whenever data are collected via EMG, some realism is lost. Second, the work was paced to simulate the speed observed in a distribution environment. Even though the average pace matched that of a warehouse order selector's task, in reality, a warehouse order selector works more in spurts (lifting several boxes within a few minutes and then not lifting again until a new bin location is located). Thus, these results may not reflect the full impact of the dynamic nature of the job. Third, the model-predicted spine loads were indirectly validated through the calibration results. However, the calibration results indicated that the model was indeed robust (see the Methods for model performance variables). Furthermore, the model has been validated in three-dimensions through several previous studies (Marras and Reilly 1988, Reilly and Marras 1989, Marras and Sommerich 1991a,b, Granata and Marras 1993, 1995, Mirka and Marras 1993, Marras and Granata 1995, 1997, Davis *et al.* 1998a). Finally, these results may not be generalizable to a female population since it would be expected that the loading patterns would be different. Future research should evaluate these population groups to enable a wider application of the results.

5. Conclusions

(1) The presence of handles on the boxes had a profound effect of reducing mean maximum L_5/S_1 compression forces and A/P shear forces. The reduction of compression forces from the use of handles most likely resulted from the decrease in external moments, which indicated that the load was able to be held closer to the body. A relationship emerged between handles and box

weight, in that the compression values for boxes lifted without handles were approximately equivalent to lifting boxes with handles weighing 4.5 kg more.

(2) Box weight significantly influenced spinal loading and, therefore, risk of LBD. The mean maximum L_5/S_1 compression forces for the lower weight boxes without handles positioned at the middle and top layers of the pallet, were at or below the NIOSH acceptable 3400 N. However, these were mean maximum values, and the standard deviations around these means suggests that there were observations (e.g. some subjects' responses) >3400 N.

(3) The region of the pallet from which boxes were lifted also had a profound impact on compression. The results implied that, as boxes were located lower on a pallet, risk increased. Boxes that were lifted from the bottom layer of the pallet, regardless of the weight or the handle condition, produced mean maximum L_5/S_1 compression forces above the NIOSH acceptable compression force 3400 N. However, lifting the 18.2 kg box with handles did approach a lower risk compression force level (3855.4 N).

(4) The quantitative understanding of the conditions under which spine loadings become excessive, as described in this study, can serve as a basis for job and box feature redesign in distribution centres.

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