The effect of pallet distance on torso kinematics and low back disorder risk

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The effect of pallet distance on torso kinematics and low back disorder risk

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Intervention research for prevention of occupational low back injuries has focused on the effects of reducing extreme torso flexion and the external moment. Little is known about prevention strategies for torso twisting and lateral bending. The objective of this study was to assess the effect of pallet distance with regard to a constant lift origin on the torso kinematics and a measure of low back disorder risk. Fifteen male participants transferred 11.3 kg boxes from a constant origin to six different regions on a pallet. Two pallet distances with regard to the lift origin were investigated. ANOVA indicated that increasing the pallet distance resulted in increases in torso kinematics (velocities and accelerations) as well as a measure of risk of low back disorder. The increases in torso kinematics (e.g. twisting and lateral awkward postures and bending velocities) occurred mostly at the lower height regions on the pallet. It is concluded that increasing the pallet distance with regard to the lifting origin, with the intention to influence the participant to take a step during a palletizing task does not appear to be an effective intervention strategy to reduce the risk of low back disorder associated with torso kinematics.

Keywords: Palletizing; Torso kinematics; Low back disorders; Manual materials handling; Intervention

1. Introduction

Despite increases in automation, manual material handling (MMH) activities (e.g. palletizing or depalletizing) is still widely performed in the manufacturing sector. The majority of occupational low back pain (LBP) cases (e.g. low back strains) have been found to be associated with MMH activities (Dempsey and Hashemi 1999), and lifting is the activity most commonly associated with the reports of LBP cases (Snook et al. 1978, Klein et al. 1984, Kraus et al. 1997, Kuiper et al. 1999).

Torso twisting has been identified as a risk factor for reporting occupational LBP (Kelsey et al. 1984, Punnett et al. 1991, National Institute for Occupational Safety and
Health 1997, Hoogendoorn et al. 2000, National Academy of Sciences 2001), where the biomechanics of twisting and its relationship to increased risk of LBP has been thoroughly described by Kumar (2004). Kuorinka et al. (1994) estimated that torso twisting occurred in 77% of box transfers observed in a grocery warehouse, whereas Drury et al. (1982) found that fewer than 20% of box handling tasks such as pallet loading and order picking were free from torso twisting at the origin of the task. Thus, awkward torso postures such as twisting are quite prevalent in MMH tasks.

Torso flexion has consistently been identified in epidemiological studies as being associated with increases in risk of LBP. Marras et al. (1993, 1995) and Norman et al. (1998) found that peak torso flexion was associated with reports of LBP cases. Punnett et al. (1991) reported that longer duration of the task in mild (20° to 45°) and severe ( > 45°) torso flexion increased the risk of being a LBP case, whereas Hoogendoorn et al. (2000) found that working in extreme torso flexion ( > 60°) of posture increased the risk of being a LBP case. The external moment about the low back generated by the external load and torso has been shown to be highly associated with the incidence rate of subsequent low back injuries (Chaffin and Park 1973). Marras et al. (1993, 1995) found that the maximum external moment in a job with MMH was the best single predictor of the probability of being a high-risk job for LBP case, whereas Norman et al. (1998) found that the cumulative moment was predictive of being a LBP case.

Several studies have found positive effects of engineering-based interventions to reduce the risk of occupational LBP from risk factors associated with MMH. Davis et al. (1998) and Marras et al. (1999) found that adding handles to cases reduced the predicted spinal loading. The use of lift tables was shown to significantly reduce the risk and incidence rate of occupational LBP, presumably by reducing the peak torso flexion as well as the external load moment (Marras et al. 2000). Additionally, material handling devices (e.g. lift assist devices) were also shown to result in a significant reduction of LBP incident rate (Marras et al. 2000).

Few studies have investigated the effects of interventions aimed at reducing torso twisting and lateral bending during MMH tasks. Badger et al. (1985) suggested that a frozen bakery manufacturer locate a bag rack adjacent to the operator rather than behind the operator to reduce torso twisting when retrieving the bags from the rack; however, the effect of this intervention was not investigated. Gagnon et al. (1993) found that pivoting the feet rather than twisting the torso while keeping the feet stationary when lifting a load to an adjacent surface resulted in lower torso twisting moments, whereas Lavender et al. (1995) reported that taking a step while lifting a load to an adjacent surface resulted in decreases in torso kinematics compared to the resulting torso kinematics when not moving the feet. Thus, training workers to take a step during the transfer rather than twisting the torso may result in a decreased risk of occupational LBP during MMH. However, Chaffin et al. (1986) found that training the employees to take a step and not twist during lifting did not result in reducing the twisting during MMH tasks.

Palletizing and depalletizing are common MMH tasks in the manufacturing industry, with risk factors for occupational LBP present in these tasks. However, there is a void in the research literature regarding identification of feasible control strategies for the reduction of twisting and lateral bending postures and motions in these tasks. Pivoting and taking a step when transferring a load has been shown to result in a decrease in torso kinematics and torso moments; however, simply training the workers to take the extra step when transferring the load failed to decrease the torso twisting. Thus, the objective of this study was to investigate the influence of workplace design as an intervention strategy to reduce torso kinematics and the resulting risk of occupational LBP during a palletizing
task. It was hypothesized that by increasing the distance between the lift origin and pallet, participants would be forced to take a step toward the pallet, thus reducing the torso kinematics as well as the risk of occupational LBP.

2. Methods

2.1. Approach

This study quantified torso kinematics of male participants while transferring 11.3 kg boxes to different locations on a pallet. The distance between the lift origin and the pallet, as well as the lifting frequency, was varied to investigate if there were any effects on the torso kinematics, as well as an estimate of risk for occupational LBP.

2.2. Participants

Fifteen college-aged male participants (mean age 25.5 (SD 2.4) years; mean stature 172.8 (SD 6.0) cm; mean body mass 76.1 (SD 9.5) kg), without material handling experience and free from musculoskeletal discomfort or prior musculoskeletal disorders of the torso, volunteered to participate in this study. The objectives and procedures of the study were explained, whereupon the participants signed an informed consent form approved by the Wichita State University Internal Review Board for Human Subjects.

2.3. Experimental design

The independent variables consisted of the distance of the pallet from the lift origin (close and far), the lifting frequency (three lifts/min and five lifts/min), and the destination region of the box on the pallet (low-front, low-back, mid-front, mid-back, top-front and top-back). The dependent variables consisted of the peak torso bending positions, velocities and accelerations in the sagittal, coronal and transverse plane, the maximum horizontal distance between the load and the approximate L5/S1 location (i.e. moment arm) during the lift, and a measure of the low back disorder (LBD) risk.

2.4. Experimental procedure

The experimental task consisted of lifting and transferring 11.3 kg boxes without handles from an origin surface (76.2 cm above the floor) to a close and a far pallet position. The box dimensions were 45.7 × 30.5 × 22.9 cm (width × length × height), whereas the pallet dimensions were 121.9 × 101.6 × 14 cm (width × length × height). The palletizing was performed at two pallet orientations with regard to the lift origin, one with the pallet on the right side of the lift origin (90° adjacent) and one orientation with the pallet directly behind the participant (180° behind). The close and far pallet locations for the 90° adjacent pallet orientation were 30.5 and 91.5 cm, respectively, from the origin to the front edge of the pallet (figure 1). The close and far pallet locations for the 180° behind pallet orientation were 61 cm and 122 cm, respectively, from the origin to the front edge of the pallet (figure 1). The 61 cm difference between the close and far pallet location from the lift origin was applied to influence the participants to take a step toward the pallet for the far pallet distance. The larger space between the 180° orientation than the 90° orientation was to account for the participant’s body being directly between the lift origin and the pallet at the 180° orientation.
Participants stacked a pallet of 48 boxes for each pallet distance and lift rate combination, at each pallet orientation. The full pallet of 48 boxes was categorized into six regions for analysis purposes (figure 2) and all participants stacked the pallets in the same predetermined order. The bottom regions ranged from 14.0 cm to 58.4 cm above the floor, the mid-regions ranged from 58.4 cm to 102.9 cm above the floor and the top regions ranged from 102.9 cm to 148.6 cm above the floor. The presentation of the experimental conditions was administered to each participant in a randomized order. To reduce fatigue effects, the experiment for each participant was carried out over two non-consecutive days, with data from four pallets collected on each of the 2 d.

For each box lifted, the maximum horizontal distance between the midpoint of the hands and the approximate sagittal plane location of the L₅/S₁ intervertebral disc (i.e. moment arm) was measured using a tape measure. The torso kinematics (position, velocity and acceleration) were collected using a lumbar motion monitor (Marras et al. 1992), which is a three-dimensional electrogoniometer placed on a participant’s back.

2.5. Data analysis

For each lifting trial, the peak values for the torso position, velocity and acceleration in each of the three planes were determined from the Ballet 2.0TM software. For each pallet region, the ‘probability of high-risk group membership’ (i.e. LBD risk, Marras et al. 1993) was derived, also using the Ballet 2.0TM software. The LBD risk utilizes the lift rate, maximum moment, mean twist velocity, maximum lateral velocity and maximum sagittal flexion variables to estimate the probability that the task is a member of the high-risk group for LBDs.
2.6. Statistical analyses

The statistical analysis consisted of a three-way repeated measures ANOVA for each of the dependent variables, with participants serving as the repeated measure. Significant two-way interactions with pallet distance were investigated utilizing the least significant difference post-hoc test. A Bonferroni adjustment was utilized using an overall significance level of $\alpha = 0.05$ to reduce the probability of a type I error.

3. Results

3.1. 90° Adjacent pallet orientation

As the pallet distance increased from close to far at the 90° pallet orientation, the following torso kinematics increased significantly (table 1): maximum lateral range (9.7° to 10.6°); maximum twist (9.4° to 10.7°); maximum lateral velocity (24.4° per s to 27.3° per s); maximum sagittal velocity at the low-front pallet region (44.8° per s to 48.7° per s); maximum twist velocity (24.7° per s to 27.9° per s); maximum lateral acceleration (170° per s$^2$ to 192° per s$^2$); maximum twist acceleration (174.6° per s$^2$ to 198.2° per s$^2$); and the maximum sagittal acceleration at the fast palletizing rate (160.5° per s$^2$ to 190.2° per s$^2$). Only the maximum torso flexion decreased as the pallet distance increased (22.5° to 21.0°).

Finally, the LBD risk varied significantly as a function of the pallet distance and pallet region (figure 3). As the distance increased from close to far, the LBD risk significantly increased when palletizing to the low-back region (0.70 to 0.74), the low-front region (0.69 to 0.73) and the top-back region (0.63 to 0.66).
Table 1. ANOVA results (F-statistic) for the 90° adjacent pallet orientation as a function of pallet distance, pallet region and lift frequency

<table>
<thead>
<tr>
<th>Independent variable</th>
<th>Moment arm</th>
<th>Max lateral range</th>
<th>Max flexion</th>
<th>Max twist</th>
<th>Max lateral velocity</th>
<th>Max sagittal velocity</th>
<th>Max twist velocity</th>
<th>Max lateral acceleration</th>
<th>Max sagittal acceleration</th>
<th>Max twist acceleration</th>
<th>LBD risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance (D)</td>
<td>NS</td>
<td>9.29**</td>
<td>4.75*</td>
<td>9.85**</td>
<td>16.37**</td>
<td>NS</td>
<td>23.32***</td>
<td>23.97***</td>
<td>NS</td>
<td>30.79***</td>
<td>21.39***</td>
</tr>
<tr>
<td>Frequency (F)</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>5.12*</td>
<td>NS</td>
<td>4.69*</td>
<td>NS</td>
<td>NS</td>
<td>12.27**</td>
<td>17.36***</td>
</tr>
<tr>
<td>Region (R)</td>
<td>80.06***</td>
<td>36.79***</td>
<td>124.77***</td>
<td>38.12***</td>
<td>29.73***</td>
<td>32.36***</td>
<td>25.91***</td>
<td>19.81***</td>
<td>21.57***</td>
<td>21.43***</td>
<td>12.07***</td>
</tr>
<tr>
<td>D × F</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>D × R</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
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</tr>
<tr>
<td>F × R</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
</tbody>
</table>

* < 0.05; ** < 0.01; *** < 0.001. LBD = low back disorder.
3.2 Behind pallet orientation

As the pallet distance increased at the 180° pallet orientation, all but the sagittal velocity and sagittal acceleration were significantly affected (table 2). The lateral bending increased when increasing the pallet distance at the low-back region (11.1° to 12.4°) and the low-front region (10.1° and 11.5°; figure 4), and the torso twisting increased at the low-back region (7.7° to 9.0°; figure 5) when increasing the pallet distance. The maximum torso flexion, however, decreased at the low-front region (34.1° to 31.7°) and mid-front region (16.9° to 15.6°) as the pallet distance increased (figure 6).

Increasing the pallet distance increased the lateral torso velocity (figure 7) at the low-back region (28.7° per s to 31.6° per s) and the low-front region (24.8° per s to 29.0° per s). The torso twisting velocity increased at the low-back region (21.3° per s to 25.9° per s) when increasing the distance of the pallet (figure 8). The lateral torso acceleration increased at the low-back region (196.1° per s² to 221.2° per s²), the low-front region (172.8° per s² to 200.0° per s²) and the mid-front region (157.0° per s² to 181.1° per s²) when increasing the distance from close to far (figure 9). Similarly, the torso twisting acceleration increased in the low-back region (155.6° per s² to 186.4° per s²) and the mid-front region (165.2° per s² to 180.3° per s²) when increasing the pallet distance (figure 10). Finally, as the pallet distance increased, the LBD risk significantly increased (figure 11) at the low-back region (0.70 to 0.75), and the low-front region (0.69 to 0.72).

4. Discussion

4.1 Distance effect on torso kinematics

Based on the studies by Chaffin et al. (1986) and Lavender et al. (1995), the research hypothesis was that increasing the distance between the lift origin and destination would result in a decrease in the torso kinematics as well as an overall reduction in the LBD risk.
Table 2. ANOVA results (F-statistic) for the 180° behind pallet orientation as a function of pallet distance pallet region and lift frequency

<table>
<thead>
<tr>
<th>Independent variable</th>
<th>Moment arm</th>
<th>Max lateral range</th>
<th>Max flexion</th>
<th>Max twist</th>
<th>Max lateral velocity</th>
<th>Max sagittal velocity</th>
<th>Max twist velocity</th>
<th>Max lateral acceleration</th>
<th>Max sagittal acceleration</th>
<th>Max twist acceleration</th>
<th>LBD risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance (D)</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>6.09*</td>
<td>NS</td>
<td>NS</td>
<td>14.38**</td>
<td>NS</td>
<td>NS</td>
<td>5.91*</td>
</tr>
<tr>
<td>Frequency (F)</td>
<td>NS</td>
<td>NS</td>
<td>8.89**</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>4.64*</td>
<td>19.98***</td>
<td>9.94***</td>
<td></td>
</tr>
<tr>
<td>Region (R)</td>
<td>93.16***</td>
<td>32.26***</td>
<td>132.73***</td>
<td>38.49***</td>
<td>42.16***</td>
<td>55.65***</td>
<td>28.05***</td>
<td>26.67***</td>
<td>34.55***</td>
<td>22.15***</td>
<td>9.94***</td>
</tr>
<tr>
<td>D × F</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>7.30*</td>
<td>6.48*</td>
</tr>
<tr>
<td>D × R</td>
<td>NS</td>
<td>5.45***</td>
<td>4.26**</td>
<td>3.32**</td>
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<td>NS</td>
<td>3.09*</td>
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<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
</tbody>
</table>

* < 0.05; ** < 0.01; *** < 0.001. LBD = low back disorder.
The logic was that increasing the distance between the lift origin and the destination would influence the participants to pivot and take a step toward the pallet rather than just twist their torso to perform the palletizing task. If someone were to pivot and twist without taking a step to palletize the load at a farther distance between origin and destination, an increase in the moment arm at the farther pallet distance would be expected. However, the moment arm at the destination was not significantly affected by pallet distance; thus, it appears that increasing the pallet distance influenced the participants to take a step toward the pallet.

Figure 4. Mean (with SD bars) maximum lateral bending as a function of pallet distance. L-F = low-front; L-B = low-back; M-F = mid-front; M-B = mid-back; T-F = top-front; T-B = top-back. *Significant difference in lateral torso bending position as a function of pallet distance.

Figure 5. Mean (with SD bars) maximum torso twisting as a function of pallet distance. L-F = low-front; L-B = low-back; M-F = mid-front; M-B = mid-back; T-F = top-front; T-B = top-back. *Significant difference in maximum torso twist position as a function of pallet distance.
When the pallet was in the adjacent position with regard to the lift origin, increasing the distance between the lift origin and the front edge of the pallet from 30.5 cm to 91.5 cm resulted in increases in all peak torso bending velocities (between 3.2% and 11.9% increase), peak torso bending accelerations (between 12.9% and 18.5% increase) and maximum awkward postures (between 9.3% and 13.8% increase) except torso flexion, which decreased slightly by an overall mean of 1.5°. Although the increases in torso kinematics were modest, and the torso velocities and accelerations had magnitudes

![Figure 6](image1.png)

Figure 6. Mean (with SD bars) maximum torso flexion as a function of pallet distance. L-F = low-front; L-B = low-back; M-F = mid-front; M-B = mid-back; T-F = top-front; T-B = top-back. *Significant difference in maximum torso flexion as a function of pallet distance.

![Figure 7](image2.png)

Figure 7. Mean (with SD bars) maximum lateral torso bending velocity as a function of pallet distance. L-F = low-front; L-B = low-back; M-F = mid-front; M-B = mid-back; T-F = top-front; T-B = top-back. *Significant difference in lateral torso bending velocity as a function of pallet distance.
consistent with the low-risk LBD group found by Marras et al. (1993), the combined effect resulted in magnitudes of LBD risk that are reflective of high-risk for LBD ($0.70$), which increased as a result of increasing the pallet distance at the lower regions and top-back region.

For the $180^\circ$ pallet orientation with regard to the lift origin, increasing the pallet distance had a similar effect on torso kinematics as at the $90^\circ$ pallet orientation; however,
most of the increases in torso kinematics occurred at the lower regions of the pallet. When increasing the pallet distance, the peak lateral torso kinematics increased between 10.1% and 16.9% at the low regions, the peak torso twist kinematics increased between 16.9% and 25.6% at the low-back region, whereas the sagittal flexion decreased by 7% at the low-front region. The combined effect of increasing the pallet distance at this orientation was an increase in LBD risk of 4.3% and 7.1% at the low-front and low-back regions,
respectively. Thus, if the layout of the palletizing area is restricted to the destination pallet behind the lift origin, the strategy of increasing the pallet distance to influence the employees to take extra steps may result in increases in torso kinematics and overall LBD risk, mainly at the lower pallet regions.

Overall, increasing the pallet distance at either pallet orientation with regard to the lift origin resulted in increases in torso kinematics, as well as overall LBD risk. Thus, the research hypothesis that the torso kinematics and overall LBD risk would decrease by increasing the distance between the lift origin and pallet was not supported.

4.2. Comparison with prior studies

These findings appear to be somewhat in contrast to the findings and suggestions by other researchers on methods to reduce torso kinematics during MMH tasks. Lavender et al. (1995) found that twisting and lateral torso kinematics were reduced by allowing participants to take a step when transferring a load to an asymmetric position, compared to the torso kinematics observed when performing the same task without moving the feet. However, in the present study, there was no restriction at either the close or far pallet distance regarding keeping the feet stationary. Thus, similar to the suggestion by Chaffin et al. (1986) to have employees take an extra step to reduce twisting while lifting, the present study reflects the need to take extra steps to perform the palletizing as a result of increasing the distance between the origin and destination locations. While allowing the feet to move may in fact reduce torso kinematics for asymmetric lifts compared to keeping the feet stationary, the present results suggest that simply increasing the distance between the lift origin and destination may result in increases in torso kinematics and the resulting LBD risk, especially at the lower regions of the pallet. The reason for this increase in torso kinematics may be related to the participant’s perception that they need to return to the lift origin in time to perform the next lift. As the pallet distance increased, to account for the increased travel distance to and from the pallet, the participants may have increased their torso motion to return to the lift origin in time for the next lift.

4.3. Torso biomechanical loading

Although biomechanical loading was not investigated in this study, the effects of torso kinematics on biomechanical loading of the spine can be assessed qualitatively. The mean torso bending velocities and accelerations for this study are consistent with those found within the range for low-risk LBD jobs in the studies by Marras et al. (1993, 1995). However, the torso kinematics increased when increasing the pallet distance, at both pallet orientations. It is known that as the torso bending velocity increases (twisting and lateral directions), torso muscle coactivity increases (Marras and Granata 1995, 1997). Increases in muscle coactivation due to increases in torso bending velocities have also been shown to increase predicted spinal loading, such as compression and shear forces in the sagittal plane and coronal plane (Marras and Granata 1995, 1997). Furthermore, increases in torso motion in multiple planes have been shown to increase the complex loading on the spine (Fathallah et al. 1998), further increasing the risk of LBD.

Increasing the pallet distance also resulted in increases in all torso acceleration measures. Although the maximum accelerations were in the range found by Marras et al. (1993) for jobs with demonstrated low-risk of LBD, the increases in torso acceleration when increasing the pallet distance would be expected to increase torso muscle co-contraction and result in increases in spinal loading, particularly shear forces (Marras
and Mirka 1990, 1993), to which the spine has a much lower tolerance than for compression (McGill 1997). Thus, the increases in torso kinematics would be expected to increase the spinal loading, which have already been shown to present elevated risk for LBD for similar tasks studied in this investigation (Marras et al. 1997, 1999, Granata and Marras 1999).

The findings of this study should be viewed within the context of some methodological considerations. First, this was a laboratory intervention study that was intended to reflect an industrial setting. Although the participants were notified as to when to begin the lift, this may differ from an industrial setting, where participants can actually see the conveyor line and the boxes approaching. This difference may result in different strategies for timing of lifting, which could possibly increase the torso kinematics due to the need to keep up with the line. Second, the participants in this study were young healthy college-aged males with little to no material handling experience. Thus, these findings may more appropriately reflect an inexperienced material handling population.

5. Conclusions

This study found that by increasing the distance between the lift origin and the pallet destination increases in the torso kinematics and LBD risk resulted, mostly at the lower pallet regions. It appears that interventions such as increasing the distance between origin and destination aimed at influencing employees to take a step during the transfer of a load do not reduce the torso motion and LBD risk. Thus, there is insufficient evidence from the perspective of torso kinematics and LBD risk regarding the effectiveness of this LBD prevention strategy.

References


