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The effects of operator position, pallet orientation, and palletizing condition on low back loads in manual bag palletizing operations

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ABSTRACT

Many mining commodities are packaged and shipped using bags. Small bags are typically loaded onto pallets for transport and require a significant amount of manual handling by workers. This specific task of manual bag handling has been associated with the development of musculoskeletal disorders (MSDs), especially low back disorders. This study evaluates the biomechanical demands of different work layouts when performing manual palletizing of small bags, and evaluates the biomechanical stresses associated with different stacking techniques. Results indicate that peak forward bending moments as well as spinal compression and shear forces are higher when the pallet is situated at the side of the conveyor as opposed to the end of the conveyor. At low levels of the pallet, controlled bag placement results in higher peak forward bending moments than stacking at higher levels and when dropping the bag to lower levels. The results of this study will be used to inform the development of an audit tool for bagging operations in the mining industry.

Relevance to industry: In many cases for workers loading small bags, compression forces exceed the NIOSH criterion of 3400 N. Orientation of the pallet has a significant impact on spinal compression, and positioning the pallet at the end of the conveyor reduces the estimated compressive loading on the lumbar spine by approximately 800 N.

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1. Introduction

Many mining commodities are packaged and shipped using bags. These may be small bags that are manually handled or bulk bags that may weigh several hundred kilograms (kg). Small bags (typically weighing 23 kg but with weights up to 46 kg) are usually loaded onto pallets for transport and require a significant amount of manual handling by workers. While the loading of small bags onto pallets has been automated in some loading facilities, at many operations the repetitive job of loading small bags onto pallets is still performed manually. Manual handling is associated with the development of musculoskeletal disorders (MSDs), especially low back sprains and strains (Dempsey and Hashemi, 1999). This is particularly true if the workplace layout is poorly designed and/or appropriate lifting aids (such as lift tables) are not provided (Keyserling et al., 1988).

In the United States, the Mine Safety and Health Administration (MSHA) requires all mines to report all injuries, illnesses, and fatalities. These data are in the public domain, and are provided in statistical analysis software format (IBM SPSS, Somers, NY) by the National Institute for Occupational Safety and Health (http://www.cdc.gov/niosh/mining/data/default.html). For this study, accident, injury, and illness reports from MSHA were obtained for the calendar years 2007–2011. After filtering for cases that occurred only in mills and preparation plants and that were considered non-fatal injuries with days lost, the MSHA database contains 217 injuries that can be classified as occurring during bag palletizing. The number of days lost and restricted activity days due to palletizing-related injuries over this time period was 10,047, with a median of 17 days per injury. Overwhelmingly, the specific mineworker activity at the time of injury was handling material or rock, accounting for over 88% of all accidents. The predominant nature of injury was sprains and strains (68%), with a few scattered contusions and fracture cases. Overexertion was the predominant

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accident type (70%). The back was the part of body most frequently injured when handling bags (34% of cases), followed by shoulders (15%), and hands/fingers (11%).

To begin to address the worker safety concerns revealed by these numbers, this study evaluated the biomechanical demands of different work layouts when performing manual palletizing of small bags. Specifically, investigators observed during field visits that manual palletizing operations in which bags were delivered via conveyor were typically performed by workers stacking bags onto two different pallet orientations relative to the conveyor: pallet at the end of the conveyor, or pallet at the side of the conveyor. Thus, one purpose of this study was to evaluate the biomechanical stresses on workers performing bag palletizing tasks with the pallets in these two orientations. Furthermore, field visits revealed that some workers maintained their grasp on the bag through the final placement on the pallet, while others would drop the bag into place, particularly at the lower layers of the pallet. A secondary purpose of the study was to evaluate the biomechanical stresses associated with these techniques. Finally, the effects of the lift destination height and worker position (left or right side) with respect to the pallet were investigated.

One of the issues of interest in this study was the influence of pallet positioning on spinal loading during palletizing tasks. Spinal compression is traditionally assumed to be the principal biomechanical mechanism associated with occupationally related low back disorder (LBD) (Granata and Marras, 1999; Waters et al., 1993). However, Granata and Marras (1999) found that the biomechanical sources of low back pain (LBP) are dynamic, multifaceted, and multidimensional, with spinal shear and torsion loading also playing roles. Occupational low back injury prevention research has focused on the effects of reducing extreme torso flexion and the external moment, with little emphasis on torso twisting and lateral bending (Jorgensen et al., 2005). Torso twisting has also been identified as a risk factor for occupational LBP (Hoogendoorn et al., 2000; Kelsey et al., 1984; National Institute for Occupational Safety and Health, 1997; National Research Council, 2001; Punnett et al., 1991).

Though previous studies have examined the torso kinematics and biomechanical loading associated with changes in pallet position with loading boxes, no studies have looked at these factors with respect to positioning of workers at the side versus the end of the conveyor when palletizing bags. Thus, this study examined the effect of operator position relative to the conveyor on lumbar loading, and also evaluated the effects of control of the load during lifting (dropping versus controlled placement) and lift destinations (high vs low levels of pallet) on loading of the lumbar spine.

2. Methods

2.1. Experimental design

A split-split-split plot experimental design was employed to evaluate the physical demands of lifting bags off a conveyor and placing them onto a pallet. Ground reaction force and kinematic data were used to drive a biomechanical model that estimated joint forces and moments and low back compression experienced during the lifting task.

This study evaluated torso twisting in two different conveyor configurations. From the motion analysis data collected in this experiment, the spinal compression and shear can be estimated and compared with the dynamic lifting components.

2.2. Study population and participant inclusion criteria

Eight male participants from the National Institute for Occupational Safety and Health (NIOSH) in Pittsburgh, PA, participated in this study. The average ± standard deviation of the age and weight were 33 ± 5.3 years and 88.6 kg ± 10.5 kg, respectively. Two participants were left-handed and six were right-handed. Participants were healthy with no symptoms for cardiovascular disease and no history of hand, wrist, arm, back, and neck or shoulder injuries. Before participating, each participant read and signed an informed consent form approved by the NIOSH Human Subjects Review Board.

2.3. Independent variables

Several independent variables were examined in this study (Table 1). First, the orientation of the pallet relative to the conveyor (variable name of pallet orientation with values *End* versus *Side*) was of interest. Pallet orientation is directly related to the location of the operator. When the pallet is on the *Side*, the operator removes the bags from the side of the conveyor. When the pallet is on the *End*, the operator removes the bags from the end of the conveyor. There were two operator positions: *Position1*, in which the operator is on right of pallet and needs to move to his left to place bag on pallet, and *Position2*, in which the operator is on left of pallet and needs to move to his right to place bag on pallet. Examples of these different scenarios can be seen in Fig. 1. Next, three levels of bags were stacked on the pallet in each trial (see Fig. 2): *Level1* (the bottom three bags), *Level2* (two bags, laid on top of and in a perpendicular orientation to *Level1*), and *Level3* (three bags, laid on top of *Level2*, placed as in *Level1*). Bags were stacked in one column at the part of the pallet closest to the operator. Additionally, three palletizing conditions were examined: a lower pallet level (*Level1* 6″ above floor level) with controlled bag placement (*LPLcontrol*), a lower pallet level while dropping the bag into place on the pallet (*LPLdrop*), Fig. 2A, and an upper pallet level (*Level1* 30″ above the floor) with controlled bag placement (*UPLcontrol*), Fig. 2B. Finally, bag destination (which is horizontal lifting distance) for the closest and farthest bag from the conveyor for each level (with values *Near* or *Far*), was an independent variable. For this variable, the middle bags of *Level1* and *Level3* were omitted from the analysis.

2.4. Dependent variables

Moments calculated about L5-S1 were the primary dependent variables in the study. These included the Peak Forward Bending (PFB) moment, Peak Left Lateral Bending (PLLB) moment, Peak Right Lateral Bending (PRLB) moment, Peak Left Twisting (PLT) moment, and Peak Right Twisting (PRT) moment. Estimates of the Compression and A–P Shear Forces acting about L5-S1 were obtained through the use of a regression equation developed by Van Dieen and Kingma (2005) which are based on the value of the net L5-S1 moment. Data from each operator position (*Position1* and *Position2*) were analyzed separately, as bending and twisting moments would be occurring in opposite directions in these two positions.

2.5. Data collection procedure

Participants were positioned on two force plates and then performed twelve lifting tasks (two pallet orientations [*Side* or *End*], three palletizing conditions [*UPLcontrol*, *LPLcontrol*, *LDLdrop*], and two operator positions [*Position1* or *Position2*]) in a completely randomized order.

Each task consisted of 8 lifts of 11.3-kg (25-lb.) bags off of a conveyor and onto a pallet. The bag weight of 11.3 kg was used due to NIOSH Human Subjects Review Board restrictions. The bags were obtained from a mining company and dimensions were 22″

Table 1
Variable names, values, and descriptions used in this study.

Variable name	Values	Definition
Pallet orientation	*End*	Pallet located at end of conveyor
	Side	Pallet located at side of conveyor
Operator position	*Position1*	Operator is on the right side of the pallet
	Position2	Operator is on the left side of the pallet
Bag level	*Level1*	Bottom three bags on pallet
	Level2	Middle two bags
	Level3	Top three bags
Palletizing conditions	*UPLcontrol*	Top of pallet is 30″ above floor; bag is placed on pallet
	LPLcontrol	Top of pallet is 6″ above floor; bag is placed on pallet
	LPLdrop	Top of pallet is 6″ above floor; bag is dropped onto pallet
Bag destination	*Near*	Bags on the pallet that are closest to conveyor
	Far	Bags on the pallet that are farthest from conveyor

long × 15″wide × 5.5″high. The bags were packed with filler material to achieve the desired weight and fullness. Each participant completed a total of 96 lifts. For each lifting task, the participants stacked the eight bags on the pallet with three bags on the bottom layer stacked lengthwise (*Level1*). The next two bags were laid perpendicular to the first layer (*Level2*), and finally three were laid lengthwise again as the third layer (*Level3*), as shown in Fig. 2. For each pallet orientation and operator position, there were three palletizing conditions: control placement, drop placement, and high placement. The controlled placement (*LPLcontrol*) and drop placement (*LPLdrop*) occurred with the bottom layer (*Level1*) starting on top of the pallet on the floor (approximately 6″ above the floor). The high placement (*UPLcontrol*) had the bottom layer starting on a tabletop at 30″ above the floor.

Bags were sent down the conveyor at intervals of 10 s. Participants were instructed on how the lifting tasks should be performed (dropping bags and controlled placement) and were allowed to practice until they felt comfortable with the tasks. After completion of each task, the participant was given a rest period of at least two minutes per the recommendations of Caldwell et al. (1974) for studies involving physical exertion.

Two force plates (0R6-5-2000, Advanced Mechanical Technology, Inc. [AMTI], Watertown, MA) were used to capture ground reaction forces and center of pressure data of both feet. Researchers watched the participants' feet to make sure they did not move off of the force plates and touch the floor; however, participants were allowed to lift a leg and stand on one force plate if needed. The force plate data was collected at 600 Hz using the EvaRT 5.0.4 software (Motion Analysis Corporation, Santa Rosa, CA) through an analog-to-digital board (PCI-6071E, National Instruments, Austin, TX).

A motion capture system (Eagle Digital Real Time System; manufactured by Motion Analysis Corporation, Santa Rosa, CA) utilizing retro-reflective markers placed on the surface of the skin (or on shoes, socks, or clothing) was used to determine the orientation of the body at a sampling rate of 60 Hz. Kinematic motion analysis data was collected using EvaRT software from Motion Analysis Corporation. Retro-reflective markers were placed on various joints of the body using the modified Helen Hayes marker set (Fig. 3) (Davis et al., 1991). A total of 31 markers were affixed with double-sided adhesive electrode collars. The motion analysis system was calibrated at the beginning of each day of testing. After each participant completed the twelve lifting tasks, the captured motion analysis data was post-processed to make sure the markers were labeled correctly and to make sure no markers were missing.

Random noise is usually characterized by high-frequency content while the movement signal is generally limited to a band of low frequencies. In MATLAB, a fourth-order 10 Hz low pass Butterworth filter was used to remove the high-frequency (noise) components and retain those of the low frequency (movement signal) in both the motion analysis and force data.

2.6. Biomechanical model

Biomechanical models employing both bottom-up and top-down approaches were used to analyze the data; however, only the bottom-up model results are presented here. The 14 body segments and local coordinate system for L5-S1 are shown in Fig. 4A. Mass distributions for each body segment are based upon data provided by Dempster (1955), as corrected for fluid loss by Clauser et al. (1969). Three-dimensional forces, moments, and center of pressure data obtained from AMTI force plates were used to calculate moment estimates for L5-S1. Axes established for the

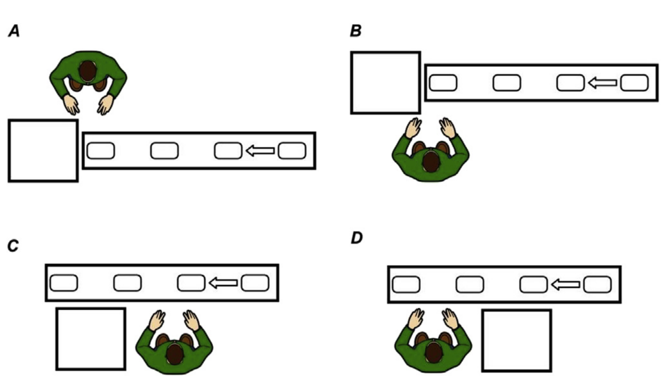

Fig. 1. **A**) Pallet orientation at *End* of conveyor for *Position2* (operator is on left of pallet and needs to move to his right to place bag on pallet). **B**) Pallet orientation *End* for *Position1* (operator is on right of pallet and needs to move to his left to place bag on pallet). **C**) Pallet orientation *Side*, for *Position1*. **D**) Pallet orientation *Side* for *Position2*.

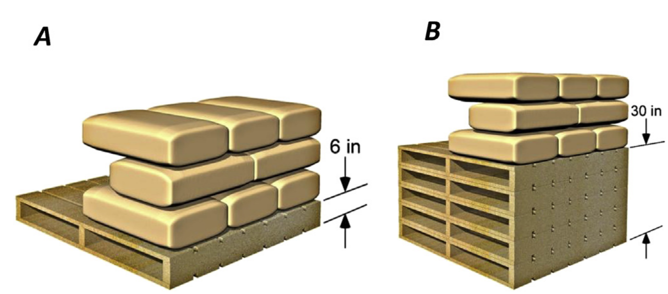

Fig. 2. **A**) The three bags on the bottom row (*Level1*) are 6 inches above the floor. The two bags in the middle row make up *Level2*, and the top three bags make up *Level3*. Note the stacking pattern in which *Level2* is perpendicular to *Level1* and *Level3*. This resembles palletizing conditions for *LPLcontrol* and *LPLdrop*. **B**) Palletizing condition *UPLcontrol*, in which *Level1* is 30 inches above the floor. In this condition, bags are placed onto the pallet.

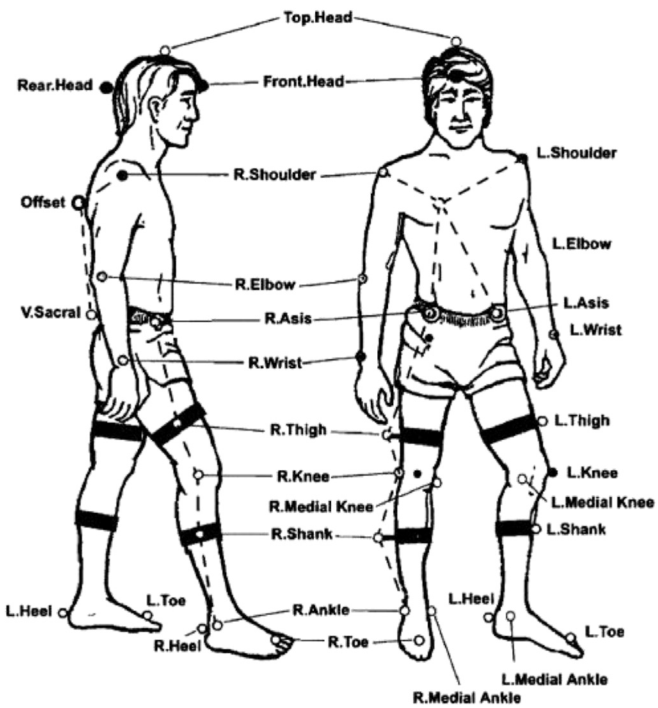

Fig. 3. Modified Helen Hayes marker set used to obtain motion data in the study.

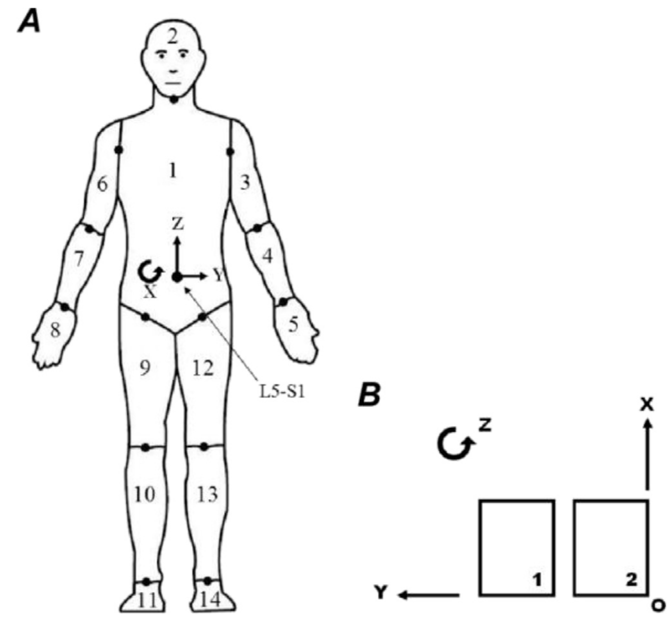

Fig. 4. A) The fourteen body segments and local coordinate system for L5-S1. **B**) Axes established for the force plates using the right-hand rule.

force plates use the “right-hand” rule and are illustrated in Fig. 4B. The position estimate for L5-S1 is operationally defined as a point lying 40% of the distance (posterior to anterior) from the sacral motion analysis marker (V.SACRAL) to a point bisecting the line connecting markers on the right and left anterior superior iliac spines (R.ASIS and L.ASIS) as described in Gallagher et al. (2009). To estimate the forward lumbar bending moment, for example, the following calculation was made:

$$My_{L5\text{-}S1} = [(x_{fp1} - x_{L5\text{-}S1}) \times Fz_{fp1}] + [(x_{fp2} - x_{L5\text{-}S1}) \times Fz_{fp2}] - (z_{L5\text{-}S1} \times Fx_{fp1}) - (z_{L5\text{-}S1} \times Fx_{fp2}) - My_{rt} - My_{rs} - My_{rf} - My_{lt} - My_{ls} - My_{lf}$$

where $My_{L5\text{-}S1}$ is the estimated forward bending moment about the lumbosacral joint; $x_{fp1,2}$ is the center of pressure in the x direction calculated from force plate 1 or 2, $Fz_{fp1,2}$ is the ground reaction force in the z direction measured by the force plate 1 or 2, $z_{L5\text{-}S1}$ is the position of L5-S1 in the z direction, $Fx_{fp1,2}$ is the force measured by force plate 1 or 2 in the x direction, and My_{rt} … My_{lf} represent the moments about y associated with various links of the legs (thigh, shank, foot). The total force (including calculated inertial forces for each body segment) of these segments was used in the low leg link corrections.

Inertial forces were calculated using a dynamic model described by Huston et al. (1976) and Huston (2013). Since participants pivoted during the performance of the palletizing tasks, moments about L5-S1 were rotated based on the position of the markers L.ASIS and R.ASIS so that consistent moment estimates about the local coordinate system at L5-S1 were maintained.

2.7. Data analysis

Data was analyzed using a 2 × 3 × 3 × 2 (pallet orientation [*Side* vs. *End*] × palletizing condition [*High controlled* vs. *Low drop* vs. *Low controlled*] × bag level [*Level1* vs. *Level2 vs. Level3*]) × bag destination (*Near* vs. *Far*) split-split-split plot analysis of variance (ANOVA) with no between subjects variable. Separate ANOVAs were run for conditions where participants were in different operator positions (*Position1* vs. *Position2*) due to the fact that when participants were on the right side of the pallet they would bend or twist in one direction, but would bend or twist in the opposite direction when positioned on the left side. Measures such as lateral bending and twisting would thus be occurring in opposite directions (positive in one versus negative in the other), which made estimates of effects problematic due to cancellation of directional influences. Variance-covariance matrix equality and form were assumed. Tukey's Honestly Significant Difference (HSD) post-hoc tests were performed for significant omnibus F tests. To control for alpha inflation associated with the multiple dependent variables, a Bonferroni-corrected alpha level was used. The Bonferroni correction required that F-tests for each variable achieve $p < 0.01$ to be considered significant, thus maintaining a family-wise Type I error rate of 0.05.

3. Results

Results of ANOVA were examined and ANOVA assumptions tested (including examination of equality of variances, normality of residuals, and outliers) and no violations were observed for any variable. Tables 2 and 3 provide summaries of significant effects on forward bending, lateral bending, and twisting moments when participants were located in *Position1* and *Position2*, respectively. Effect sizes (η^2) are also provided in these tables.

3.1. Operator Position1 (operator is on the right side of pallet and moves towards the left to place bag on pallet)

Peak Forward Bending (PFB) moments were affected by pallet orientation, palletizing condition, bag level, and bag destination (Table 2). PFB moments were significantly higher ($p < 0.01$) during bag transfers when pallets were oriented at the *Side* of the conveyor as opposed to being oriented at the *End* of the conveyor. The PFB moment averaged 38% higher when lifting to a pallet on the conveyor *Side* (Fig. 5A).

Table 2
Significant main effects and interactions when operator was in *Position1*. Interactions not included in the table were not significant for any dependent variable. Statistical significance is indicated by asterisks (*) with * meaning p < 0.01, and ** indicating p < 0.001. Effect size (η^2) is provided for significant effects, except for main effects that are involved in an interaction due to the unreliability of the effect size estimate in such cases.

	Pallet orientation (*End* vs *Side*) (A)	Palletizing condition (upper control vs low control vs low drop) (B)	Bag level (*Level1* vs *Level2* vs *Level3*) (C)	Bag destination (*Near* vs *Far*) (D)	A*D	B*D	C*D
Peak forward bending moment	* $\eta^2 = 0.242$	** $\eta^2 = 0.125$	** $\eta^2 = 0.013$	** $\eta^2 = 0.017$			
Peak left lateral bending moment				**	* $\eta^2 = 0.026$		
Peak right lateral bending moment				*			** $\eta^2 = 0.034$
Peak left twisting moment		*		*		** $\eta^2 = 0.026$	
Peak right twisting moment	**		* $\eta^2 = 0.015$	**	** $\eta^2 = 0.053$		

Table 3
Significant main effects and interactions when the operator was in *Position2*. Interactions not included in table were not significant for any dependent variable. Statistical significance is indicated by asterisks (*) with * meaning p < 0.01, and ** indicating p < 0.001. Effect size (η^2) is provided for significant effects, except for main effects that are involved in an interaction due to the unreliability of effect size estimates in such cases.

	Pallet orientation (*End* vs *Side*) (A)	Palletizing condition (upper control vs low control vs low drop) (B)	Bag level (*Level1* vs *Level2* vs *Level3*) (C)	Bag destination (*Near* vs *Far*) (D)	A*B	A*C	A*D	B*D	C*D	A*C*D
Peak forward bending moment		**	** $\eta^2 = 0.018$	**	* $\eta^2 = 0.053$					
Peak left lateral bending moment	**						** $\eta^2 = 0.030$	** $\eta^2 = 0.053$		
Peak right lateral bending moment			*	**			** $\eta^2 = 0.031$		* $\eta^2 = 0.020$	
Peak left twisting moment			** $\eta^2 = 0.043$	**	** $\eta^2 = 0.107$		** $\eta^2 = 0.026$			
Peak right twisting moment	**								*	** $\eta^2 = 0.017$

PFB moments were also affected by palletizing condition (*upper* vs. *low*) (p < 0.001). Post-hoc tests indicate that a controlled stacking technique (maintaining control of the bag to the pallet) when stacking below knee level resulted in higher forward bending moments than stacking at waist level or dropping the bag into position on the pallet (Fig. 5B). The latter conditions were not statistically different from one another in terms of PFB moment (p > 0.05). The bag level also affected PFB moments, with the lowest level of stacking resulting in higher PFB moments compared to the middle or top levels of stacking (regardless of whether palletizing condition was at the lower level or upper level) (p < 0.001). Finally, PFB moments were greater when the bag destination was farther from the conveyor as opposed to nearer (p < 0.001).

Peak Left Lateral Bending (PLLB) moments was affected by interactions between pallet orientation and bag destination (p < 0.01) as shown in Table 2. Peak Right Lateral Bending (PRLB) moments was affected by an interaction between bag level and bag destination (*Near* vs. *Far*) (p < 0.001) as shown in Table 2.

Peak Left Twisting (PLT) moments in *Position1* were affected by an interaction between palletizing condition and bag destination (p < 0.001). In this interaction, it appears that the *Near* distances resulted in lower PLT moments in waist level and dropping the bag below knee level; however, with controlled stacking below knee level, twisting moments were similar with both *Near* and *Far* bag destinations.

Peak Right Twisting (PRT) moments were affected by bag level, with *Level2* resulting in lower PRT moments than *Level1* or *Level3* (p < 0.01). PRT moments were also affected by an interaction between pallet orientation and bag destination (p < 0.001). This interaction is shown in Fig. 6 and the pallet on the *Side* of conveyor condition resulted in higher PRT moments, but these moments varied according to the respective interacting variable.

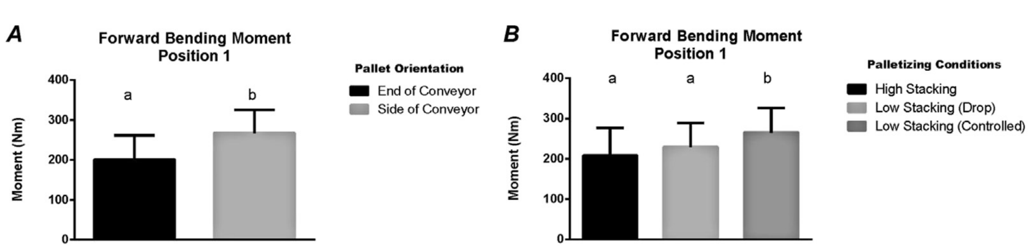

Fig. 5. **A**) Peak forward bending moments for *Position1*. L5-S1 moments were significantly higher when the pallet was placed on the *Side* of the conveyor (b) compared to the *End* of the conveyor (a). **B**) A controlled stacking technique when stacking below knee level resulted in significantly higher forward bending moments (b) than stacking at waist level or dropping the bag into position on the pallet (both a).

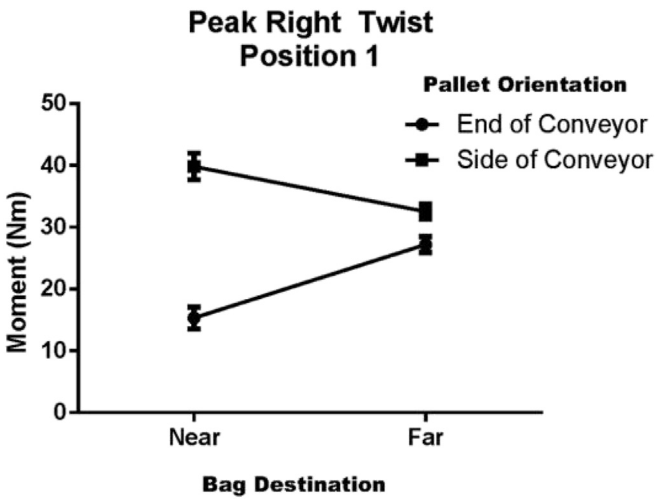

Fig. 6. Peak right twisting moment was affected by an interaction between pallet orientation and bag destination. L5-S1 moments were higher when pallet orientation was at the *Side* of the conveyor compared to the *End* of the conveyor, but the benefit of pallet orientation at the *End* of the conveyor was minimized with bag destinations that were further away.

Estimated peak spinal compressive and peak spinal shear forces for *Position1* (based on the net L5-S1 moment) were both affected by the main effects of pallet orientation, palletizing condition, bag level, and bag destination, with no significant interactions to report. This difference between lifting at the side versus the end of the conveyor resulted in a 840 N increase on the estimated peak compressive forces on the spine and a 90 N increase in estimated shear forces on the spine (Fig. 7).

3.2. Operator Position2 (operator is on the left side of pallet and moves towards the right to place bag on pallet)

PFB moments for operator *Position2* were affected by the main effect of bag level ($p < 0.001$) and an interaction between pallet orientation and palletizing condition ($p < 0.01$). The bag level main effect found that PFB moments were greater at the lowest pallet level (240.9 Nm) as opposed to medium and high levels (216.3 Nm and 222.8 Nm, respectively). The interaction demonstrated that the PFB moments were very similar between pallet orientations with

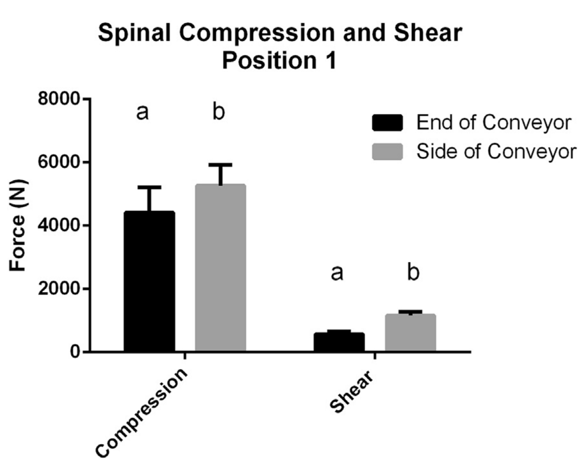

Fig. 7. Estimated peak compressive and shear forces on the spine for *Position1*. Compression and shear forces on the spine were higher when the pallet orientation was on the *Side* of the conveyor.

palletizing conditions of high placement and low level palletizing when dropping the bag on the pallet (*UPLcontrol* and *LPLdrop*); however, with low controlled palletizing (*LPLcontrol*), higher PFB moments were seen when the operator was positioned at the *Side* versus *End* of the conveyor.

PLLB moments in *Position2* were affected by an interaction of pallet orientation and bag destination ($p < 0.001$) and an interaction between palletizing condition and bag destination ($p < 0.001$) as seen in Fig. 8. For the former interaction, PLLB moments were generally higher at the *End* than at the *Side* orientation; however, PLB moments increased with bag destination when at the *End* of the conveyor, but decreased with bag destination when at the conveyor's *Side*. The crossover interaction between palletizing condition and bag destination indicated that PLLB moments were higher with *Far* lifts in the *UPLcontrol* condition, and higher with *Near* lifts in the *LPLcontrol* condition, while both *Near* and *Far* lifts resulted in equivalent PLB moments in the *LPLdrop* condition.

For PRLB moments, interactions were observed between bag level and bag destination ($p < 0.001$) and pallet orientation by bag destination ($p < 0.001$). The bag level × bag destination interaction was characterized by a generally high PRLB moments when bag destination was *Far*; however, as bag level increased (low to high) the magnitude of this difference diminished. The interaction of pallet orientation by bag destination indicated a large effect of bag destination when pallet orientation was at the *End* of the conveyor; however, PRLB moments were decreased when pallet orientation was at the *Side* of the conveyor, and the magnitude of the bag destination (N*ear* or *Far*) was much smaller when positioned at the *Side* of the conveyor.

Table 3 shows that PRT moments in *Position2* were affected by a triple ($p < 0.01$) interaction. This interaction did not demonstrate any clear or consistent pattern of response to the combinations of independent variables.

Estimated peak spinal compressive and peak spinal shear forces for *Position2* were both affected by an interaction of pallet orientation and palletizing condition ($p < 0.001$). Fig. 9 shows the interaction between pallet orientation and palletizing condition for spinal compression and spinal shear forces. The *End* and *Side* pallet orientations have similar compressive and shear forces for the low (drop) (*LPLdrop*) palletizing condition. However, the *Side* of conveyor pallet orientation is significantly higher than the *End* pallet orientation for the low (control) palletizing condition (*LPLcontrol*); while the opposite result is observed for the high palletizing condition (higher spinal compression and shear forces when positioned at the end of the conveyor).

4. Discussion

Design of operator workstations (such as a bagging workstation) can be an effective method of reducing the risk of worker injury. Of particular interest in the current study is the impact of the orientation of the pallet at the *End* of conveyor as opposed to the *Side* of the conveyor when performing palletizing operations with bags commonly found in industry. Results of this analysis clearly demonstrate that positioning the pallet at the *End* of the conveyor results in a significant reduction in loading on the lumbar spine compared to positioning the pallet on the *Side* of the conveyor. This may be due to the ability to use the momentum of the bag as it comes off of the conveyor when the pallet is at the conveyor end, as opposed to having to forcefully redirect the bag from its course along the conveyor when the pallet is located on the *Side*. For example, having the pallet at the *End* of the conveyor resulted in compression estimates that were over 840 N lower than when the pallet was located at the *Side* in *Position1*. This represents a 19% change in lumbar spine loading – a significant decrease.

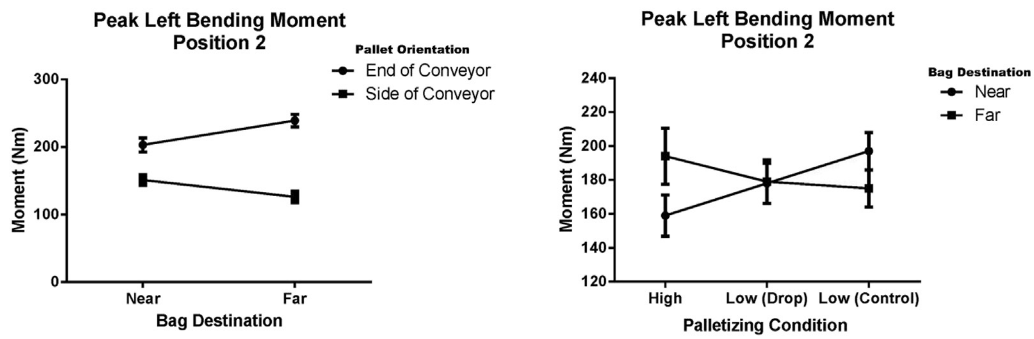

Fig. 8. Peak left bending moments were generally higher at the *End* than at the *Side* orientation; however, PLB moments increased with bag destination when at the end of the conveyor, but decreased with bag destination when at the conveyor's *Side* (left). The crossover interaction (right) between palletizing condition and bag destination showed that PLB moments were greater with *Far* lifts in the high condition, and higher with *Near* lifts in the low controlled condition, while both the N*ear* and *Far* lifts resulted in equivalent PLB moments in the low drop condition.

Not surprisingly, the technique of dropping the bag to lower levels (often observed in industrial bag palletizing operations) appeared to convey significant benefits when loading the lower levels of the pallet, when compared to controlled lifts to the lower pallet levels. In some cases, this technique was statistically "tied" in terms of the lowest lumbar stresses with lifting to the higher pallet level. In other situations it was rated as second-best to lifting to the higher pallet levels. Estimates of lumbar compression for the drop technique overall were approximately 600–800 N lower than those for controlled placement at the lower levels. Though some wastage of material could result from this practice, the benefits in terms of reduced spinal loading might still be a favorable trade-off for manufacturers.

Recent evidence has suggested that low back disorders (and most likely all MSDs) are likely the result of a process of fatigue failure in affected tissues (Gallagher and Heberger, 2013; Barbe et al., 2013). All known materials experience fatigue failure (i.e., material failure at submaximal levels of loading), including biomaterials tested in *in vitro* studies (Brinckmann et al., 1988; Schechtman and Bader, 1997; Gallagher et al., 2005, 2007). It would be surprising if biomaterials *in vivo* did not also share this inherent material property. Although no currently available ergonomics assessment tools have used fatigue failure theory to assess MSD risk, several tenets of fatigue failure theory may help provide some context to the results presented in this paper.

One fundamental precept of fatigue failure theory is that if a tissue is loaded at a high level of stress relative to its Ultimate Stress (US) – the stress at which it will fail in one cycle – it will fail in a rather limited number of loading cycles. If the material is loaded repetitively at 80% of its US, it can still be made to fail, but it may take 100 cycles to do so. Loading at 50% of ultimate stress may cause failure in 1000 cycles. Interestingly, for many materials there exists a so-called "endurance limit" (usually at around 30% US) where materials can be loaded for a very large number of cycles – in some cases indefinitely – without failure (Ashby et al., 2010). It is also important to recognize that since the fatigue failure curve is indexed to the US of a material, individuals with different US values will incur damage at different rates when exposed to the same absolute load. For example, exposure to a 3000 N load may be acceptable for an individual with a spine whose US is 12 kN, but the same load may lead to more rapid damage accumulation for an individual with a spine whose US is 5 kN.

When considering the effects of bagging workstation design demonstrated in this paper, it is clear that certain decisions in the setup of a workstation may lead to significantly increased (or decreased) risk of LBDs in manual bag palletizing. The 840 N decrease in lumbar spine loading associated with placing the pallet at the end of the conveyor will decrease the rate of cumulative damage incurred by spinal tissues, as would the 600–800 N decreased spinal loading associated with dropping the bags when

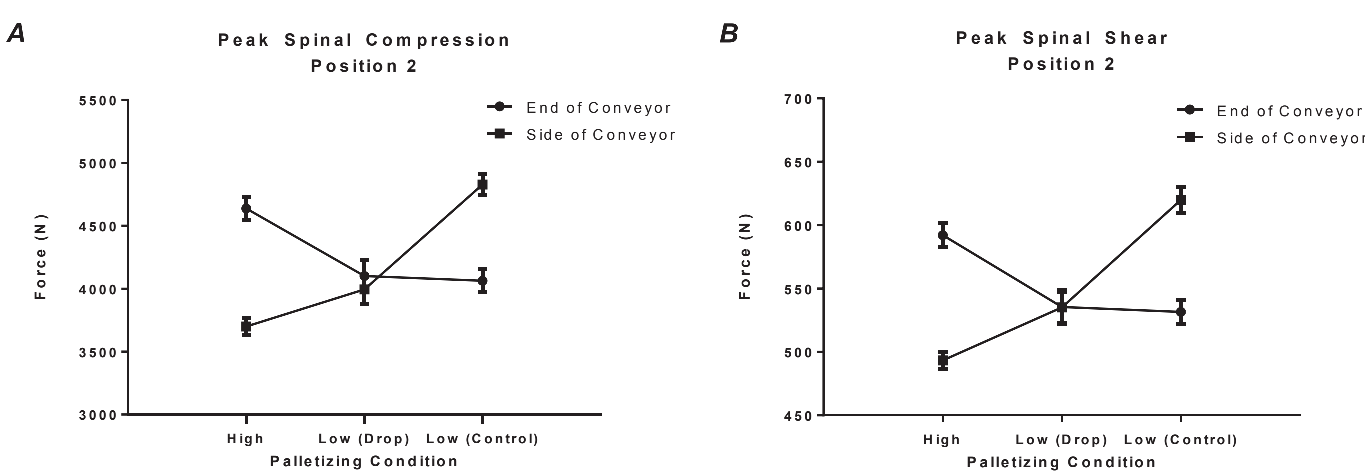

Fig. 9. **A**) and **B**) The interaction of pallet orientation and palletizing condition for spinal compression forces and spinal shear forces indicates compression and shear forces at the side-of-conveyor orientation are significantly higher than the *End*-of-conveyor orientation at the low controlled palletizing condition; however, the opposite occurs with the high palletizing condition.

palletizing the lower levels (compared to controlling the bag at the end of the lift). Furthermore, maintaining a lifting level at or around waist level (similar to the high lifting conditions in this study) will reduce lumbar loading to a similar degree, as demonstrated previously (Jorgensen et al., 2005; Marras et al., 1997; Davis et al., 2010). The reduced loading associated with such design changes will reduce the rate of cumulative damage in spinal tissues in accordance with fatigue failure theory. Nevertheless, it is important to recognize that reducing the rate of damage does not necessarily translate to lack of development of cumulative trauma in the lumbar spine. However, if the compressive loading is reduced to a low percentage of an individual's US (e.g., 30% US), damage can be minimized and healing of damaged tissue may be possible.

It is apparent that significant loads on the lumbar spine can be experienced even when palletizing 11.3-kg bags. However, this load is much lower than is usually handled in actual bagging operations, where bags can range from 23 to 46 kg. As manual bag palletizing is a task that involves both high loads on the lumbar spine and high rates of repetition, the risk of LBDs would be quite significant based on previous epidemiology data (Gallagher and Heberger, 2013), and fatigue failure theory. Clearly the preferred method of bag palletizing is through the use of robots or use of mechanical aids such as vacuum hoists (Gallagher et al., 2011). However, if no such method is available, several aspects of the bag stacking workplace design can help to reduce the loads on workers. This study suggests that positioning of the pallet at the end of the conveyor (as opposed to the side) can reduce lumbar loading significantly (>800 N). If possible, pallets should be positioned at the end of the conveyor. Lumbar loads are also lower when dropping the bag to lower levels of the pallet rather than placing the bag with control. Such a technique is recommended if lift tables are not available.

The main limitations of this study include the use of 11.3-kg bags, rather than bags found in industry that usually weigh 23–46 kg. Using a heavier bag would have resulted in significantly increased loads on the lumbar spine. In addition, the study participants were not experienced with palletizing tasks and their methods may differ from more experienced materials handlers. Loads on the spine may also be influenced by such differences in lifting technique.

Results of this study will be used to inform the development of an audit tool for bagging operations in the mining industry as described by Dempsey et al. (2012), as well as to make recommendations for design of bag palletizing workstations. In particular, based on our conclusions it is recommended that where possible, companies with manual palletizing operations design their systems so that pallets and workers who are palletizing are positioned at the end of the conveyor belt.

5. Conclusion

On the basis of the results of this study, the following conclusions are drawn:

1. The peak forward bending moment experienced when the pallet is oriented on the side of the conveyor is significantly higher than when the pallet is located at the end of the conveyor. Placing the pallet on the side of the conveyor increased the estimated compressive loading on the spine by over 800 N.
2. Controlled stacking at the lower levels of the pallet resulted in higher peak forward bending moments than stacking at the higher pallet levels or dropping the bags to the lower pallet level. The difference in estimated lumbar compressive loading ranged from 600 to 800 N.
3. Estimates of average peak lumbar compressive forces exceeded the 3400 N Action Limit recommended by NIOSH even when lifting 11.3-kg bags. Bags in industry may weigh up to 46 kg, which would lead to extremely dangerous compressive forces.
4. Proper design of the palletizing workstation can help to reduce lumbar loading to a degree; however, manual bag palletizing (even when designed properly) is a task that tends to involve high repetition and high lumbar loads, the combination of which leads to a dramatic escalation of LBD risk (Gallagher and Heberger, 2013).

Disclaimer

The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health.

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