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Effectiveness of a vacuum lifting system in reducing spinal load during airline baggage handling

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ABSTRACT

Information on spinal loading for using lift assist systems for airport baggage handling is lacking. We conducted a laboratory study to evaluate a vacuum lift system for reducing lumbar spinal loads during baggage loading/unloading tasks. Ten subjects performed the tasks using the industry average baggage weight of 14.5 kg on a typical two-shelved baggage cart with or without using the lift system (i.e. lifting technique). Repeated measures analysis of variance (2 tasks × 2 shelf heights x 2 techniques) was used. Spinal loads were estimated by an electromyography-driven biomechanical model. On average, the vacuum lift system reduced spinal compressive forces on the lumbar spine by 39% and below the 3400 N damage threshold. The system also resulted in a 25% reduction in the anterior-posterior shear force at the L5/S1 inferior endplate level. This study provides evidence for the potential to reduce spinal loads when using a vacuum lift system.

1. Introduction

Baggage handlers working at airports are at risk of developing musculoskeletal disorders (MSDs) (Dell, 1998; Tafazzol et al., 2016; Thygesen et al., 2016). In 2015, the overall annual incidence rate of work-related injuries resulting in days away from work, job transfer, or restricted work for the airport passenger transportation industry was 5.1% (The Bureau of Labor Statistics or BLS, 2016). This most recent rate was more than 3 times the rate for the private industry (1.6%) as a whole, and the third highest in all job classifications used by BLS (2016). Most injuries in baggage handlers are musculoskeletal in nature, particularly in the lower back and shoulder regions (Tafazzol et al., 2016; Bergsten et al., 2015; Thygesen et al., 2016). A previous study shows that 55% of airline employees' back injuries may be attributed to baggage handling (Reddell et al., 1992).

Airline companies employ baggage handlers to handle baggage transfer in various locations of an airport. Two main locations for baggage transfer are the ramp and the baggage make-up areas. The ramp (or tarmac) area is an area where baggage handlers provide services to an aircraft between the time it arrives at a terminal gate and the time it departs. The make-up area is an area where baggage handlers receive checked baggage and distribute it to gates for departure or receive baggage from aircrafts and distribute it to baggage claim areas. In the ramp area, baggage handlers' services typically include directing aircrafts to gates, securing aircrafts by placing wheel chocks, transferring checked baggage on and off aircrafts, and operating equipment for other ground operations. For departure flights, conveyor systems are typically used for transporting checked bags from ticketing counters to the baggage make-up area. In this area, bags are transferred manually by baggage handlers from the conveyor systems to baggage carts. Subsequently, a baggage handler drives the carts to the ramp area for unloading bags to an aircraft with other baggage handlers. For an arrival flight, they reverse the process by unloading bags from an aircraft to carts, followed by transferring bags from the carts to the conveyor systems in the baggage make-up area. Finally, the conveyor systems transport bags to baggage claim areas. In addition to handling checked bags, baggage handlers are also engaged in transferring bags that are checked at the gate.

High MSD rates in the baggage handlers are likely to be attributed to the manual processes of baggage handling, in particular operations in the ramp area (Oxley et al., 2009). In this area, baggage handlers are required to manually handle and lift baggage from baggage carts to a belt loader or power lift platform, either of which is positioned to the doorway of the cargo hold or compartment of an aircraft. One to two baggage handlers receive baggage from the belt loader or power lift system and manually stack bags in the cargo hold. For off-loading, baggage handlers unstack bags in the cargo hold and reverse the loading process to load baggage to carts. Baggage handling tasks in the

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ramp area have been shown to be associated with a variety of physical risk factors for MSDs, including heavy and frequent lifting, awkward body posture, and pushing and pulling (Bern et al., 2013; Bergsten et al., 2015). The mean values of checked baggage weights have been reported to be about 15 kg in two previous studies (Thygesen et al., 2016; Tafazzol et al., 2016). During our walk-through survey at the Greater Cincinnati/Northern Kentucky Airport (airport code: CVG), we obtained baggage weight data on all checked bags during a typical work day. Based on a total of 2960 measurements, the mean and median values of the baggage weights were 14.5 kg and 15 kg, respectively. Although airlines limited the maximal weight for coach class checked bags, a small percentage (3%) of checked bags in our survey was found to exceed the weight limit of 23 kg. The baggage that exceeded the weight limit may have resulted from the first class checked bags that generally were not subject to the weight limit. In short, the above baggage weight information suggests frequent heavy lifting for baggage handlers; and in some cases, their manual lifting tasks exceed the maximal recommended weight limit of 23 kg for safe lifting (NIOSH, 1994; ISO, 2003).

Some have found lifting with certain mechanical lift assist systems to be effective in reducing the risk of MSDs in baggage handlers, as compared to manual lifting (Tapley and Riley, 2005; Oxley et al., 2009). These studies evaluated the lifting assist systems via an observational method and subjective risk rating (Tapley and Riley, 2005). The purpose of the present study is to use an objective risk assessment method to evaluate a new vacuum lifting assist system that has yet to be examined in any formal scientific investigation. Vacuum lift systems may be used in the ramp and make-up areas and are hypothesized to reduce the risk of musculoskeletal injury, especially to the low back.

2. Methods

2.1. Approach

A typical airline baggage handling operation in the ramp area was replicated in a controlled laboratory environment in order to evaluate the effectiveness of a vacuum lifting assist system (Vaculex Inc. model TP) in reducing biomechanical loading to the lumbar spine (T12/L1-L5/S1). The baggage operation involved loading baggage from a conveyor to a baggage cart and vice versa. The effectiveness of the vacuum lifting assist system was evaluated by comparing the magnitudes of spinal loading variables with and without using the lifting aid for the baggage loading/unloading operation.

2.2. Lifting assist system

The lifting assist system evaluated in the present study is a powered vacuum lifting aid with a capacity of 50 kg. A controller is attached to one end of the vacuum hose that provides suction power. The other end of the hose is connected to an electric pump mounted in a silencing box measuring 52 × 75 × 51 cm in size. When the pump is turned on, constant suction is provided even when no bag is attached to the controller. The lifting assist system can handle a variety of bags in different shapes, sizes, and soft and hard fabrics. Once the bag is picked up by the controller, the operator can rotate the bag freely in 360° direction to fit where needed. When the bag is picked up, the height of the bag can be controlled by operating the handle. The operator can move the bag with the handle of the controller within the perimeter allowed by the length of the articulating arm. When the bag is moved to the destination, the operator disengages the bag from the controller by depressing a thumb trigger located above the handle.

2.3. Participants

Ten subjects (8 males and 2 females) were recruited for this study (age 26.2 ± 6.3 years, mass 77.9 ± 10.9 kg, and stature 177.2 ± 7.3 cm). They were asymptomatic for low back pain within the past 6 months at the time of study participation. The subjects were novice users of the vacuum lifting assist system and had no prior experience with workplace baggage handling. They were right hand-dominant except for one male, though exertions were performed using the same technique across all subjects independent of handedness. The subjects wore protective hard toe shoes for protection in case a bag was dropped during experimental trials.

2.4. Study design

A repeated measures two-way analysis of variance (ANOVA) was used for assessing the effects of three main experiment factors, including technique (i.e., manual lifting or lifting with vacuum lift system), task (i.e., loading or unloading suitcase) and baggage cart shelf height (61 cm or 133.4 cm), on lumbar spinal loads. Trials were counter-balanced across subjects based upon task, while both shelf height and technique were randomized. There were three repetitions of each experimental condition, with repetitions performed sequentially.

2.5. Apparatus and instrumentation

Kinematic data were captured using a 22 camera OptiTrack infrared motion capture system (NaturalPoint, Corvallis, OR, USA). Kinematic data were collected at 120 Hz and were low-pass filtered using a conservative zero-phase fourth-order Butterworth filter with a cutoff frequency of 10 Hz. Kinetic data were collected during model calibration using a force plate (Bertec 4050A, Bertec, Worthington, OH, USA) sampling at a frequency of 1000 Hz.

EMG were captured with a Motion Lab Systems MA300-XIV (Motion Lab Systems, Baton Rouge, LA, USA) at 1000 Hz using bipolar surface electrodes placed bilaterally over the erector spinae, latissimus dorsi, rectus abdominis, external oblique, and internal oblique muscles with an inter-electrode distance of 3 cm. These data were notch filtered at 60 Hz and its aliases, band-pass filtered at 30–450 Hz, rectified, smoothed using a moving average filter, and normalized/personalized via a non-MVC calibration procedure described by Dufour et al. (2013).

A representation of the simulated airline baggage handling operation is shown in Fig. 1. The height of the conveyor was fixed at 51 cm from the floor. A powered lift table was used to simulate two different shelf heights of a baggage cart. A conference table 74 cm in height was placed on top of the power lift table to simulate the roof of the baggage cart. Adjustments to the shelf height of the simulated baggage cart were made using the powered lift table.

2.6. Experimental procedure

Subjects were informed of the risks and benefits of the study and signed an informed consent document per the university institutional review board requirements. Prior to trials, EMG sensors were placed onto ten power-producing trunk muscles according to standard placement procedures (Mirka and Marras, 1993). Forty-one optical motion capture markers were placed onto the body from head to toe for capturing body kinematic information consistent with the baseline placement locations specific to OptiTrack's motion capture software (Motive v1.10.1); this marker set provided the location and orientation of all the body segments with submillimeter accuracy.

Once prepped with all of the required sensors, subjects performed a series of basic calibration exertions while standing on a force plate. These exertions consisted of dynamic concentric and eccentric lumbar motions in multiple planes performed at a comfortable self-selected pace while holding a 9.07 kg weight. These exertions encouraged dynamic ranges of muscle length, muscle velocity, and muscle activity, and the data derived from these exertions were used to optimize personalized muscle and other model properties individual to each subject. Previously described by Dufour et al. (2013), this calibration procedure

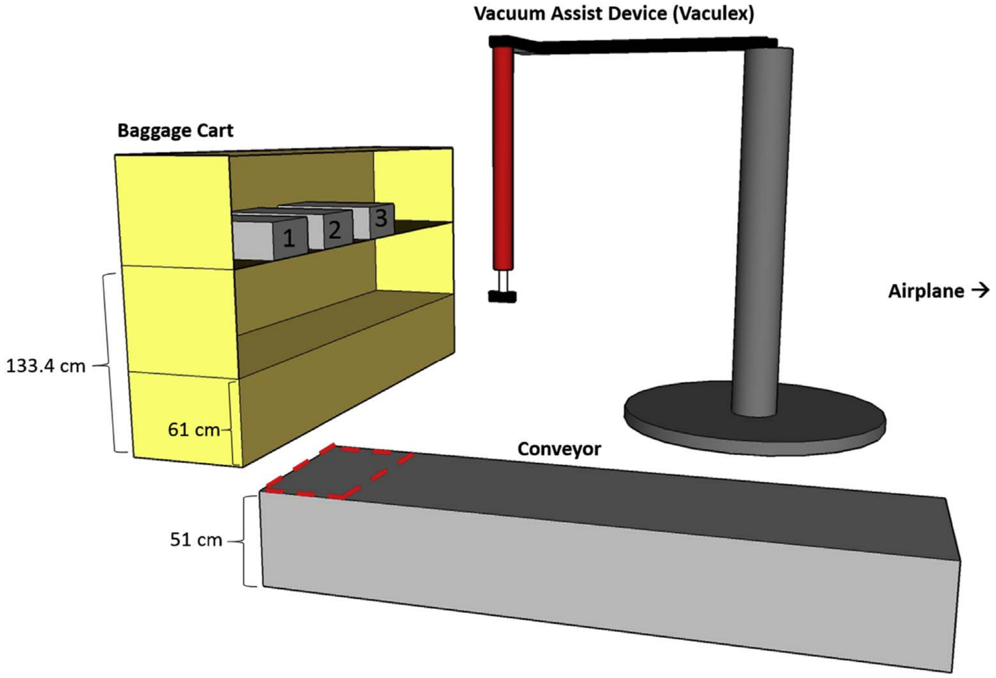

Fig. 1. Schematic of the simulated airline baggage handling operation. In the laboratory, a power lift table was used to simulate a typical baggage cart with two shelves. Stacked plastic shelves were used to simulate the end of a conveyor used for loading baggage to the compartments of an airplane in the ramp area. The area marked by dotted red lines was the lift origin and destination for baggage loading and unloading tasks, respectively. Three identical suitcases weighing 14.5 kg were used for three repeated trials for each test condition. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

also eliminated the need to collect maximum voluntary contractions (MVC) for EMG normalization.

After model calibration, subjects were trained for thirty minutes on the vacuum lift assist system, practicing both baggage loading and unloading. In both training and experimental trials, subjects were instructed to transport a suitcase (Travelers Choice Travel Select Amsterdam; Model: TS6950R25) from a mocked up conveyor to a baggage cart (loading) or from a baggage cart to a conveyor (unloading). The suitcase was 63.5 × 38.1 × 22.9 cm in size and 14.5 kg in weight (i.e., the industry average weight). Rock salt was used and evenly distributed in the suitcase to bring up to the average weight. Subjects were instructed to load or unload the suitcase on two different baggage cart heights either manually or with the help of the vacuum lifting assist system. Baggage handling technique was fixed for all trials in which the left hand was always placed on the handle at the top of the baggage (opposite the roll wheels) and the right hand was placed either onto the handle of the vacuum lifting assist system or the handle at the bottom of the baggage (near the roll wheels) depending on the technique being investigated for that particular trial. Three repetitions of each trial type were performed sequentially using three suitcases of the same make and weight. Subjects were instructed to perform each trial at a relaxed pace.

2.7. *Data processing*

Kinematic data derived via motion capture, kinetic data recorded during model calibration, electromyographical data for the power-producing muscles of the torso, subject anthropometry, MRI-derived muscle cross sectional areas and moment arms (Jorgensen et al., 2001; Marras et al., 2001), and tissue mechanical properties were processed together as inputs to the aforementioned EMG-driven biomechanical spine model. This model has been used extensively to evaluate both lifting and pushing and pulling. It has also been well-validated within the scientific literature (Marras and Sommerich 1991a, 1991b; Granata and Marras 1993, 1995; Knapik and Marras, 2009; Dufour et al., 2013; Hwang et al., 2016). Model outputs included peak spinal loads in each dimension of loading (compression, A/P shear, and lateral shear) for the superior and inferior endplate levels from T12/L1 down to L5/S1.

2.8. *Statistical analysis*

A total of 240 trials were analyzed using JMP 11.0 (SAS Institute Inc., Cary, NC, USA) for the two-way ANOVA with a significance level of $\alpha = 0.05$. Independent variables for the ANOVA included technique, task and baggage cart shelf height, as well as all possible two-term interaction effects. Dependent measures for statistical analysis were the peak spinal loads in each dimension of loading (compression, A/P shear, lateral shear) at the vertebral endplate in which the highest magnitude of loading was observed. All data were evaluated for statistical significance but were also interpreted relative to assumed biomechanical and biological significance in which only differences in spinal loading of 100 N or more between experimental conditions will be discussed further. Biomechanical and biological significance was operationally defined and is based upon both the resolution of the EMG-driven spine model employed. These spinal loads were also subsequently assessed in terms of biomechanical risk and were analyzed relative to documented damage thresholds for spinal loading (NIOSH, 1981; Gallagher and Marras, 2012).

3. Results

Significant main effects for each of the three independent variables as well as a Task * Shelf interaction effect were observed. Technique*Task and Technique*Shelf interactions did not reach statistical significance. The effects of the independent variables and their interactions on the risk of low back disorders are reported in terms of three different spinal loading variables.

3.1. *Spinal compression*

The highest magnitude of spinal compression was observed at the L3/L4 Inferior endplate level; main and interaction effects for L3/L4 Inferior compression can be found in Fig. 2. Notably, the use of the vacuum lifting assist system significantly reduced spinal compression ($p < 0.0001$). While 34.4% of all trials employing manual handling methods recorded values of spinal compression over the 3400 N NIOSH action limit, use of the vacuum lift aid reduced spinal compression by 39% on average and placed compressive spinal loads under this damage threshold for all subjects and trials.

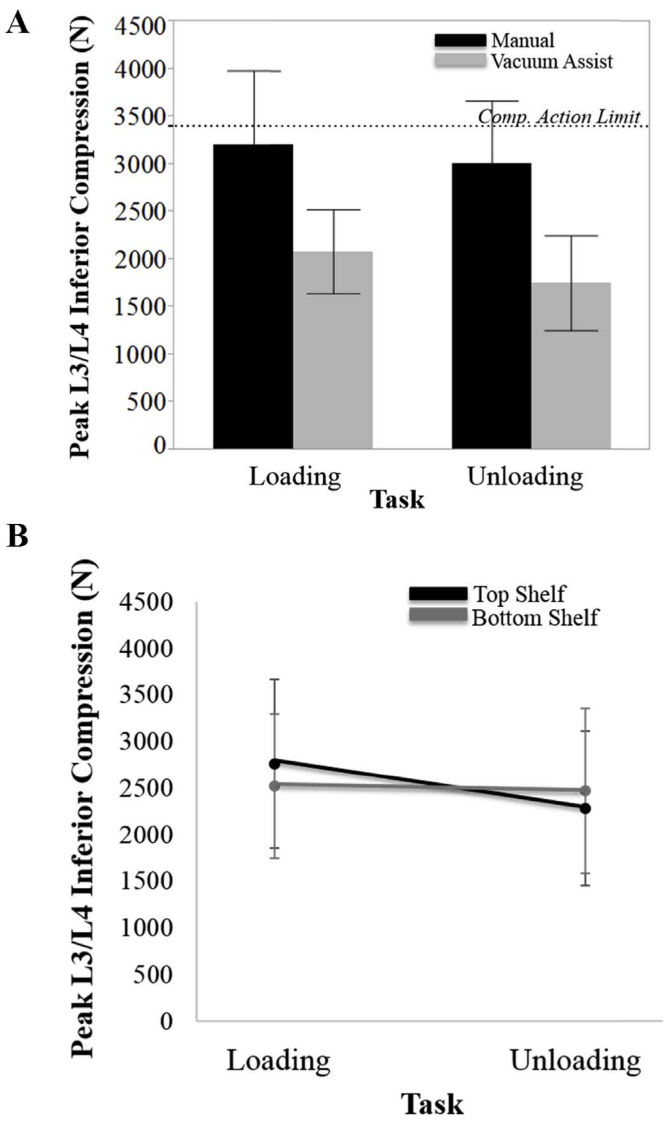

Fig. 2. (A) Main effects of task and technique on L3/L4 Inferior compressive spinal load showing decreased compression for unloading task and vacuum assist use (B) Task*shelf interaction effect for spinal compression.

In terms of the other independent variables, peak spinal compression was 10.9% higher on average across all endplate levels when loading suitcases compared to unloading ($p < 0.01$). There was also a significant task * shelf interaction observed in which loading suitcases onto the top shelf resulted in higher magnitudes of spinal compression compared to the bottom shelf condition, whereas unloading suitcases from the top shelf resulted in lower magnitudes of spinal compression compared to the bottom shelf condition ($p < 0.001$).

3.2. *A/P shear*

The highest magnitude of A/P shear was observed at the L5/S1 Inferior endplate level. At this endplate, use of the vacuum lift aid significantly reduced A/P shear ($p < 0.001$) by 25% (Fig. 3). Whereas five male and two female subjects had at least one exertion above the 700 N damage threshold for shear loading using manual handling techniques (31.9% of all trials), only two male subjects had exertions above the damage threshold for shear loading using the vacuum assist device (1.7% of all trials). L5/S1 Superior A/P shear was also increased for loading suitcases relative to unloading ($p < 0.001$).

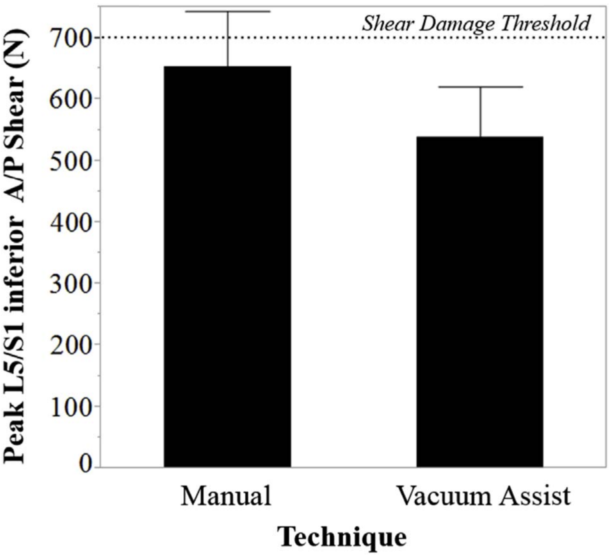

Fig. 3. Peak L5/S1 Inferior A/P shear for manual and vacuum assist techniques. Use of the vacuum assist device was accompanied by a 25% reduction in A/P shear.

3.3. *Lateral shear*

The highest magnitude of peak lateral shear forces were observed at the L5/S1 Superior endplate. Though statistically significant effects of technique, shelf, and task*shelf interactions were observed, none of these effects were deemed biologically significant. All experimental conditions tested were determined to be of low lateral shear risk for all subjects; thus, lateral shear results were not interpreted further.

4. Discussion

Using an observational method for posture risk analysis, Oxley et al. (2009) concluded a hierarchy of MSD risk reduction for airport baggage handling using the following work methods: EBL, belt loader, power lift platform and manual loading methods. However, none of the methods eliminate manual baggage handling from baggage carts to any of the lifting assist systems or vice versa. We evaluated a vacuum lift system as an add-on risk reduction intervention for this particular manual baggage handling operation.

Using the vacuum lift assist system for baggage lifting produced significant reductions in all three spinal loading variables (compression, AP and lateral shear forces) both statistically ($P < 0.05$) and biomechanically (> 100N). On average, the vacuum lift assist system reduced spinal compressive forces on the lumbar spine by 39% and placed spinal compressive loads below the 3400 N damage threshold (NIOSH, 1981) for typical baggage loading and unloading tasks in the ramp area. The system also reduced A/P shear forces significantly across the intervertebral discs in the lumbar spine – notably, a 25% reduction in the A/P shear force at the L5/S1 inferior endplate level. Because increased spinal loads have been associated with occurrences of low back disorders (Chaffin and Park, 1973; Herrin et al., 1986; Marras et al., 1995; Marras, 2000), reductions in the spinal loading variables for using the vacuum lifting assist system may have a great potential for prevention of low back disorders in baggage handlers.

It is expected that reductions in peak spinal load when using the Vaculex arose from several factors. The most likely mechanism for load reduction from the Vaculex comes from its ability to support the entire weight of the bag. Since the load is often both heavy and located far away from the spine during baggage handling, offloading the weight of the bag would greatly reduce the external moment exposure, which in turn would require less force to be produced by the muscles and lower spinal loads. Admittedly, the vacuum lift intervention still requires pushing and pulling forces exerted by the user of the device to Vaculex arm (not quantified in this study). However, these forces are exerted at a shorter moment arm relative to the spine and do not appear to be enough of an additional moment generator to neglect the benefits of supporting the weight of the bag. Another potential mechanism by which the Vaculex could have decreased loading in this investigation is by reducing the moment created by the upper body due to observed reduced torso flexion. As subjects could pick up bags by engaging the vacuum system on top of each bag as opposed to having to grab underneath it (as is necessary in manual baggage handling), the intervention's use facilitated reduced sagittal torso flexion and subsequently a reduced moment placed onto the lumbar spine due to the mass of the torso itself. Since the contributions of each of these two factors are difficult to separate and were not the focus of this study, we can only hypothesize their influence. However, we hypothesize that because changes in peak spinal loads were rather drastic (up to 39%), the changes observed are expected to be attributed much more to the reduced external moment on the spine from the vacuum assist device supporting the entire weight of the bag than the reduced external moment from a slightly less flexed torso.

The vacuum lift assist system used in the present study was evaluated in the field in Lu et al.'s study (2014) using the University of Michigan's Three Dimensional Static Strength Prediction Program (3DSSPP). That study recorded a mean 63% reduction in spinal compressive force at the center of the L4/L5 intervertebral disc as a result of using the vacuum lift system. In the present study, the mean (39%) reduction in spinal compressive force as a result of using the same lift assist system is smaller than that recorded in the prior study. However, unlike static 3DSSPP models, the biomechanical model employed in the present investigation is dynamic and accounts for trunk muscle coactivity. Previous studies have reported that biomechanical models that do not account for trunk muscle coactivity can significantly underpredict spinal loads (Granata and Marras, 1995; Granata et al., 2005), which may account for the differences observed. In other words, the 3DSSPP did not account for the risk associated with dynamics of baggage lifting while using the vacuum lift system, which resulted in an increased risk reduction, as compared to our findings.

It should be noted that the spinal loading information presented in the present study was based on lifting the average baggage weight (14.5 kg). Lifting bags greater than the average weight may lead to an increased risk of low back disorders, as peak spinal load has been shown to be the most sensitive predictor for low back disorders (NRC/IOM, 2001). Although spinal loading information is unavailable for lifting heavier baggage in the present study, it is anticipated that using the lift assist system would reduce greater magnitudes of the spinal loading variables for heavier baggage than the average baggage weight. The rationale for this anticipation is that the external forces to the human system are generally in proportion to the weight lifted while the required hand force for using the lifting assist system varies from only 2–4 lbs. for bags weighing from 11 to 23 kg (Lu et al., 2014).

Two way interaction of task and shelf (Fig. 2B) indicates that among all four possible tasks with the two variables, loading baggage onto the top shelf resulted in largest magnitudes of the spinal compressive force at the L3/L4 inferior plate, while unloading baggage from the top shelf resulted in lowest magnitudes of compressive force. Loading and unloading the bottom shelf did not have a significant difference in the compressive force. The similar compressive forces for loading and unloading baggage on the bottom shelf were the direct results of the similar lifting heights (51 and 61 cm) of the origin and destination of the lifting trials. Although the mean of the spinal compressive forces for loading and unloading baggage on the top shelf may be comparable to that for loading and unloading baggage on the bottom shelf, loading baggage to the top shelf should be avoided. This is because the peak risk exposure occurred during loading baggage to the top shelf. If the vacuum lift assist system may be used, it should be prioritized for loading baggage to the top shelf of a baggage cart. Although we evaluated baggage handling tasks in the ramp area, the loading/unloading baggage tasks are also common in the baggage make-up area. Therefore, the vacuum lift system can be used in the make-up area for overall risk reductions. In addition, because of the one-handed operation, the vacuum lift assist system is particularly useful when one-handed baggage lifting is required in some work conditions.

Job rotation, frequent breaks, and different lifting methods for stacking baggage are administrative controls that may help reduce the risk of MSDs (Dell, 1998; Korkmaz et al., 2006; NIOSH, 2007). Other than physical risk factors for MSDs, baggage handlers are exposed to low job control, time pressure, low social support and dissatisfaction with leadership (Rosskam, 2007; Bergsten et al., 2015). The workplace psychosocial factors may interact with body biomechanics for baggage lifting, which may result in increased risks of MSDs (NIOSH, 1997; Marras et al., 2000; Chany et al., 2006; Da Costa and Vieira, 2010). When evaluating the vacuum lift assist system in the field, one should consider the psychosocial risk factors for MSDs in addition to the spinal loading variables.

Limitations of the study include the laboratory-based task simulation, one type of bag, the self-paced lifting frequency, the use of subjects that had no prior experience in baggage handling, practicality issues, and the limited number of subjects, particularly in female sex. The reason for using two female subjects in the study was based on an estimate of female population (20%) in the baggage handling industry. The effect of sex on the spinal loading variables was not observed (results from ANCOVA; data not shown). This finding is likely to result from an insufficient statistical power for detecting the sex effect. More research is recommended for clarifying the role sex plays in affecting magnitudes of spinal loading for baggage handling. The frequency of baggage handling depends on the flight schedule, time of year, number of passenger and number of baggage handlers (Oxley et al., 2009). Self-paced lifting frequencies and techniques used in the present study may not be realistic when baggage handlers are required to lift bags under time pressure during rush travel times. The use of college students as subjects instead of experienced baggage handlers may ignore the effect of muscle coordination and efficiency used by baggage handlers in reducing the spinal loading variables (Chany et al., 2006; Marras et al., 2006). Finally, while results of the present study clearly show the biomechanical benefits, the practicality of the vacuum lift system is unclear. Given the different sizes, shapes, surface types and conditions of bags (e.g. how dirty or slippery) as well as power accessibility, the ability of the vacuum lift system to operate under these real world conditions should be explored. Productivity of using the vacuum lift system is not assessed in the present study. Therefore, the ability of the vacuum lift system to keep up with required productivities is unknown.

5. Conclusions and recommendations

Using a vacuum lift assist system resulted in significant reductions in spinal loading variables (39% for compressive force; 25% in AP shear force) in the lumbar region for loading and unloading a baggage cart to the aircraft cargo hold in the ramp area. If manual baggage lifting is necessary, lifting baggage from the conveyor or belt loader to the top shelf of a baggage cart should be avoided. Similarly, if the vacuum lift assist system is to be used, loading baggage to the top shelf of a baggage cart should be prioritized among other tasks to reduce peak risk exposures.

Acknowledgments

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