Applied Ergonomics 58 (2017) 398–404

Contents lists available at ScienceDirect

Applied Ergonomics

journal homepage: www.elsevier.com/locate/apergo

An electromyographic and kinematic comparison between an extendable conveyor system and an articulating belt conveyor used for truck loading and unloading tasks

Steven A. Lavender [a, b, c, *], Shasank Nagavarapu [a], W. Gary Allread [a, c]

[a] Integrated Systems Engineering, The Ohio State University, United States
[b] Orthopaedics, The Ohio State University, United States
[c] Institute for Ergonomics, The Ohio State University, United States

ARTICLE INFO

Article history:
Received 2 January 2016
Received in revised form
26 July 2016
Accepted 27 July 2016
Available online 10 August 2016

Keywords:
Musculoskeletal disorders
Distribution centers
Conveyor systems

ABSTRACT

Many retail distribution centers (DCs) manually load and unload boxes into or out of trailers and shipping containers. This study investigated whether an articulating belt conveyor with a height adjustable platform, positioned at the end of an extendable conveyor, significantly reduces shoulder and back muscle loading and the spine kinematics associated with these tasks. Electromyographic and kinematic data were collected from eight volunteer employees as trailers at a shoe DC were unloaded and from nine volunteer employees as trailers at an apparel DC were loaded. Participants in this repeated measures study handled boxes with a conventional powered extendable conveyor system and with the articulating belt conveyor positioned at the end of the extendable conveyor. Bilaterally the normalized activation levels of the erector spinae and anterior deltoid muscles were reduced when loading and unloading boxes with the articulating belt conveyor. Spine movement speeds were also reduced with the articulating conveyor.

1. Introduction

Injury data from the warehousing and storage industry indicates there are a significant number of musculoskeletal injuries occurring within this sector (BLS, 2013). Some of the higher risk back injury jobs within distribution centers are those where people are manually unloading and loading trailers or containers (Lavender et al., 2012). In the inbound operation with “floor-loaded” trailers, people are manually moving each individual box to a pallet or an extendable conveyor. Likewise, in the outbound operation, many trailers are floor-loaded by removing material from extendable conveyors and manually stacking the material within the trailers. Given that the rationale for floor-loading rather than pallet loading is to minimize unused space in the containers or trailers, people in these jobs will be placing cases from floor level to levels very near the ceiling of the trailer or container, which for trailers in the United States is approximately 2.8 m.

Articulating belt conveyors that can be interfaced with the extendable conveyor used for loading and unloading trailers have been developed to bridge the gap between the wall of boxes being loaded or unloaded and the extendable conveyor used for moving materials into or out of the trailer. Ideally, the articulating conveyor is designed so the distal end can be laterally and vertically shifted so that it can be positioned directly in front of the loading or unloading site, as this potentially allows the handled materials to be slid, rather than lifted, when unloading operations are performed. Likewise, when performing a loading function, a well-positioned articulating belt conveyor should allow material to be essentially pushed or guided into position. As a result, the biomechanical loads experienced by the operator should be reduced, as there should be less actual lifting, thereby reducing the risk of employee injury.

Many ergonomic interventions are introduced with the assumption that they will improve the health and safety of the targeted workers. However, there is often little evidence gathered as to whether these interventions actually reduce the physical demands on worker. Therefore, the primary goal of this study was to objectively evaluate the biomechanical and kinematic impact of using an operator-controlled, powered articulating conveyor belt to assist with the manual loading and unloading of trailers.

* Corresponding author. Integrated Systems Engineering, 1971 Neil Avenue, Rm. 210, Columbus, OH 43210, United States.
E-mail address: Lavender.1@osu.edu (S.A. Lavender).

http://dx.doi.org/10.1016/j.apergo.2016.07.016
0003-6870/

Specifically, this study investigated whether this type of device could reduce the demands on back and shoulder muscles, and reduce the spine motions of workers as they manually unloaded and loaded trailers. Specifically, this study tested the hypothesis that an articulating belt conveyor, which can move both vertically and horizontally and which provides an elevating work platform, can reduce the activation levels of the back and shoulder muscles and reduce the spine motions as trucks are unloaded and loaded relative to conventionally used methods.

2. Methods

Two investigations, one for unloading trailers and one for loading trailers, were conducted at two different facilities as workers unloaded inbound and loaded outbound trailers. The data for the unloading operation were obtained at a shoe distribution center. The data for the loading operation were obtained at a "T-shirt" apparel distribution center. In both distribution centers the data were collected during normal operations. Thus, for each participant, efforts were made to keep the material handled, and therefore the size and weights of the cases, consistent across conveyor conditions.

2.1. Participants

In the unloading study, the eight recruited volunteers, seven male and one female, were between the ages of 20 and 57 years and had between 1.5 and 31 years of distribution center work experience. The mean height and weight of the participants was 1.75 m (1.60–1.88 m) and 81.3 kg (59–105 kg), respectively. The maximum vertical reach height for these participants ranged from 2.06 to 2.39 m (mean 2.23 m). The equipment was being evaluated for purchase by this facility and was therefore installed on a trial basis. A representative from the equipment manufacturing company trained the employees the week before the data collection was initiated and encouraged the employees to use the equipment during their work periods.

Nine male volunteers participated in the loading study. They were between the ages of 21 and 43 years and had between 3 and 12 years of distribution center work experience. The mean height and weight of the participants was 1.74 m (1.65–1.83 m) and 77.2 kg (66–91 kg), respectively. The maximum vertical reach height for these participants ranged from 2.04 to 2.39 m (mean 2.20 m). This study was conducted in a facility that had purchased the equipment approximately one year prior to the study. Therefore the participants had between 3 and 12 months of experience using the equipment (mean = 7.8 months), so no additional training was required.

Both samples were assumed to be asymptomatic at the time of the study as participants were currently working these jobs. Therefore, no formal assessment of symptoms was conducted.

2.2. Experimental design

At each site a repeated measures design was used in which the recruited participants perform the task with the extendable conveyor or with the articulating belt conveyor. The sequence of conditions were counter-balanced to control for potential fatigue effects. In each operation the "wall" of boxes in the trailer was divided into 9 work zones (see Fig. 1a) based on height and lateral position relative to the available work area within the trailer. Thus, the two independent variables for each of the studies was the conveyor condition (using the articulating belt conveyor equipment vs. using only the normal extendable conveyor), and the work zone. The dependent measures for each participant were derived from the surface electromyographic (EMG) data obtained from the back (erector spinae) and shoulder (anterior deltoid) muscles and the trunk kinematics measured using a lumbar motion monitor (LMM). The weight of the cases was generally consistent for each worker sampled but did vary in the unloading study from 9.1 to 13.6 kg and varied in the loading study from 9.1 to 19.1 kg. The size of the cases were also variable. In the unloading study the smaller boxes were approximately 45 × 30 × 30 cm (L × W × H) and the larger boxes were approximately 45 × 38 × 38 cm. In the loading study cases sizes were more consistent (L:61 × W:40 × H:40 cm) and were typically stacked six cases high and six cases wide in the trailers.

2.3. Apparatus

The articulating belt conveyor tested in this study was manufactured by Engineered Lifting Systems & Equipment, Inc. The specific conveyor product, the Destuff-IT™/Restuff-IT™ materials handling system (www.engliftsystems.com), is shown in use in Fig. 1b. The mechanical drawings of the device shown in Fig. 2 indicate that the articulating portion of the belt can be raised up to an angle of 30° above the horizontal and tilted downward 27° below the horizontal. It swivels 13° to each side, which given the length of the belt, can result in up to 0.35 m of displacement from centerline. In addition to the powered articulating belt, this equipment also includes a 2.0 by 0.5 m powered adjustable height platform, which can raise the operator 0.61 m, to facilitate the loading and unloading of the material near the roof of the trailer. This platform raises/lowers at a rate of 7.9 m/minute. The speed of the conveyor belt is adjustable and can range from 23 to 37 m/minute.

Surface electromyographic data were collected using a Delsys (Boston, MA) Trigno wireless EMG system. Data were sampled at 1000 Hz using the Motion Monitor Software™ (Chicago, IL). A telemetered lumbar motion monitor (LMM) (Biomec, Inc., Cleveland, OH) was used to measure the spine kinematics during the loading and unloading tasks.

2.4. Procedure

After signing an institutional review board approved informed consent document, the volunteers were prepared for the study by placing surface EMG electrodes bilaterally over the: (1) erector spinae muscles at the L_3 level approximately five cm from the midline; and (2) over the belly of the anterior deltoid muscles. A baseline sample of the EMG activity during quiet standing (resting EMG) was obtained.

Maximal voluntary isometric exertions were performed to elicit maximal EMG signal amplitudes for each muscle that could be used for normalizing the data obtained during the work tasks. These tasks were performed in postures that approximated the postures where the greatest loads would likely occur. The maximal exertion task for the erector spinae muscles required participants to perform a back-style lift by pulling upward on a handle strapped to a platform from a position in which their torsos were flexed approximately 60°. Anterior deltoid maximal exertions were performed by having the participant, standing on a platform, pull upward on a handle that was adjusted such that their shoulder was flexed approximately 90° and the elbow fully extended. Following these maximal exertions, the LMM was placed on the participant's back, and baseline data were obtained as the participant stood in an upright neutral posture.

For each conveyor condition participants were instructed to remove or load the cartons at their normal pace and in whatever sequence they desired, thus, while the work zones were

Fig. 1. The extendable conveyor (a) and articulating conveyor system (b) used in the study. The grid and numbers over-laid on the extendable conveyor photo show the 3 by 3 work zone grid used in the analysis. The same grid (with the same height zones) was used with the articulating conveyor as it referred to work locations relative to the trailer rather than the work locations relative to the worker.

documented, the sequence of work zones was not controlled in this study. Workers unloaded starting from the upper zones and finished unloading each wall of boxes from the lower zones. The reverse was true when loading. Workers chose where to stand as they performed their respective unloading and loading tasks. No additional assistive equipment (i.e. step stools) was used when working with the extendable conveyor. Data were sampled for up to 60 s at a time. A marker in the data stream was used to indicate when lifts occurred, and each lift coded as to the zone where the box was lifted from or placed during the unloading and loading, respectively. Between four and 19 samples were obtained from each zone for each participant. Generally more lifts were sampled in the middle height work zones (zones 4, 5, & 6), as this work zone was the largest vertically and contained the most cases.

2.5. Data analysis

The EMG data were filtered using a 20 Hz high pass filter, a 500 Hz low pass filter, and 4th order Butterworth filter. The data also were notch filtered, at multiples of 60 Hz, from 60 to 360 Hz. The data were exported and then further processed through a custom program written in MATLAB® (MathWorks, Natick, MA). The outliers were removed before the data were rectified. The data were then processed through a 75 ms moving average window, followed by the application of a Hanning filter.

The processed EMG data from each muscle were normalized to their maximum values obtained during the prior maximum isometric contractions. Timing marker data were used to extract data from each individual lift from the data stream. For each lift, the 90th percentile EMG values were obtained and then averaged across the samples within each lifting zone. The rationale for using the 90th percentile benchmark was that we anticipated there would be short peaks in the EMG activity as the boxes were initially accelerated or placed and that these peaks would be most representative of the physical demands for each condition. These averaged 90th percentile values were used in the statistical analysis procedures.

The peak postural deviation and the movement velocities measured with the LMM were obtained for each sampled lift. These were averaged across all the lifts for a given zone for each participant. These averages were used in the analysis of variance procedure. In addition, the peak velocities in each plane of motion were extracted for each sampled lift, averaged across the lifts performed in each zone with each conveyor system for each subject. These subject means for each experimental condition were used in the statistical analyses.

The dependent measures from the EMG and kinematic data were analyzed using analysis of variance procedures (Proc GLM) within the SAS software (SAS Enterprise, Version 4.3). Post-hoc analyses of the interactions for the zones were conducted using a Bonferroni correction.

3. Results

3.1. Truck unloading analysis

A summary of the statistical analyses of the EMG and kinematic data is shown in Table 1. The four muscles sampled showed a significant decrease in activation levels due to the use of the articulating conveyor system (Fig. 3). The shoulder muscles showed an average decrease in the 90th percentile values of 24 percent and 20 percent for the left and right deltoid, respectively. The back muscles showed an average decrease in their 90th percentile values of 18 and 21 percent for the left and right erector spinae muscles, respectively. For both the left and right erector spinae and the left deltoid muscles, this change was independent of the work zone. The significant conveyor type by work zone interaction effect for the right deltoid muscle indicates that this muscle's activity was only significantly reduced with the articulating conveyor when the participants were working in zones 3 and 5.

Statistical analysis of the kinematic data (Table 1) showed that the most extreme forward bending postures increased with the articulating conveyor system whereas the maximum amount of spine twist decreased with the articulating conveyor (Fig. 4). The analysis of the significant conveyor type by work zone interaction found that the increased forward bending postures with the articulating belt conveyor occurred at the three middle height work zones (Fig. 5). There was no change in the degree of lateral bending. The analysis of spine movement speeds showed slower lateral bending, twisting, and spine extension motions ($p < 0.001$) when the articulating conveyor was used. However, the significant conveyor type by work zone interaction indicated that this effect on extension velocity was limited to two of the three upper work zones (zones 2 and 3) and the lower three work zones (zones 7, 8, and 9).

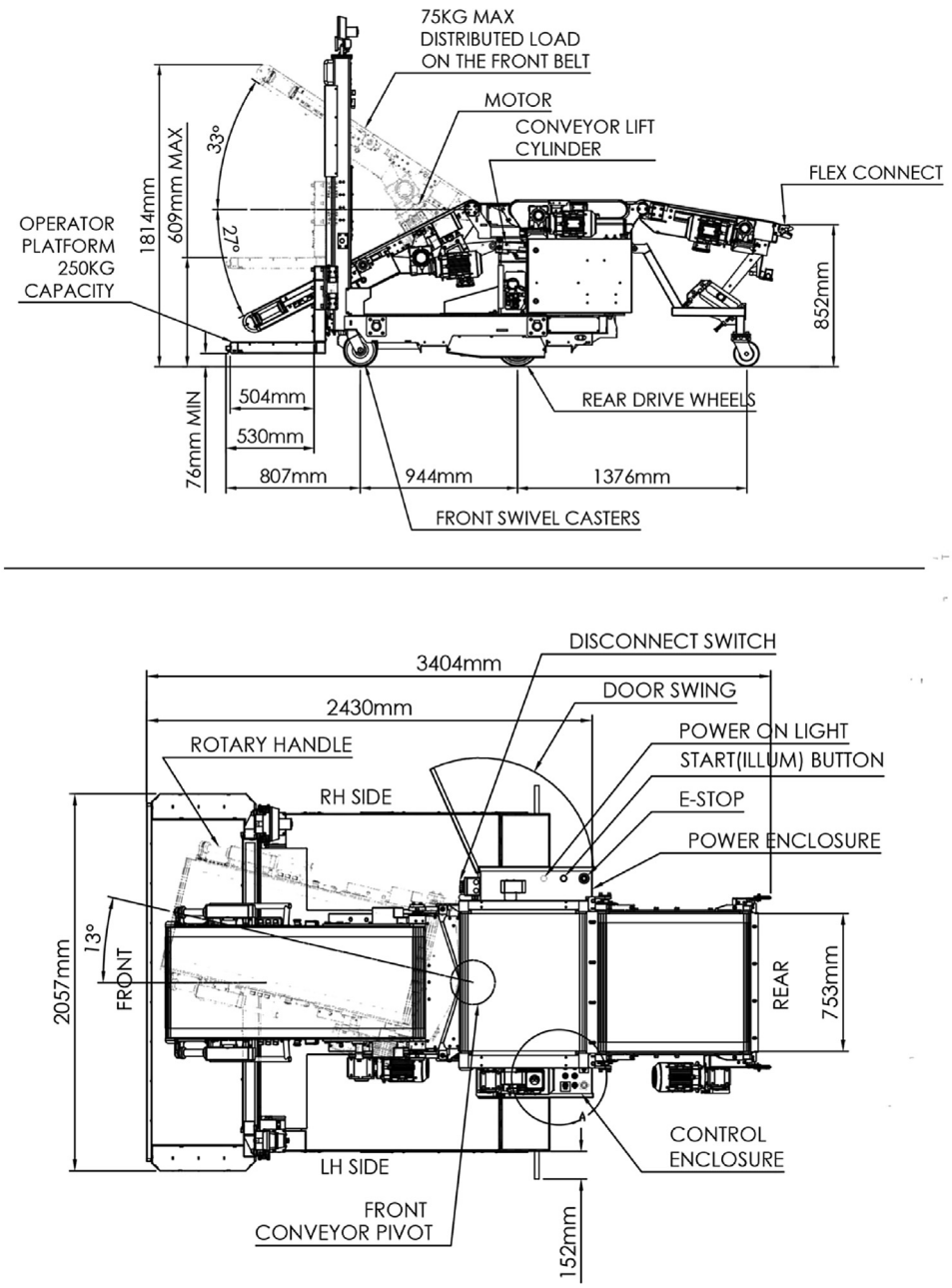

Fig. 2. Mechanical drawings of the articulating conveyor system provided by Engineered Lift Systems, Inc.

Table 1
Statistical analysis of data collected during the unloading operation.

	Measure	Conveyor	Conveyor × work zone
EMG results	Left erector spinae	<0.001	ns
	Right erector spinae	<0.011	ns
	Left anterior deltoid	<0.028	ns
	Right anterior deltoid	<0.001	0.015[a]
Spine motion results	Lateral bending posture	ns	ns
	Forward bending posture	<0.001	0.021[b]
	Twisting posture	<0.001	ns
	Lateral bending velocity	<0.001	ns
	Extension velocity	<0.001	<0.001[c]
	Twisting velocity	<0.001	ns

[a] Significant difference in work zones 3 & 5 (articulating conveyor < extendable conveyor).
[b] Significant difference in work zones 4, 5 & 6 (articulating conveyor > extendable conveyor).
[c] Significant difference in work zones 2, 3, 7, 8, & 9 (articulating conveyor < extendable conveyor).

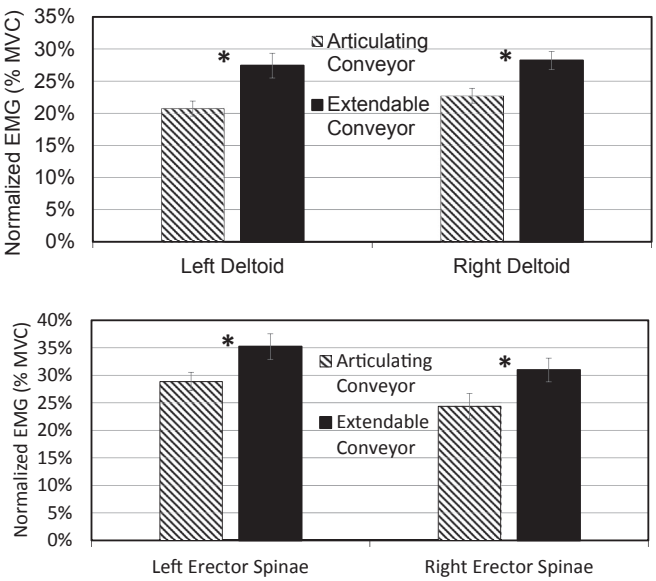

Fig. 3. The normalized EMG obtained from the shoulder muscles (top) and the back muscles (bottom) as workers used the articulating conveyor and the standard extendable conveyor to unload a trailer. An "*" indicates a statistically significant difference ($p < 0.05$). Error bars represent one standard error of the mean.

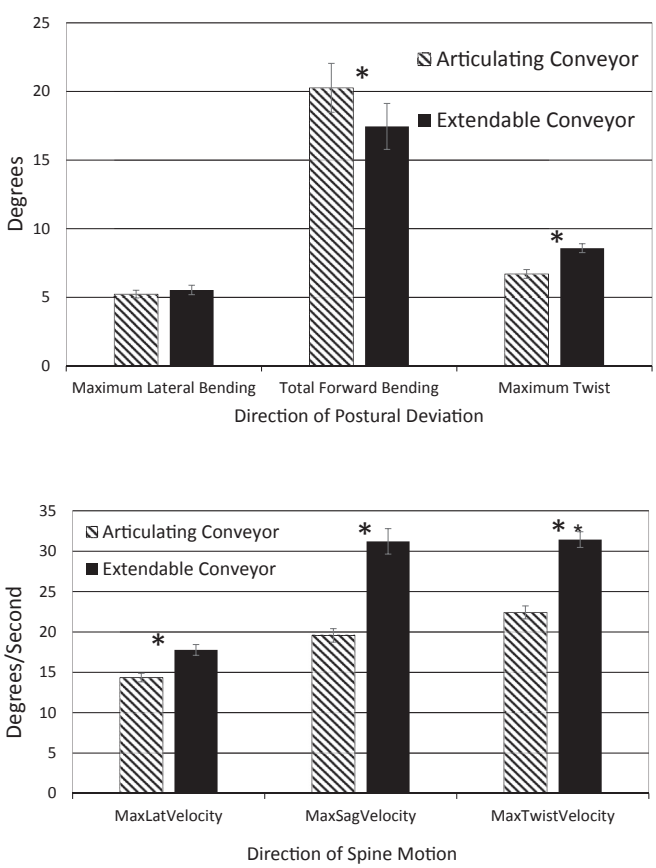

Fig. 4. The average of the peak postural deviations from a neutral spine posture (top) and movement velocities (bottom) by plane of motion as workers used the articulating conveyor and the standard extendable conveyor to unload a trailer. An "*" indicates a statistically significant difference ($p < 0.05$). Error bars represent one standard error of the mean.

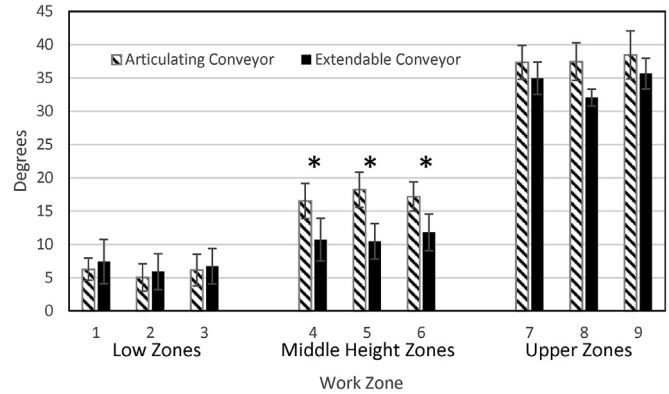

Fig. 5. The forward bending shown as a function of the work zones identified in Fig. 1 and the type of conveyor system used to unload a trailer. An "*" indicates a statistically significant difference ($p < 0.05$). Error bars represent one standard error of the mean.

3.2. Truck loading analysis

All sampled muscles showed a significant decrease in their normalized activity levels when using the articulating conveyor, relative to the normal extendable conveyor, during the loading operation (Table 2). The largest decrease was seen in the right deltoid muscle (37 percent). As for the erector spinae muscles, the largest decrease (26 percent) was seen on the left side, which tended to be the contralateral side given that workers generally stood on left side (when looking into the trailer) of the articulating conveyor (Fig. 6). While there was an overall effect for the right erector spine muscles, the significant interaction effect indicates that the activity in this muscle was only reduced when workers loaded boxes into zones 1 and 2.

The most extreme postural deviations of the spine significantly decreased in each of the three cardinal planes when loading boxes using the articulating conveyor (Fig. 7). The largest reduction was in the forward bending motion, followed by modest changes in the lateral bending and twisting motions. Similarly, the articulating conveyor led to a significant decline in the speed of the movement in each plane relative to those observed with the standard extendable conveyor. The significant conveyor type by zone interaction indicated that declines in the lateral bending velocity were limited to zones 1, 3, and 4.

4. Discussion

This study found that the use of an articulating conveyor reduced the activation of all muscle sampled, albeit some effects were limited to selected work zones. This is largely due to workers sliding boxes towards and onto the conveyor during the unloading process and the use of the box's momentum derived from the final conveyor segment during loading. By removing the carrying portion of the task, this type of conveyor system could also be expected to reduce the physiologic demands on the worker.

The spine kinematics results, particularly for the unloading operation, were mixed on account of increased forward bending done by workers in the middle height zones. This is indicative of higher risk in the LMM risk analysis model (Marras et al., 1993). This is likely due to an observed tendency to reach over the belt when pulling boxes towards the conveyor. However, the speed of these sagittal plane motions in these middle height zones were not statistically different from those measured when the extendable conveyor was used. In most of the remaining work zones, the extension velocities were reduced with the articulating conveyor

Table 2
Statistical analysis of data collected during the loading operation.

	Measure	Conveyor	Conveyor × work zone
EMG results	Left erector spinae	<0.001	ns
	Right erector spinae	<0.011	0.029[a]
	Left deltoid	0.028	ns
	Right deltoid	<0.001	ns
Spine motion results	Lateral bending posture	<0.001	ns
	Forward bending posture	<0.001	ns
	Twisting posture	<0.001	ns
	Lateral bending velocity	<0.001	0.012[b]
	Sagittal velocity	<0.001	ns
	Twisting velocity	<0.001	ns

[a] Significant difference in work zones 1 and 2 (articulating conveyor < Extendable Conveyor).
[b] Significant difference in work zones 1, 3, & 4 (articulating conveyor < extendable conveyor).

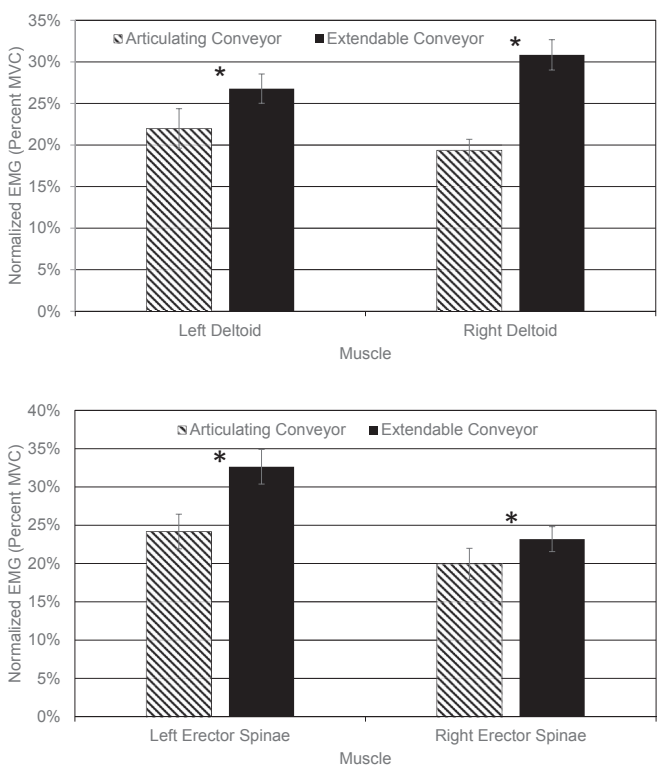

Fig. 6. The normalized EMG obtained from the shoulder muscles (top) and the back muscles (bottom) as workers used the articulating conveyor and the standard extendable conveyor to load a trailer. An "*" indicates a statistically significant difference ($p < 0.05$). Error bars represent one standard error of the mean.

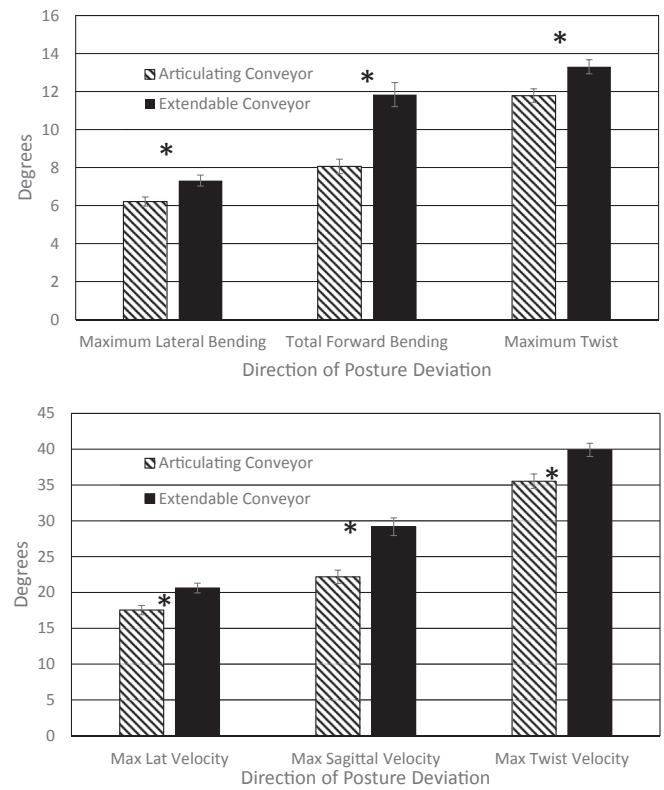

Fig. 7. The average of the peak postural deviations from a neutral spine posture (top) and movement velocities (bottom) by plane of motion as workers used the articulating conveyor and the standard extendable conveyor to load a trailer. An "*" indicates a statistically significant difference ($p < 0.001$). Error bars represent one standard error of the mean.

system. Slower movement speeds have been associated with lower muscle forces and compressive forces acting on the spine. (Marras and Mirka, 1992; Granata and Marras, 1995).

The back injury risk model developed by Lavender et al. (2012) includes three factors to predict back injury risk: the mean of the peak load moment exposures; the mean of the peak horizontal forces; and the amount of time between lifts. The articulating conveyor, when used appropriately, can substantially reduce the load moment exposures as the boxes are slid onto the conveyor when unloading and the box momentum from the conveyor is used when loading boxes. The horizontal forces when unloading could be expected to remain relatively consistent between conditions as the boxes need to be pulled either toward the worker prior to lifting or towards the articulating conveyor. It is possible that when loading, the horizontal forces are reduced if the box momentum from the conveyor is used. The duration of time between exertions will likely decrease as the manufacturer of the articulating conveyor system has reported productivity gains associated with the use of their equipment (Engineered Lifting Systems, personal conversation). A limitation of this study is that we were unable to independently assess productivity as we periodically needed to interrupt the worker during data collection process in order to save the collected EMG data.

The adjustable height work platform integrated with the articulating conveyor system reduced the amount of work that was done above shoulder level. For both the loading and unloading the height adjustable platform reduced the demand on shoulder muscles as the working height was lowered relative to the worker. This led to a 15 percent and 17 percent decrease in the left and right deltoid muscle recruitments, respectively, in the three upper work

zones. This is consistent with literature showing higher deltoid activations when lifting loads with increased shoulder flexion angles (Lee and Chee, 2011). This finding also is consistent with the literature showing reduced shoulder demands with lifts from shoulder height as opposed to eye height. Blache et al. (2015) reported a decrease in anterior deltoid force when lifting to eye level as opposed to shoulder level, but this decrease was offset by substantial increases in the supraspinatus, upper trapezius, and infraspinatus muscle forces predicted by their model. Pope et al. (2001) conducted a cross-sectional study that looked at the effects of physical demands, including manual handling demands, on one month period prevalence of disabling shoulder pain lasting more than 24 h in a mixed sample of workers where disability was assessed as a "limitation in carrying out activities of daily living" based on responses to a shoulder disability questionnaire. Among the factors identified by their univariate analyses were durations of exposure to work above shoulder level and lifting above shoulder level. Similarly, Harkness et al. (2003) reported the onset of shoulder pain was associated with lifting at or above shoulder level.

As mentioned above, the participants tended to stand more often to the left side of the articulating conveyor's platform. This may be due to more people being right hand dominant and were more used to working from this position. A limitation of this work is that we did not assess the handedness of the participants in this study and therefore could not address the effects of handedness on work position. However, we can speculate that from this left-side position the right arm would be better positioned when handling the cases both during the unloading and the loading operations. Again, the EMG data support the increased tendency to more heavily use the right arm during these tasks.

A second limitation is that the lateral deltoid muscles were not sampled in this study. In retrospect, given the work did include some lateral reaching when retrieving boxes during the unloading and some shoulder abduction when placing the boxes, these data could have been informative. However, we believe that the anterior deltoid activity largely captures most of the shoulder use given that most of the lifting was done in front of the worker's torso.

A third limitation of this study was our inability to assess productivity levels. These could be assessed by looking at the time to load or unload a complete trailer. Given the reduced time spent carrying, the overall productivity will likely be enhanced. The handled materials for both the loading and unloading study were contained in cardboard boxes. These tend to slide relatively easily over one another. We cannot generalize these results to materials that have higher coefficients of friction, such as automotive tires. However, a similar articulating conveyor system (Power Stow, Tjæreby, Denmark) is available for airline baggage handling within narrow body aircraft. Even though this work is done in kneeling or stooped postures in these aircraft, the unloading of bags by sliding onto the articulated conveyor and the loading using the bag momentum imparted by the conveyor would likely produce similar results, although this should be verified with a controlled study.

A fourth limitation was the skill levels of the operators tested. While the loading function was tested with workers who had used the articulating conveyor for six months or more, this was not the case for the participants in unloading test. At the site where the unloading data were collected, the participants had only worked with the articulating equipment for a limited amount of time prior to the data collection. However, we would expect that had the workers had the opportunity to become more proficient at moving the articulating conveyor, the existing differences between the articulating and extendable conveyor equipment would be wider than those currently reported.

One more limitation of this field study was our inability to keep the loads handled consistent across participants. The trailers being loaded or unloaded contained mixed freight. As mentioned in the methods section, the weights were generally consistent for a given participant as we could limit the observations to selected batches of freight. However, this variation in box weights across participants should allow the results presented here to generalize to a wider range of box sizes and weights.

In summary, this study shows that the use of an articulating belt conveyor system that allows boxes to be slid directly onto the conveyor when unloading trailers or slid and placed in position when loading trailers reduces the physical demands on the back and shoulders in these jobs. The reduced spine movement speeds further support that using this type of equipment potentially reduces the risk of low back injury in these occupations.

Acknowledgement

This study was funded by the Ohio Bureau of Workers' Compensation. We wish to thank Mike Lampl and Carol Morrison for their support. In addition, we are grateful to Richard Kat, Corinne Dekker, Rhoda Bowman, and Chelsey Cayen of Engineered Lifting Systems, for their assistance in coordinating use of the Destuff-IT™/Restuff-IT™ equipment.

References

Blache, Y., Desmoulins, L., Allard, P., Plamondon, A., Begon, M., 2015. Effects of height and load weight on shoulder muscle work during overhead lifting task. Ergonomics 58 (5), 748–761. http://dx.doi.org/10.1080/00140139.2014.980336.

Bureau of Labor Statistics (BLS), 2013. Annual Survey of Occupational Injuries and Illnesses. Vol. U.S. Department of Labor.

Granata, K.P., Marras, W.S., 1995. An EMG-assisted model of trunk loading during free-dynamic lifting. J. Biomech. 28, 1309–1317.

Harkness, E.F., Macfarlane, G.J., Nahit, E.S., Silman, A.J., Mcbeth, J., 2003. Mechanical and psychosocial factors predict new onset shoulder pain: a prospective cohort study of newly employed workers. Occup. Environ. Med. 60, 850–857.

Lavender, S.A., Marras, W.S., Ferguson, S.A., Splittstoesser, R.E., Yang, G., 2012. Developing physical exposure based back injury risk models applicable to manual handling jobs in distribution centers. J. Occup. Environ. Hyg. 9, 450–459.

Lee, Y.J., Chee, Y.J., 2011. Evaluation method of physical workload in overhead lifting posture using surface EMG analysis. J. Biomed. Eng. Res. 32, 328–325.

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

Marras, W.S., Mirka, G.A., 1992. A comprehensive evaluation of trunk response to asymmetric trunk motion. Spine 17, 318–326.

Pope, D.P., Silman, A.J., Cherry, N.M., Pritchard, C., Macfarlane, G.J., 2001. Association of occupational physical demands and psychosocial working environment with disabling shoulder pain. Ann. Rheum. Dis. 60, 852–858.