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Ergonomic considerations when slotting piece-pick operations in distribution centers

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ABSTRACT

Many warehouse slotting algorithms have overlooked worker ergonomics. This research aimed to develop ergonomics slotting guidelines based upon the back and shoulder postures and electromyographic (EMG) responses of the deltoid and erector spinae muscles when individual items are picked from, or full cases replenished to, different shelf heights In the first study of two studies, participants lifted small items representative of piece-pick tasks from seven shelf heights. In the second study, participants performed a simulated full case replenishment task in which they lifted boxes weighing between 2.7 and 10.9 kg from a cart into a flow rack. Shelf height significantly affected all postural and EMG variables and there was a trade-off between back and shoulder muscle activity across the varying shelf heights. Together, these studies were used to develop some general ergonomic slotting guidelines that could be implemented to reduce biomechanical load exposures experienced by distribution center workers.

1. Introduction

Warehouse order picking is not only one of the most time-intensive and labor-intensive jobs, but it is also one of the most physically demanding jobs in the warehouse industry (Battini et al., 2016; de Koster, Le-Duc and Roodbergen, 2007; Grosse et al., 2017). Bartholdi and Hackman (2019) suggest that order picking in a warehouse typically accounts for about 55 % of the total warehousing operating costs. Thus, order pickers are required to reduce the operating time as much as possible to improve efficiency. Meanwhile, order pickers also need to ensure the accuracy of the types and quantities of products picked for customers' orders because underperformance in order picking can cause high operation costs and have a negative effect on customer satisfaction (De Koster et al., 2007).

It should be noted, that a significant proportion of order picking tasks are performed manually, even in e-commerce settings, despite the development of automation in the warehouse industry (De Koster et al., 2007). Manual materials handling, which includes manual lifting, lowering, carrying, pushing and pulling loads, can have high physical demands during the process of order picking (Weisnera and Deusea, 2014). Due to the high amount of repetitive manual lifting, such as continuous lifting of heavy loads and working in awkward postures, manual lifting activities performed in a warehouse expose order pickers to high risk of musculoskeletal disorders (Calzavara et al., 2017, Glock et al., 2019, Grosse et al., 2015, Persona and Sgarbossa, 2017; Lavender et al., 2012). According to the (Bureau of Labor Statistics, 2018), sprains, strains, tears, soreness, pain, also known as musculoskeletal disorders (MSDs) accounted for 62 percent of the reported injuries in Warehousing and Storage" in 2018.

In distribution center operations, one-handed lifting tasks are frequently performed when workers are picking individual products, often referred to as piece picking, to fulfill customer orders. It has been the lead author's observation that many of workers in these piece-picking operations are female. The items picked may include many of the products one can purchase at a pharmacy, for example individual bottles of shampoo. These individual items are often picked from boxes located on multi-level flow racks. While the one-handed lifting tasks involved with piece picking have gained much less attention than two-handed lifting in the literature (Kingma and van Dieën, 2004), in the same part of the warehouse, two-handed lifting tasks are routinely performed as material on the shelves or flow rack designated for piece picking is replenished. Full cases of material are typically lifted from carts or forklifts and placed in the designated locations. These jobs require the capacity for heavy repetitive lifting and it has been the lead

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author's observations that these jobs are typically performed by male workers.

In many of the previous studies, the decisions regarding warehouse pick area layouts and item locations, also known as "slotting", are mainly focused on reduction of *economic* cost by reducing the traveling time to improve order picking performance. Often these approaches could increase the *ergonomic* costs, defined as the amount of muscle force required and the assumption of non-neutral work postures, which, until recently, have received little attention in the warehousing literature (Glock et al., 2019; Grosse et al., 2015). Although Sadiq et al. (1996) stock location assignment algorithm does assign faster moving and/or heavier items to locations between waist and shoulder level, this does not seem to be widely implemented. Given the number of stock keeping units (SKUs) that need to be accommodated in many distribution centers, not all lifts can occur at these heights. As stated by Witt (2006), "The objective of any slotting plan is to minimize travel time and reach time for employees in the distribution center". Ergonomic data are needed to further refine slotting algorithms to incorporate ergonomic cost (Larco et al., 2017). It should be recognized that in many retail distribution centers, slotting decisions are also made based upon product family, affinity, and crushability (Bartholdi and Hackman, 2019).

It should also be noted that the prior models have assessed the order picking component but have not considered the manual full case replenishment on the back side of the flow rack. Thus, the overall goal of this research was to develop some data-driven slotting guidelines that could be used when making slotting decisions within piece-pick distribution center operations that take into account the ergonomic needs of both the piece-pick and the full case replenishment workers. Towards this goal, this paper reports on two studies. One study was designed to quantify the ergonomic and time costs of one-handed picking and the other study was designed to quantify two-handed replenishment activities performed as a function of shelf height. Specifically, this research aimed to quantify the ergonomic cost in terms of electromyographic response as an indicator of the muscle force required in the shoulder and back muscles, as well as the shoulder and torso postures used, when individual items are picked from, or full cases replenished to, different shelving heights. Additionally, this research aimed to quantify the time required for these tasks as a function of varying shelf heights, because lifts from near floor level or above shoulder level may require more time, considering the extra movements of shoulders and the back. Therefore, the time cost for reaching or bending also needs to be considered when developing ergonomic slotting guidelines.

2. Methods – study 1

Experimental Design. This study stimulated one-handed piece picking activities in a distribution center. The three independent variables were: (a) the item weight (0.45 kg and 0.9 kg), (b) the height of the shelf from which the item was picked, and (c) the travel distance to reach the item. Participants lifted the items, which were jars with lids measuring 13.3 cm high and filled with sand, from 7 shelf heights: 10.8, 37.1, 63.5, 89.9, 116.2, 142.6, 168.9 cm above the floor and placed them in a tray (78 cm above the floor) on a cart to their left side located 1 m away from the shelving unit. The upper shelf height was selected based on standing vertical grip reach (Pheasant, 1988), such that the top of the jar at this height could be grasped by 90 percent of the adult female population. The remaining shelf heights were selected to maximize the number of shelf height conditions given the jar height and the clearance needed to remove the jar from the box. At each height two tasks were performed. For task 1, the subject started from a position that was 1 m away from the location of the first jar to be lifted (Fig. 1). The subject stepped forward and lifted the item, a glass jar, from the shelf to the cart. Task 2 occurred immediately after lifting task 1 and differed from lifting task 1 in that the participant did not have to take any steps for before lifting the second item. Each subject's sequence of the 14 shelf height and item weight condition combinations was fully randomized. Within each condition, there were three repetitions that were performed sequentially.

The dependent variables were derived from the surface electromyographic (EMG) signals and postural data at the time when the lift occurred. EMG data were obtained from the right Anterior Deltoid, right Lateral Deltoid, left Erector Spinae and right Erector Spinae muscles. The posture data included the peak postural deviation from an upright neutral posture for spine flexion, spine lateral flexion, spine twist, right shoulder flexion and right shoulder abduction. In addition, the duration of each lifting task was obtained using data from force plates located under the shelving unit and the cart that detected when the measured forces decreased and increased, respectively.

Participants. Seventeen females, without back or shoulder injury history, were recruited for this study. All the participants were between the ages of 18 and 23 years and none had any relevant industry or warehouse order picking experience. Their mean height and weight were 1.66 m (range:1.55–1.83 m) and 62.1 kg (range: 49.5–93.4 kg), respectively. Before the experiment, each participant reviewed and signed an informed consent form approved by the University's Institutional Review Board.

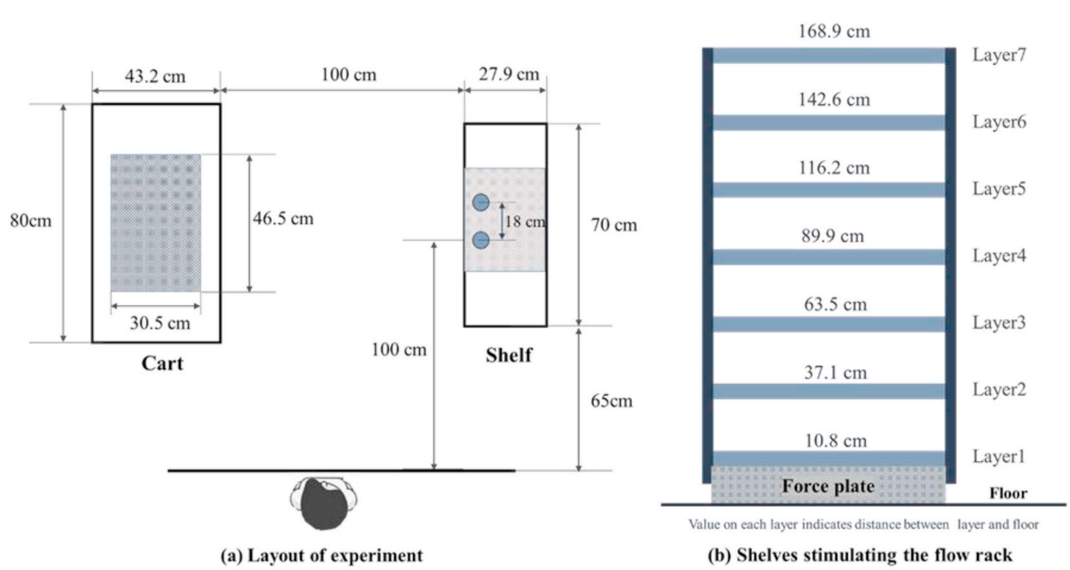

Fig. 1. A top view of the lifting task layout (a) and shelves stimulating the flow rack (b).

Procedures. Surface electromyographic (EMG) electrodes for the deltoid muscles were placed over the anterior portion of right deltoid muscle and over the most lateral portion of the right deltoid muscle midway between the acromion and the distal end of the muscle. Electrodes for the Erector Spinae muscles were placed at the L3 level 2–3 cm away from the midline, over the belly of the muscles. A ground electrode was placed over the collar bone. EMG signals were obtained using a Delsys Bagnoli System (Delsys, Natick, MA) and recorded at a rate of 900 Hz using a Motion Monitor data acquisition system (Innovative Sports Training, Inc., Chicago, IL). The participant then performed a series of three isometric maximal muscle exertion activities to obtain maximal EMG signals to be used for normalization of the data obtained during the lifting tasks. These activities were performed in postures where maximal task muscle recruitments were expected to occur, for example in postures with approximately 60 degrees of trunk flexion and upright postures with 90 degrees of shoulder flexion. In addition, a resting sample was collected to provide baseline data for the normalization process.

Following the maximal muscle exertion activities, motion capture sensors (Flock of Birds, Ascension Technologies) were attached to the participants to obtain the postural data. Sensors recording spine postures were placed over the first thoracic vertebrae and the sacrum. Sensors used to capture shoulder motion were placed on the right and left upper arm. Once instrumented, each subject was set up using the Motion Monitor System software (Innsport, Inc.) to create a digital model of the subject. A neutral reference position was sampled prior to initiating the data collection process during the lifting tasks. All kinematic data were sampled at 60 Hz.

When given the signal to start by the investigator the participant was instructed to walk the 1 m distance, read aloud labels attached to the shelf that simulated check digits (a quality control procedure used in distribution centers), pick up the jar with her right hand, pass the jar to her left hand and place the jar in a tray positioned on the cart, thereby completing "Lifting Task 1" (see Fig. 2). The participant was then instructed to read aloud labels attached to the shelf that simulated check digits, lift the second jar from the shelf, with her right hand, pass the jar to her left hand, and place it in the tray thereby completing "Lifting Task 2". The initial distance between the two jars on the shelf was 18 cm. The subjects were also instructed not to initiate the second lift task before placing the first jar on the cart. After each trial, which included two lifts (Lifting Task 1 and Lifting Task 2), the participant returned to the starting position and had a rest period of about 1 min. Each condition was repeated three times in succession.

Data processing. Within the Motion Monitor System, the raw EMG data were bandpass filtered (20–450 Hz), and notch filtered at each multiple of 60 Hz within the bandpass range. The RMS values were computed using a 100 m s time constant and exported so that they could be read by a custom program, written in MATLAB (Mathworks, Natick, MA).

During the process of data collection, two force plates and one of the motion capture sensors were used to collect the data indicating when subjects started to move, when they started to lift the items from the shelf and when they put the items down onto the cart. The shelf and cart were set onto force plates. Each lift started when the participant lifted an item from the shelf as signaled by a decline in the weight (Fz) measured by the shelf force plate; and ended when the participant put the item on the cart, signaled by an increase in the weight (Fz) measured by the cart force plate. One complete lifting trial consisted of two lifting tasks (Lifting Task 1 followed by Lifting Task 2): each lift started when the item was lifted from the shelf and ended when the same item was placed onto the cart (Fig. 3a).

When using the MATLAB program to process the RMS EMG data, the data were selected from a one-second time period that included data from 0.5 s before the initiation of lifting to 0.5 s after the initiation of lifting (Fig. 3b). This time period included the peak muscle exertions for each of the sampled muscles during the lifting portion of the task, which

Fig. 2. The task elements for the two lifting tasks in Study 1.

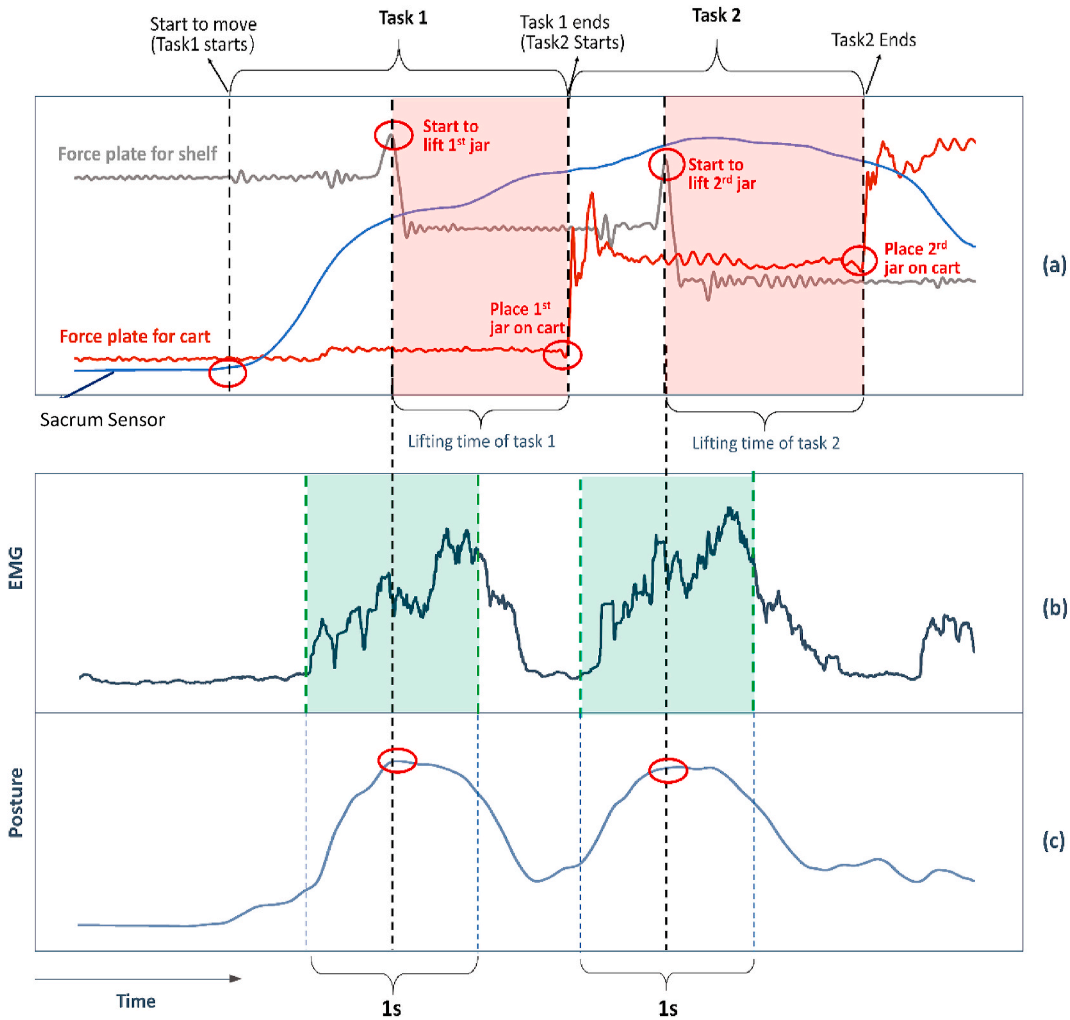

Fig. 3. A complete lifting trial with the two lifting tasks. In chart "a" the gray line is the reading from the shelf force plate and the red line is the reading from the cart force plate. The blue line is the location data from the motion capture sensor located on the subject's sacrum, which indicates when the subject initially stepped forward at the beginning of the trial. Charts "b" and "c" show respective EMG and postural data from the same lift.

was the focus of the study. The RMS EMG data were normalized relative to maximal muscle exertion values and resting values (Mirka, 1991) using the MATLAB program (see equation (1)). The 90th percentile data for each lifting task were then obtained from the 1 s normalized data stream. The 90th percentile values obtained from the three trials within each experimental condition were then averaged for each subject.

$$\text{Norm EMG(muscle i)} = \frac{\text{RMS Task EMG(i)} - \text{Resting EMG(i)}}{\text{Max(i)} - \text{Resting EMG(i)}} \times 100 \qquad \text{(Eq. 1)}$$

For the kinematics analysis, the data points at the moment of lifting were selected for analysis (Fig. 3c). The raw kinematic data were normalized by subtracting the initial data values obtained before the subject initiated movement towards the shelf.

Statistical analysis. After processing the data with MATLAB, normality tests were conducted for EMG and postural data to check the data for normality. At some shelf heights, the p-values from the Kolmogorov-Smirnov tests for the normalized EMG data were smaller than 0.05. However, from visual inspection of the distribution, the histograms showed that the EMG and postural values were generally bell shaped. For this study there were total of 68 observations for each shelf height (17 subjects* 2 item weight * 2 lifting tasks). Therefore, it was considered appropriate to use parametric statistical tests.

To determine whether there were significant differences in the EMG and kinematics data due to shelf height, item weight, and/or lifting task, a three-way ANOVA was initially performed. However, given there were no significant three-way interactions, two-way ANOVAs were used to examine combined effects (shelf height & item weight, shelf height & lifting task, item weight & lifting task) on the dependent variables. Post-hoc REGWQ tests were used to examine the differences between different shelf heights for EMG and postural data. In addition, where the interaction effect of shelf height and item weight or the interaction effect of shelf height and lifting task was significant, a Bonferroni correction was used in pairwise tests to determine if there were significant differences between item weight and lifting task at each shelf height. Here, the alpha value applied for each comparison was 0.007, corresponding to 0.05/7 (α/number of shelf heights).

3. Results – study 1

3.1. Lifting postures

Table 1 shows the main effect of shelf height was highly significant for all the spine and shoulder peak postural measures. The task significantly affected all postural measures except spine flexion ($p = 0.09$). There were, however, significant interaction effects for shelf height and task for all postural measures. In addition, the interaction effect of item weight and lifting task affected the spine flexion ($p = 0.021$). There were

Table 1
The p-values for significant differences in peak postural measures due to shelf height, item weight, task, and their interactions in Study 1. Non-significant effects are indicated by "ns".

	Spine Rotation	Spine Flexion	Spine Lateral Flexion	Right Shoulder Flexion	Right Shoulder Abduction
Shelf Height	<0.001	<0.001	<0.001	<0.001	<0.001
Item Weight	ns	ns	ns	ns	ns
Lifting task	<0.001	0.090	0.045	0.036	0.008
Shelf Height * Weight	ns	ns	ns	ns	ns
Shelf Height * Lifting task	0.026	<0.001	<0.001	0.003	<0.001
Weight * Lifting task	ns	0.021	ns	ns	ns
Shelf Height * Weight * Lifting task	ns	ns	ns	ns	ns

no main effects for item weight or interaction effects that included item weight for any of the postural variables.

3.1.1. Effect of shelf height

Fig. 4a shows that when the shelf heights were 10.8, 37.1, 63.5, 168.9 cm above the ground, the values of spine rotation were negative, which means the subjects twisted their spines to the left as they reached for the jars with their right hand. This left twist serves to further extend a subject's reach with her right hand. The forward flexion, as expected, was reduced with each shelf height above 37.1 cm (Fig. 4b). While there was more spine flexion at the 10.8 cm shelf, as compared with the 37.1 cm shelf height this difference was not statistically significant. At shelf heights of 142.6 cm and 168.9 cm, the spine flexion values became negative which means the subjects' spines were in extension relative to their neutral posture.

In terms of spine right lateral flexion (Fig. 4c), the participants showed a small lateral bend to the right as they reached for an item on the three lowest shelves. Above 89.9 cm, the subjects increasingly bent their spines to the left with higher shelves to extend their upward reach with their right arm, resulting in the largest lateral bend (mean $= -14.8°$) at the highest shelf height of 168.9 cm.

The right shoulder flexion and abduction motions (Fig. 4d and e) showed similar trends in which shoulder motion was minimized with shelf heights between 63.5 and 89.9 cm. More specifically, shoulder flexion was minimized at 89.9 cm and the shoulder abduction was minimized at 63.5 and 89.9 cm. Outside of this range shoulder motion significantly increased with each change in shelf height. This is less of a concern with the lower shelves as gravity is assisting with the posture change. At higher shelf heights, there are increased demands on the shoulder muscles (see below).

3.1.2. Interaction effect of shelf height and lifting task

While there were main effects for the lifting task, many of these effects, as supported by the statistically significant interaction effects between shelf height and task, occurred at specific shelf heights. And while they were statistically different, the magnitude of these differences were generally small. For example, the spine was twisted more to the left during the second lifting task from the lower shelf heights, except at the 10.8 cm. At the upper shelf heights, there was more twisting to the right during the first lifting task. Overall, these significant differences due to the task were relatively small, between two and six degrees for each of the spine motions and did not occur at extreme postures.

As for the shoulder motion, the interaction effect of shelf height and lifting task resulted in significantly more shoulder flexion in task 2 when lifting from 10.8 cm. Likewise, task 2 increased shoulder abduction at shelf heights of 10.8 and 37.1 cm. But at these levels the shoulder postures were also assisted by gravity.

3.2. EMG results

The main effect of shelf height was statistically significant for both erector spine muscles and both shoulder muscles (Table 2). The item weights significantly affected the EMG activity in all muscles except the right Erector Spinae ($p = 0.275$). The task significantly affected both the anterior and Lateral Deltoid muscles, as well as the right Erector Spinae. In addition to these main effects, the interaction effect of shelf height and weight was statistically significant for all muscles except right Erector Spinae ($p = 0.966$). The interaction effect of shelf height and task significantly affected all muscles.

3.2.1. Effect of shelf height on EMG response

Fig. 5a and b show similar trends, in which the peak EMG activity of the anterior and Lateral Deltoid muscles reached the lowest values at the middle shelf heights (from 37.1 through 89.9 cm for the Anterior Deltoid, and 37.1 through 116.2 cm for the Lateral Deltoid). Significantly higher values were observed for both muscles once shelf height reached 142.6 cm and even higher values were observed at the 168.9 cm shelf height. Relative to the mid-level shelf heights, both of these shoulder muscles showed significantly more activity at the lowest shelf height (10.8 cm) as subjects reached out more during these low-level lifting conditions.

The left and right Erector Spinae muscles also shared a similar trend (Fig. 5c and d), in that both muscles had significantly higher activation levels at the three lowest shelf heights. Both Erector Spinae muscles also had relatively low levels of activity that were not statistically different at shelf heights at and above 89.9 cm. Overall the EMG activity of the left, contralateral, Erector Spinae was higher than the right, ipsilateral, Erector Spinae at the three lower shelf heights because subjects lifted items with their right arm.

3.2.2. Effect of item weight on EMG response

The mean peak normalized EMG activity of Anterior Deltoid, Lateral Deltoid and Left Erector Spinae muscles increased at the heavier item weight. Overall these differences were small, 2.3, 1.8, and 1.0 percent MVC, for the Anterior Deltoid, Lateral Deltoid, and the Left Erector Spine, respectively.

3.2.3. Effect of lifting task on EMG response

The peak EMG activity values of the Anterior Deltoid and the Lateral Deltoid muscles were higher for lifting task 2 than lifting task 1. In the second lifting task, depending upon where the subjects stood, they often needed to reach further to grab the second jar than they did for the first jar, thereby requiring a larger shoulder muscle exertion. However, the peak EMG activity levels of the left Erector Spinae and right Erector Spinae muscles did not differ between the two lifting tasks.

3.2.4. Interaction effect of shelf height and item weight on EMG response

Although the interaction effect of shelf height and item weight on peak EMG activity levels of the Anterior Deltoid, Lateral Deltoid and left Erector Spinae were statistically significant (Table 2), the differences due to item weight mainly occurred at the upper shelf heights (116.2, 142.6, 168.9 cm). It was observed that the Anterior Deltoid EMG activity increased with the heavier item weight at the two highest shelf heights of 142.6 and 168.9 cm. For the Lateral Deltoid, the peak EMG activity level was greater in response to the heavier item weight at the shelf heights of 116.2 and 142.6 cm. The left Erector Spinae muscle showed increased activation with the heavier item weight at the upper shelf heights, however, these values were low overall (generally less than 15%MVC).

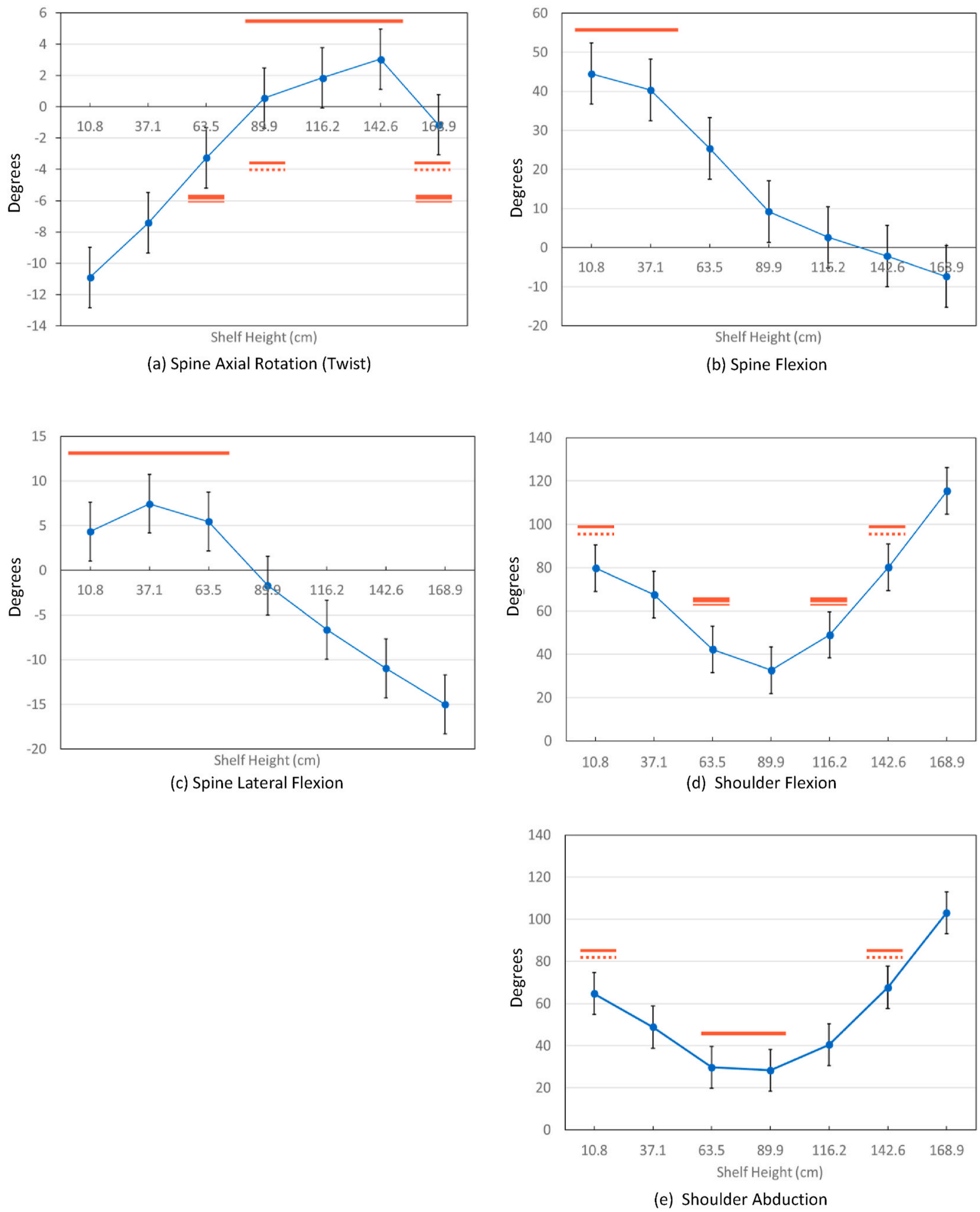

Fig. 4. Spine and shoulder postures when lifts were initiated as a function of shelf height. Positive axial rotation and lateral flexion values indicate motion towards the right. Error bars represent plus and minus one standard error of the mean. Horizontal lines of the same type indicate conditions that were not statistically different in post-hoc tests.

3.2.5. Interaction effect of shelf height and lifting task on EMG response

The interaction effect of shelf height and task was significant for all of the spine and right shoulder muscles sampled (Table 2). The differences between lift task were more prevalent across shelf heights for the right shoulder muscles as compared with the Erector Spinae muscles. Where there were effects on shoulder muscle activity, the task 2 values were always larger than the task 1 values, because there was more reaching out required for task 2 considering the second jar was placed further from the initial starting location. For Anterior Deltoid, the differences between task 1 and task 2 occurred at all shelf heights except 63.5 and 116.2 cm shelf heights. The significant difference between task 1 and task 2 for the Lateral Deltoid occurred at shelf heights of 10.8, 37.1, 63.5 and 89.9 cm. For the left Erector Spinae, the peak EMG activity during task 1 was higher than task 2 when lifting items from the 116.2 cm shelf height. The response of the right Erector Spinae muscle was greater during task 2, but only at the 63.5 cm shelf height.

3.2.6. Time cost results

The shelf height had a significant effect on walk time ($p < 0.01$). The duration of the lifting component was also affected by shelf height and the item weight, respectively. Here the walk time is the time duration between the time of the sacrum sensor starts to move (Fig. 3) and the time of initiation of task 1, and the lifting time is the time to lift and move the item form the shelf to cart. There was no significant interaction effect between shelf height and task for either the lifting time or the walk time. At the shelf height of 116.2 cm, the walk time was the shortest

Table 2
The p-values for main effects and interaction effects of shelf height, item weight and lifting task on the EMG activity of muscles in Study 1 (n.s = non-significant tests).

Effects	Anterior Deltoid	Lateral Deltoid	Left Erector Spinae	Right Erector Spinae
Shelf Height	<0.001	<0.001	<0.001	<0.001
Item Weight	<0.001	0.001	0.039	n.s
Task	<0.001	<0.001	n.s	n.s
Shelf Height * Item Weight	<0.001	0.002	<0.001	n.s
Shelf Height * Task	<0.001	0.003	<0.001	0.001
Item Weight * Task	n.s	n.s	n.s	n.s
Shelf Height * Item Weight * Task	n.s	n.s	n.s	n.s

(Fig. 6a). When the shelf height was above or below 116.2 cm, the walk time increased, and it took more time to walk and reach towards the lowest shelf height compared with the upper shelves (above 142.6 cm) as this walk time measure consists of the time needed for walking one step and time needed for reaching out to touch the first item to be lifted. The lifting time, averaged across task 1 and 2, was relatively shorter for shelf heights from 63.5 to 116.2 cm compared with that at lower and higher shelves (Fig. 6b). Fig. 6c shows the total time for walking and lifting (task 1) varies by nearly 0.5 s between the slowest and fastest conditions. . The total time to complete task 2 (Fig. 6c) consists of: 1) the time between the end of task 1 and start of the task 2, which includes the necessary movements of the arms and the torso, and 2) the time it takes to lift and move the second object from the shelf to the cart (lifting time of task 2). The results indicated that shelf height had a significant effect on the time required to complete both task 1 and task 2. The time to complete task 1 was longer than the time to complete task 2 at each shelf height, and time difference was relatively consistent, the average of which was 0.75 s (Fig. 6c).

4. Methods – study 2: full case replenishment

Experimental Design. This study investigated two-handed lifting simulating full case replenishment. The two independent variables were the destination height and the case weight. Six destination heights were evaluated (Fig. 7) which included: 30.5 cm, 61 cm, 91.5 cm, 122 cm, 152.5 cm, and 183 cm above the floor. It is recognized that the 183 cm location is above what is included in the NIOSH revised lifting equation (Waters et al., 1993), however, this level has been observed by the authors in several distribution centers and was therefore included. There were four case weights which included boxes weighing 2.7 kg, 5.5 kg, 8.2 kg, and 10.9 kg. These weights were selected to represent a range of product weights that could potentially be encountered in piece-pick replenishment operations. All boxes were lifted from a cart with a surface that was 72.2 cm above the floor. The sequence of destination height and case weight combinations was randomized, and within each condition the lifting task was replicated three times.

Dependent measures included electromyographic, postural, and duration measures. The 90th percentile (peak) bilateral EMG activities were obtained from the Erector Spinae and Anterior Deltoid muscles. Shoulder flexion, knee flexion, and spine postures (flexion, lateral flexion, and twisting) were obtained with a magnetic motion capture system (Innsport, Inc). The duration of each lifting task was also obtained.

Subjects. Fourteen males and one female without back or shoulder

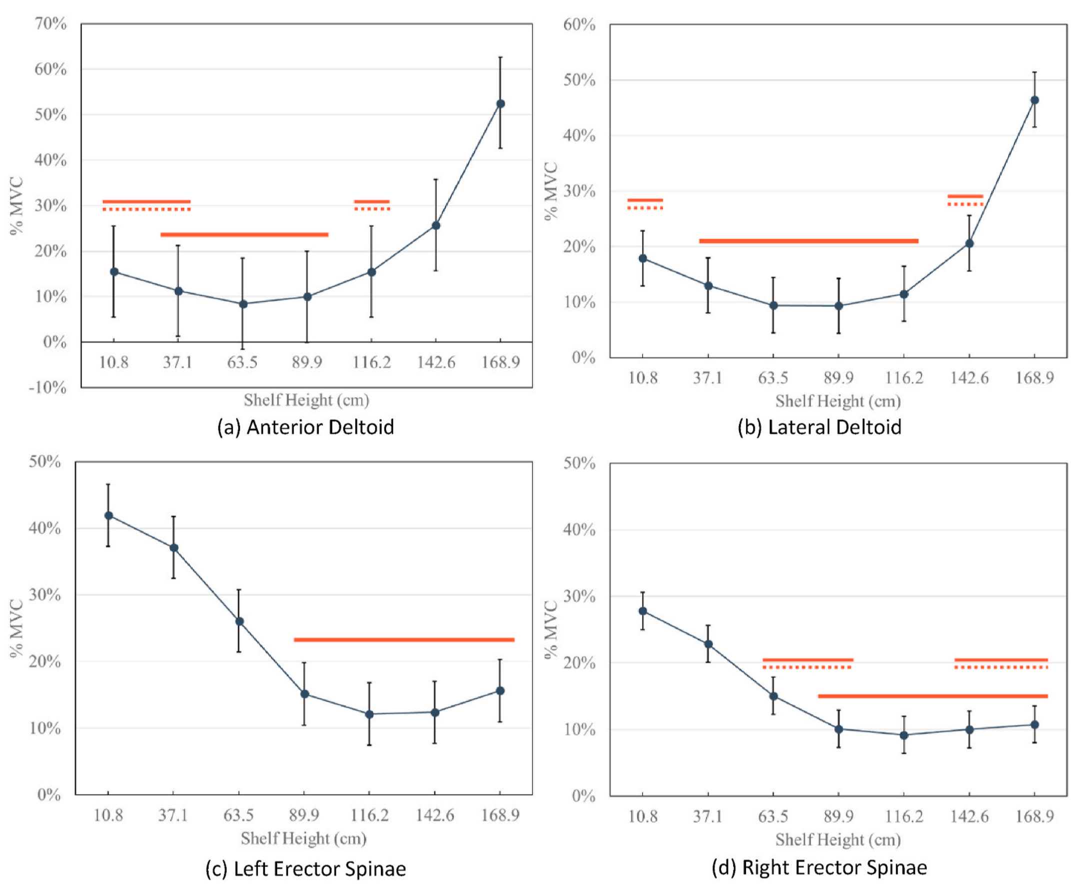

Fig. 5. EMG activity of shoulder and back muscles as a function of shelf height: Anterior Deltoid (a), Lateral Deltoid (b), Left Erector Spinae (c), and the Right Erector Spinae (d). Error bars represent plus and minus one standard error of the mean. Horizontal lines of the same type indicate conditions that were not statistically different in post-hoc tests.

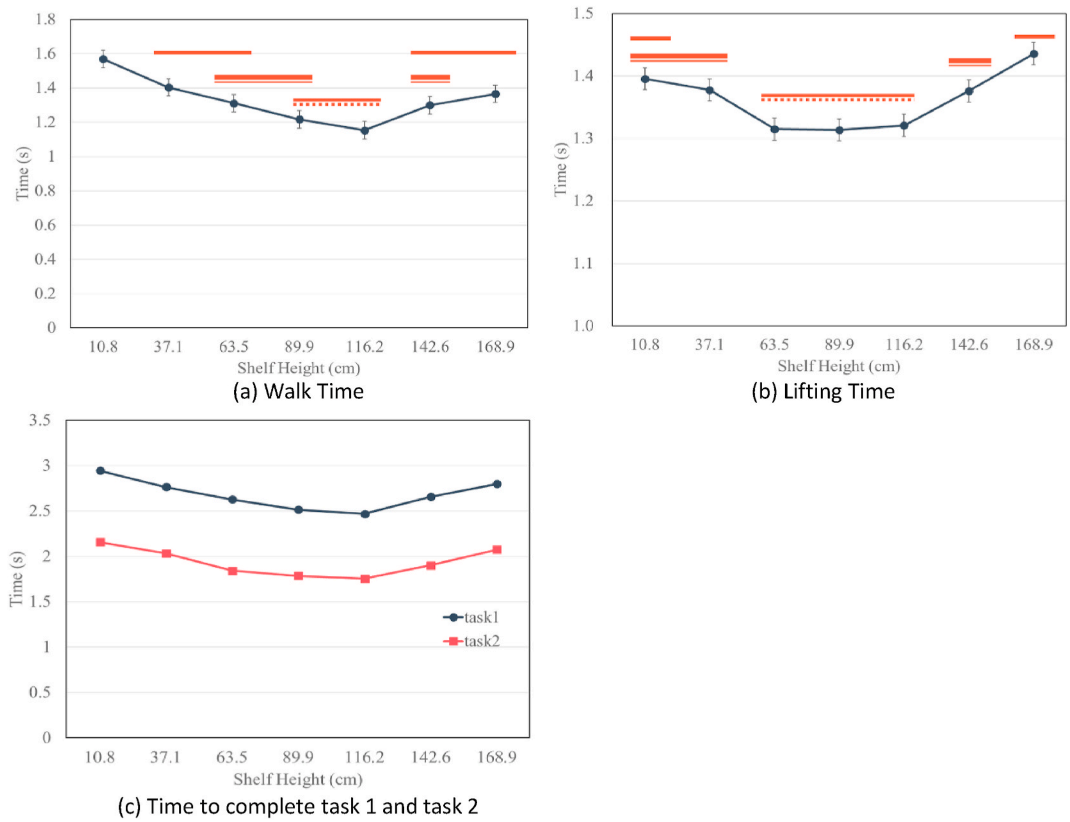

Fig. 6. The effect of shelf height on time cost where (a) shows the walk time, (b) shows the lifting time averaged across tasks 1 and 2, (c) shows total time to complete each task, which in the case of lift 1 includes the walking and lifting and for task 2 includes the turning and lifting. Horizontal lines of the same type indicate conditions that were not statistically different in post-hoc tests.

injury history were recruited for this study. All participants were between the ages of 18 and 30 years and none had any relevant industry or warehouse order picking experience. Their mean height and weight were 1.78 m (range: 1.67–1.88 m) and 81 kg (range: 51–100 kg), respectively. Before the experiment, each participant reviewed and signed an informed consent form approved by the University's Institutional Review Board.

Procedures. Surface electromyographic (EMG) electrodes were placed over the anterior portion of Deltoid muscles and over the Erector Spinae muscles at the L3 level and 2–3 cm away from the midline, over the belly of the muscles. The participant then performed a series of isometric maximal muscle exertion activities to obtain maximal EMG signals to be used for normalization of the data obtained during the lifting tasks. These activities were performed in postures where maximal task muscle recruitments were expected to occur using the procedures described for Study 1.

Motion capture sensors (Flock of Birds, Ascension Technologies) were then attached to the participants over the first thoracic vertebrae and the sacrum. Sensors used to capture arm and shoulder motion were placed on the right and left upper and lower arms. Sensors were also placed bilaterally on the shank and thigh to capture knee flexion angles. Once instrumented, each subject was set up using the Motion Monitor System software (Innsport, Inc.) to create a digital model of the subject. A neutral reference position was sampled prior to initiating the data collection for the lifting tasks. Both the simulated cart, where the lift started, and the simulated flow rack were placed on force plates. The change in the vertical force signals from these force plates was used to identify when lifts started and when they ended. All kinematic and force plate data were sampled at 60 Hz. EMG signals were recorded at a rate of 900 Hz.

When given the signal to start by the investigator, the participant was instructed to move the case to the designated destination level in the flowrack. The participants were not restricted in their foot movements during these tasks. Most elected to take one or two steps when completing these two-handed tasks. After each lift, one of the investigators removed the case from the flow rack and placed the case in the original position until three replications were sampled, at which point a different weight and shelf height combination was tested according to the randomized sequence. A 1 min rest period was provided between each lift.

Data processing. EMG and postural data were extracted using the same filters and RMS processing as described in study 1. The data selected with the Matlab program were from a one-second time period that included data from 0.5 s before the completion of the lifting task to 0.5 s after the completion of the lifting task. This time period included the peak muscle exertions for each of the sampled muscles during the placing portion of the task, which was the focus of the study. The RMS EMG data were normalized relative to maximal values and baseline values. The 90th percentile data for each lifting task was obtained from each 1-s data stream.

For the kinematics analysis, the postures were obtained at the point where the box was placed on the flow rack as indicated by the change in the vertical ground reaction force. The raw kinematic data were normalized by subtracting the neutral posture data sampled prior to the beginning the sequence of lifting tasks.

Statistical analysis. After processing data with MATLAB, normality tests were conducted for EMG and postural data to assess the normality of the data. For nearly all conditions the p-values from the Kolmogorov-Smirnov tests indicated parametric statistical procedures would be appropriate. To determine whether there were significant differences in the EMG and kinematics data due to shelf height and case weight, a two-way ANOVA was used. Post-hoc REGWQ tests were used to examine the differences between different shelf heights and case weights for the EMG and postural data.

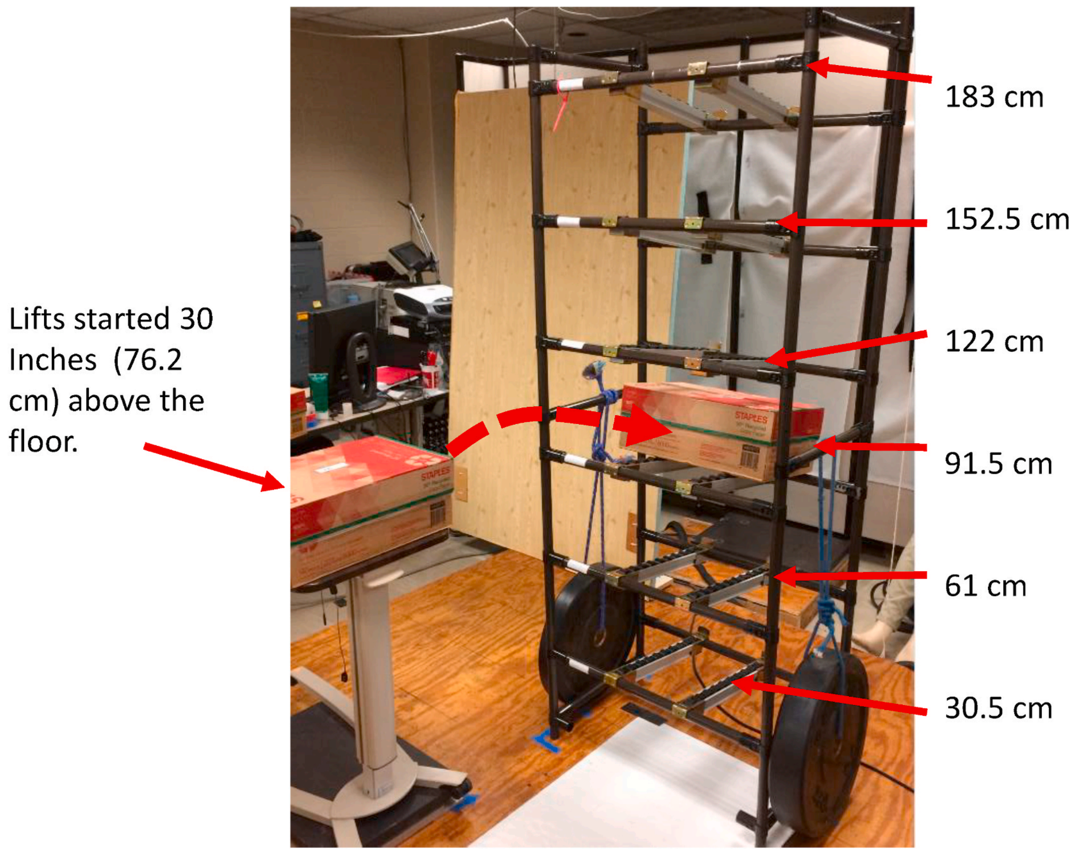

Fig. 7. The apparatus used for the simulated replenishment tasks which started from the cart on the left and ended with the box being placed on the 6 level flow rack.

5. Results – study 2

5.1. Lifting postures

Table 3 shows that the main effect of shelf height was significant for all kinematic measures. Fig. 8 shows the postures at the point of box placement at each of the destination shelf heights. Looking across all postural measures, with the exception of spine twisting, the postural data were closest to the neutral posture when the cases were placed at the 91.5 and the 122 cm heights. Below 91.5 cm there was significantly more spinal flexion, knee flexion, and shoulder flexion. However, at these lower shelf heights the shoulder flexion was largely assisted by gravity given the torso flexion angle. Above 122 cm, the participants adopted postures which included spine extension, significant shoulder flexion and spine twisting.

The weight of the box also affected the left shoulder and the left knee flexion angles. Post-hoc analyses indicated that the heaviest weight reduced shoulder flexion by approximately two degrees. Likewise the heaviest box reduced knee flexion by approximately 4° relative to the lightest box. The significant interaction effect between shelf height and case weight for the spine flexion was largely due to variations in the response when lifting the 2.7 kg box as compared with the other three boxes. There was less spine flexion at the 61 cm shelf height and less spine extension at the 183 cm shelf height when lifting the relatively light load.

Table 3
The p-values for significant differences in peak postural measures due to shelf height, box weight, and their interactions in Study 2. Non-significant effects are indicated by "ns".

Variable	Height	Weight	Height*Weight
Spine Flexion	<.001	ns	<.001
Spine Twisting	<.001	ns	ns
Spine Lateral Flexion	0.023	ns	ns
Right Shoulder Flexion	<.001	ns	ns
Left Shoulder Flexion	<.001	0.009	ns
Right Knee Flexion	<.001	ns	ns
Left Knee Flexion	<.001	0.024	ns

5.2. EMG results

Each of the shoulder and back muscles sampled showed significant changes in activation due to the shelf height, the weight handled, and the combination of these factors ($p < 0.001$ for all main and interaction effects). The interaction effects are shown in Fig. 9.

Post hoc tests for shelf height, independent of weight, showed activity of the left Anterior Deltoid was minimized at shelf heights 61 and 91.5 cm. For the right Anterior Deltoid and the two Erector Spinae muscles, however, the minimal activity was found with shelf heights between 61 and 122 cm shelf. The interaction effects with box weight show some variation in this pattern, particularly with the heavier box weights, in which case the minimal activity was restricted to shelf heights between 61 and 91.5 cm.

5.3. Task duration results

The results for duration indicated highly significant effects ($p < 0.001$) for both shelf height (Fig. 10a) and box weight (Fig. 10b). Post hoc findings showed that the duration was minimized with shelf heights between 61 and 122 cm. The longest duration occurred at the 183 cm shelf height, which took approximately, 0.4 s, or 33 percent longer than lifts to the 91.5 cm height. Each 2.7 kg increase in weight significantly increased the lift duration. Relative to the 2.7 kg case weight, the 10.9 kg case weight took 0.27 s, or 16 percent longer. There was a trend towards

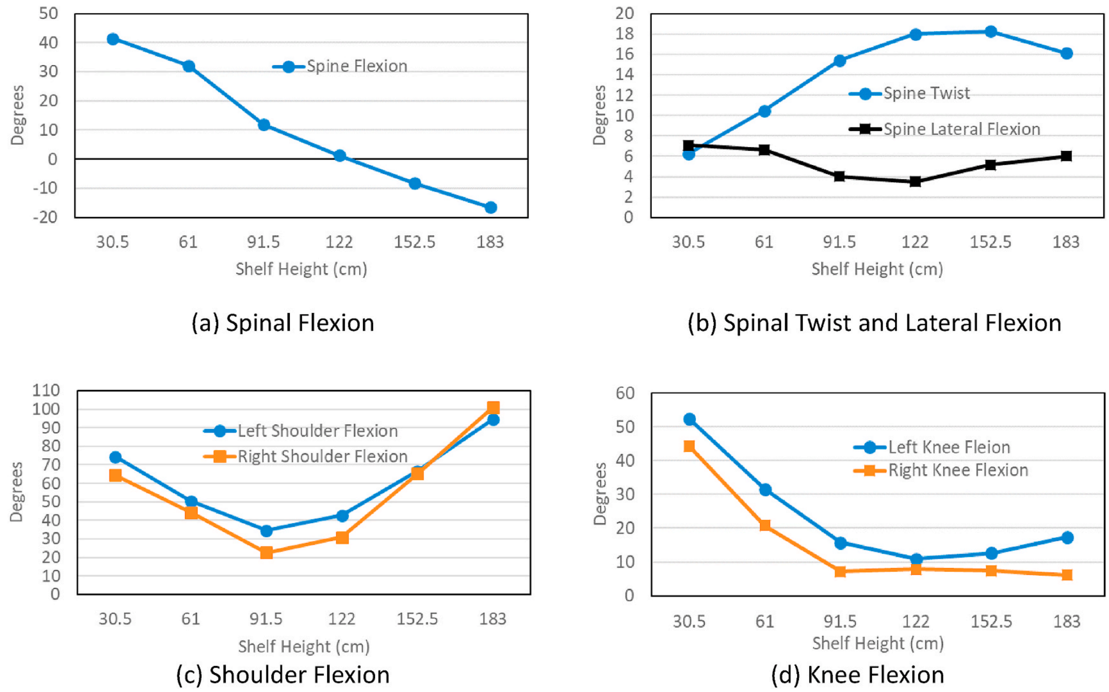

Fig. 8. Spine (a and b), shoulder (c), and knee (d) postures as a function of shelf height when the box was placed on the shelf.

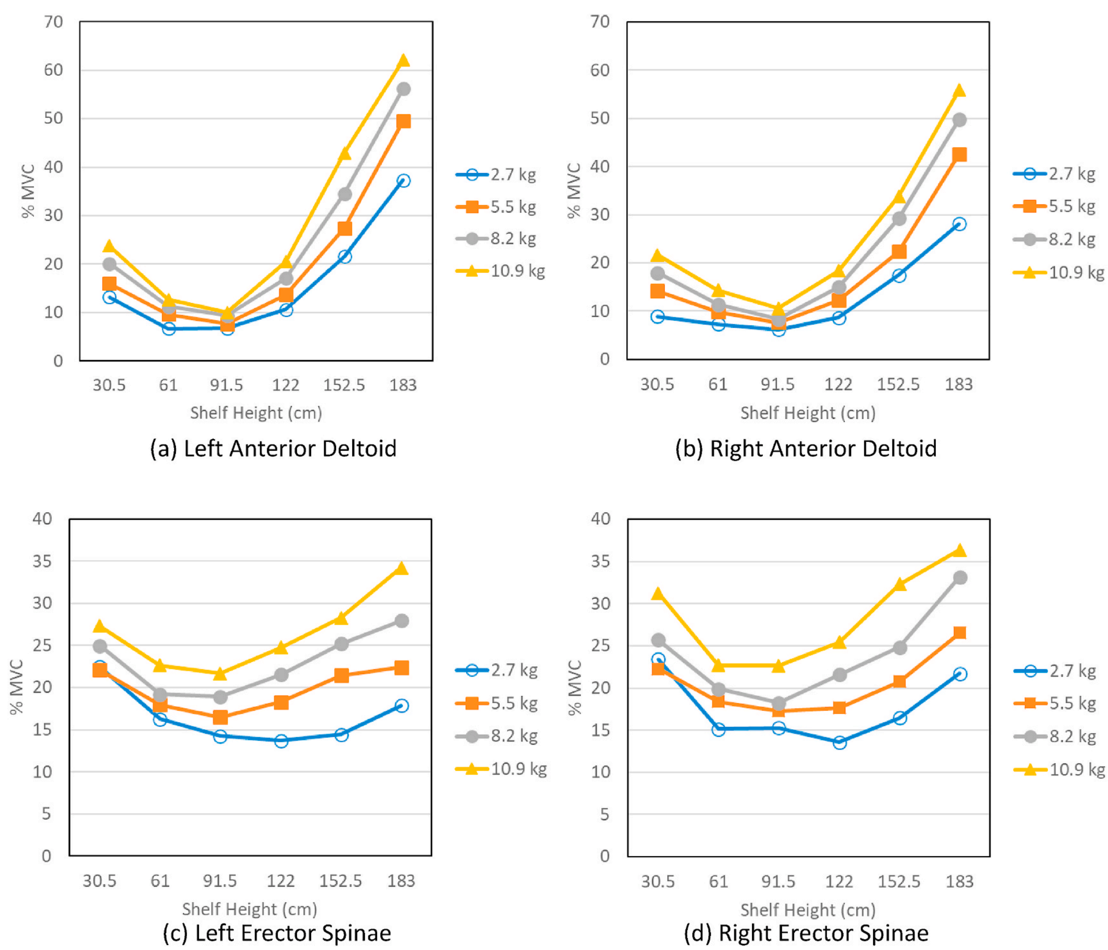

Fig. 9. Normalized muscle activation levels as a function of shelf height and box weight for the left and right anterior deltoids (a & b), and the erector spinae muscles (c & d).

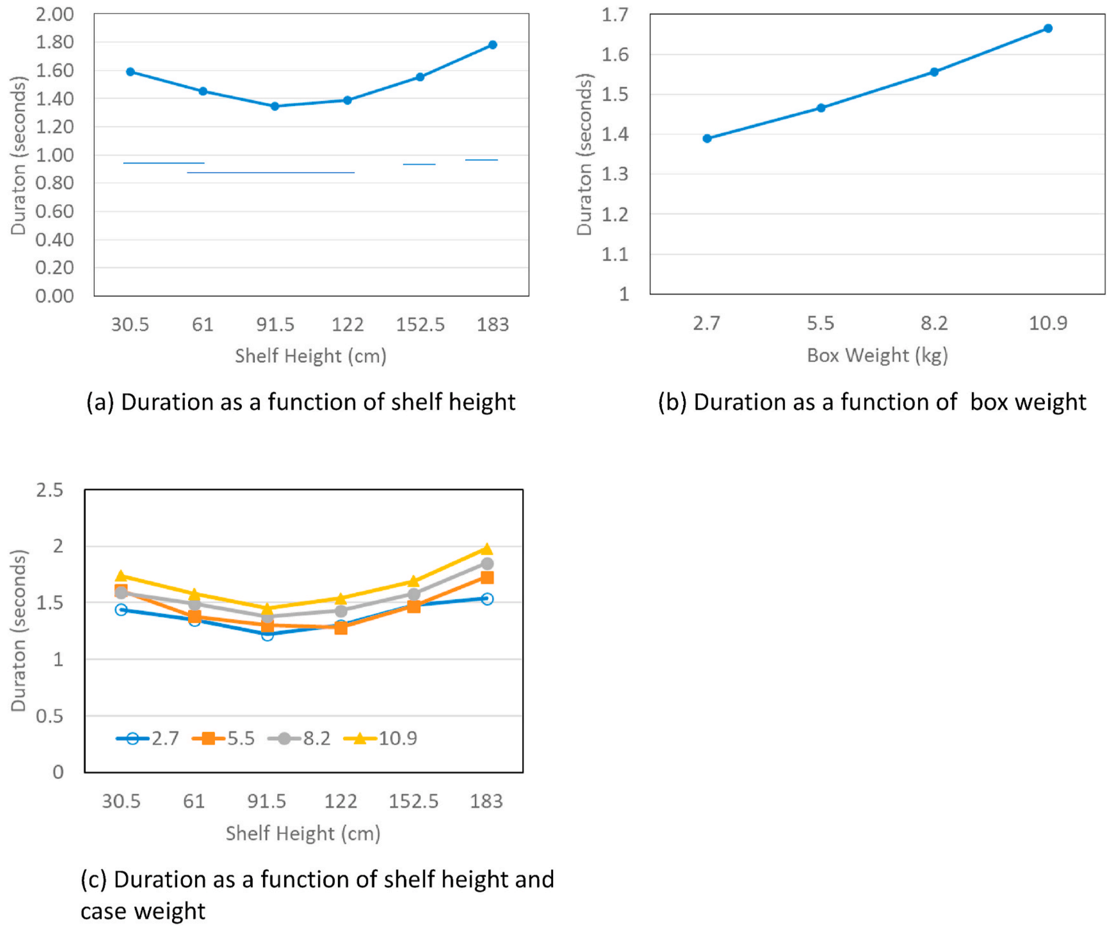

Fig. 10. The change in lift duration due to shelf height (a), case weight (cm) (b), and the combination of these factors (c). The horizontal lines in (a) indicate conditions that were not significantly different in post-hoc tests.

an interaction effect between case weight and shelf height ($p = 0.052$) that is shown in Fig. 10c. The interaction effect was largely due to the limited difference in the duration between the 2.7 and the 5.5 kg case weight conditions.

Fig. 11 combines muscle activity and task duration into a single measure of task activity cost by taking the product of the measures. One line represents the averaged bilateral Anterior Deltoid data averaged across the four case weights and the other line represents the averaged bilateral Erector Spinae data averaged across the four case weights. This analysis shown in Fig. 11 confirms that task activity cost should be based on Erector Spinae activity when considering lifting tasks at or below 122 cm and that the deltoid muscles drive the task cost function when considering lifting tasks to locations above 122 cm. Moreover, the task activity cost at the upper shelf heights is 1.8 and 3.5 times that observed at the 91.5 cm height. Likewise, the lowest shelf height sampled, 30.5 cm, has a task activity cost that is 1.7 times that observed at the 91.5 cm shelf height.

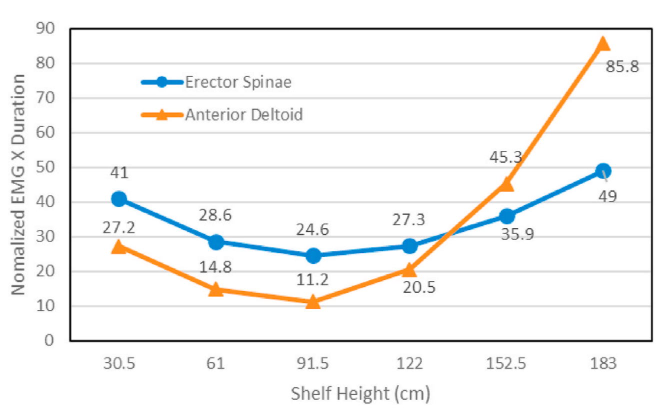

Fig. 11. The task activity cost computed by calculating the averaged bilateral EMG activity and multiplying these averages by the lift duration at each shelf height.

6. Discussion

Together, the two studies provide data that show the relative cost of picking and replenishing product as a function of shelf height, weight, and travel distance (study 1), data that are needed to incorporate order picker ergonomics in decision support models that assign stock keeping units (SKU) storage locations in warehousing operations (Grosse et al., 2017). Collectively, these results clearly show the value of picking from and replenishing to shelf heights between 60 and 120 cm in terms of minimizing the biomechanical loads experienced by selection and replenishment workers, and therefore minimizing likelihood of cumulative musculoskeletal disorders.

Petersen et al. (2005), in their simulation model showed that 'golden zone' slotting of popular SKU's improved total fulfillment time but increased travel times. Bartholdi and Hackman (2019) noted that it is important to consider the ergonomic efficiency by placing SKU's so that as much picking as possible takes place between waist and chest heights (the 'golden zone'). In addition to the ergonomic benefits with regards to picking the items in the golden zone, the current study showed the relative time cost to take an additional step was approximately 1 s, which could be reduced to half a second if, instead of picking from a high or low level, the step allowed the person to pick in the desired height zone. As suggested by Larco et al. (2017), there could be trade-offs between productivity and ergonomics, and while keeping tasks in the "golden zone" may be possible by increasing the travel distance, this will adversely affect cycle times. Their case study showed that they could achieve a 16 percent improvement in discomfort but with a 6 percent increase in cycle time (Larco et al., 2017). However, the data presented here shows that the ergonomic costs are very much non-linear with respect to the higher and lower shelf heights, which could alter the tradeoff functions considered by Larco et al. (2017). It should be pointed out that many distribution center slotting models that have started to incorporate ergonomic components, have looked at overall physiologic fatigue or general postural analyses (Calzavara et al., 2019) but have not considered the MSD risk associated with repetitive shoulder exertions (Sommerich et al., 1993) or repetitive spine motions (Marras et al., 1993) nor the cost associated with MSDs. Lavender and Marras (1994) showed that jobs associated with increased low back disorder risk were also associated with higher turnover, which substantially increases operations costs in distribution centers.

It also should be pointed out that these prior models have not simultaneously addressed the ergonomic cost associated with full case replenishment in piece-pick operations. So when distribution center operations personnel must make decisions where items should be placed, it is evident from the data presented here that, in addition to how fast items move through the facility (often referred to is item velocity), consideration must be given to the weight, particularly when it comes to replenishment. Thus, it may be necessary to consider exceptions to the advocated golden zone rule (Bartholdi and Hackman, 2019) for picking by placing slower moving but heavy cases of items in the 60–120 cm zone and some of the lighter and faster moving times outside this region.

When slotting items for piece picking operations, consideration should also be given to the size of the individually picked items. The heights evaluated in the first study and shown in the charts are the shelf heights. Actual hand heights could vary by several centimeters depending upon the size of the actual item being moved. Given the jar used in the first study was 13.3 cm, the lowest height in study 1 was actually 13.3 cm above shelf height (24.3 cm) as it was the top of the item that was grasped. And while the very top of the jar was not grasped at the upper shelf, the jar was lifted out of a tray such that the participant needed to grasp near the upper part of the jar, thereby making the actual initial lifting height closer to 180 cm. Thus, in terms of slotting decisions, it is important to consider item height when deciding whether to place slower moving products on upper versus lower shelf heights. As for replenishment, this is not typically a concern as the boxes are typically lifted with two hands that are holding the bottom of the box.

Based on the data collected, Fig. 12 shows some general slotting guidelines that should be considered when making slotting decisions that address the ergonomics of both the selector and the individual doing the replenishment task. In addition to echoing the call by others to put the fastest moving items in the "golden zone", these guidelines consider the size of the slower moving items to minimize the deviation from neutral postures and reduce muscles forces. They also indicate that it would be better to spread high velocity times horizontally rather than vertically as the data show that additional step only costs approximately half a second. At the same time these guidelines indicate that slotting decisions must also take into account the full case weights as this affects the ergonomic considerations during the replenishment tasks. Thus, there may be instances where slower velocity items need to be slotted in the golden zone if their total case weights are heavier (>8 kg). Keeping these heavier items in the golden zone make it more likely the lifts to the lower levels are compliant with the NIOSH lifting equation (Waters et al., 1993). These were reviewed by individuals responsible for operations and safety at a grocery distribution center that has several items that are individually picked from flow rack storage locations. Overall, they found the guidelines reasonable, however, future studies need to expand walking distances to further refine the costs associated with more lateral displacement of faster moving items (high velocity SKU's).

There are a couple of limitations of this study that should be noted. First, the two item weights were used in study 1 do not capture the full range of weights encountered in piece pick operations. It is recognized that both lighter and heavier objects are handled in these type of selection operations. The two weights used here were selected to explore the sensitivity of these results to item weight in this type of picking operation. Second, the subjects for both studies were comprised of participants without relevant work experience. However, they were coached on how to perform the task so that their methods replicated those observed by the authors in distribution operations. Third, there was limited anthropometric diversity in these studies. The piece pick study used only female participants as the authors have encountered a predominance of female workers in piece pick selection jobs. However, it is anticipated that electromyographic data from larger and stronger male workers would show similar trends given larger individuals have heavier body segments and the muscle forces used in the selection task are largely those required for positioning the body segments, given the

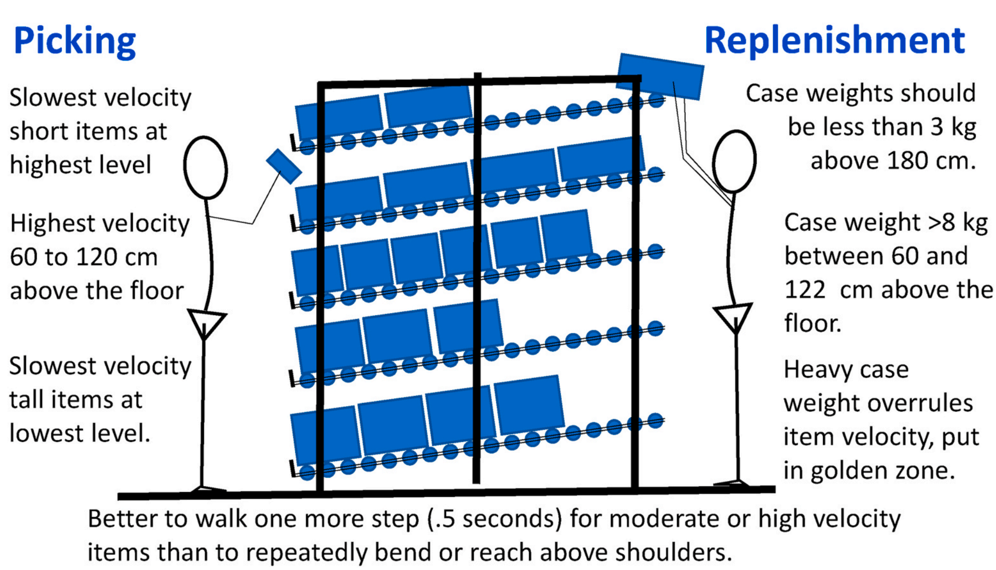

Fig. 12. Proposed slotting guidelines that address the ergonomics needs of both the selector doing the picking operation and the replenishment person that is restocking the pick locations.

small weight of the selected items relative to the weight of the body segments, especially when reaching for items at the lower and upper shelf heights. In the replenishment study, nearly all of the sampled participants were male. But this again is consistent with observations of flow rack replenishment workers who frequently lift full cases onto shelves of varying heights. In this case we want to be sure we were not putting people at risk of injury and not fatiguing the sampled muscles.

In summary, this study has quantified the relative ergonomic cost of individual item selection and full case replenishment tasks that are commonly performed in distribution centers. The data not only show the increased physical demands on the musculature, but also show how task duration is dependent upon shelf height and the weights handled for both of these tasks. Developing slotting models based on the minimization of travel distance would result in many items and cases being lifted from or to locations outside of the zone that minimizes muscle demands and postural deviations (60–120 cm), thus increasing worker fatigue and risk for musculoskeletal disorders. The time cost of taking a single step was found to be relatively small, which could be further offset if it allows one to pick from a desirable shelf height as pick and replenish tasks were faster at these central heights.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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