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Ergonomic Analysis of Mobile Cart Assisted Stocking Activities Using Electromyography

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Abstract

Workers in grocery stores are exposed to numerous musculoskeletal risks that can be reduced using assistive devices while performing stocking tasks. A regional grocery store has recently deployed a mobile cart without comprehension of its ergonomic impact on workers, which this paper investigates using normalized electromyography data (%MVC). This paper studies not only ergonomic impact based on %MVC values, but also work performance represented by a muscle force metric (MFM). The results from this study showed highest muscle groups in %MVC and MFM were the erector spinae and triceps. Interestingly, muscle activations on erector spinae were reduced when mobile cart is used. %MVC and MFM distribution for value-added- and non-value-added subtasks were slightly different, with larger differences observed for non-value-added tasks. Video recordings revealed higher work performance when mobile cart is used. In future research, the number of participants will be increased to further validate the results from this study.

Keywords: Ergonomic Risks, Electromyography, Maximum Voluntary Isometric Contraction, Workspace Volume, Spaghetti Chart.

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1. INTRODUCTION

Typical material handling in industrial applications involves repetitive lifting and lowering tasks of certain objects over long periods of time and thus is associated with various musculoskeletal injuries such as low back pain (LBP) (Webster et al., 1994; Maniadakis et al., 2000; Maetzel et al., 2002; Goetzel et al., 2003; Punnett et al., 2005; Collins et al., 2005; Dagenais et al., 2008). It has been shown in previous studies that LBP has a direct relationship with compressive forces exerted on the L5/S1 - 5th lumbar/1st sacral disc (Chaffin and Park, 1973; Olsen et al., 1992**)**. It has been also shown that the increase in LBP positively correlates with the increase in the weight and size of items being handled within a given period of time (Kraus et al., 1997).

The spine is constantly agitated on account of the shear and compressive forces applied on it while performing lifting tasks and this can cause potential injury to muscles and tissues (Panjabi, 1992; Granata et al., 2008). A decrease in muscular endurance of the back extensor muscles in the face of continuous loading increases the risks of the occurrence of LBP due to spinal instability (Chok et al., 1999; Gandevia, 2001) and, if further aggravated, the ability of actively contracting muscles to sustain its contraction over time is reduced (Luoto et al., 1995; Granata et al., 2004; Gollhofer et al., 2008). Note that attempts at correcting this agitation are made through combined intervention of both the active and passive elements of the musculoskeletal system (Cholewicki et al., 1996). When these corrections are not made in instances of prolonged bending, injuries to the spine finally occurs (Nou et al., 2012). As an effort to reduce the incidences of LBP in occupational settings, the National Institute of Occupational Safety (NIOSH) developed a revised lifting equation that was intended for the design and evaluation of manual lifting tasks. Although the equation was designed based on work physiology and biomechanical data with assumptions, its primary limitations include (*i*) the attribution of the same levels of risk to lifting and lowering, and (*ii*) the assumption that other activities, which are not lifting tasks (e.g., pulling, walking, climbing, pushing, and carrying), involve minimal use of energy, hence are not primary considerations in the implementation of the equation (Waters et al., 1993, 1994, 1999)**.** In addition, the variability in number, type and weight of items being lifted or lowered in occupational settings presents another limitation of the NIOSH equation (Dempsey, 2002).

On the other hand, biomechanical models have been applied for determining optimal postures that minimize LBP (Kuo, 1995; Ayoub, 1996; Nussbaum et al., 1998; Erdemir et al., 2007). However in these models, individual differences of participants in terms of anatomy, gender, age, specific sites of possible injury, torso posture and torso dynamics were not explicitly considered (Davis et al., 2005). In addition, precise information on how load is distributed to different muscle groups while lifting tasks are performed was not considered in those models (Andersson, 1985). Instead, muscle activations were assumed based on the past data and experience. It should be noted that electromyography (EMG) can be used to measure specific muscle groups' activities during lifting tasks and thus quantitative information on muscle exertions during lifting that is extracted directly from participant's task performance can be available.

Even though it is often conjectured and suggested that the use of assisting devices for material handling tasks can reduce stress and injury experienced by workers, the problem is that their impact on ergonomic risks has not been extensively studied (Nussbaum et al., 1999). Therefore, this study focuses on the quantitative analysis of the impact of using assisting devices such as a mobile cart on ergonomic risks. More specifically, this study considers two different scenarios of stocking activities in a regional grocery store: (*a*) with mobile cart (WM) and (*b*) without mobile cart (WOM). During stocking activities in WM and WOM scenarios, muscle activations are measured using surface electromyography sensors (sEMG) placed on eight muscle groups. Then, the collected sEMG data is analyzed, together with video data of the same tasks and self-reported questionnaires. Note that Wells et al. (1997) proposed that the use of multi-modalities can provide the ease of data comparison between alternate scenarios. Finally, a new measure is developed and tested in this study, called muscle force metric (MFM) that captures efficiency and throughput information through the combined analysis of sEMG data with workspace volume.

This paper is organized as follows: Section 2 describes the details of data collection including the nature of stocking tasks, MVC measurements and sEMG data collection. The collected data is analyzed in

Section 3 to investigate the impact of the mobile cart on ergonomic risk and work-performance. The outcomes of the study are then discussed in Section 4 and the paper is concluded in Section 5.

2. METHODS

2.1. Participants and stocking tasks

In this research, seven (7) employees at a local grocery store (six males and one female, hereinafter referred to as 'participants') with an average (stocking) work experience of 4 years, an average age of 27, and having no pre-existing musculoskeletal conditions, were made to perform repeated stocking activities over the course of four non-consecutive days. More specifically, the participants performed conventional tasks comprised of movement of sales items in a box, stacking the items on the shelves, arrangement and inter-shelf transportation of the items. All data collection was done during the early morning shift (from 4.30 a.m. to 9.30 a.m.). Two scenarios for the stocking activity were tested in the experiment: (*i*) with a mobile cart (WM) and (*ii*) without a mobile cart (WOM). The mobile cart used in this study has the following specification: size of adjustable platform – 24 by 21 (inch), an adjustable height of the platform – 23 (inch) through 53 (inch) maximum recommended carrying weight – 75 (lbs). With the replication of the same task twice, seven pairs of data from both scenarios were pooled together for analysis.

The weight of grocery packages ranges from 0.5 to 4 (kg). Without the mobile cart (WOM), participants manually picked up the packages and then placed the packages on the floor during stocking or supported against the knee that could result in strain on various muscles including the rectus femoris and erector spinae. On the other hand, items can be directly shelved with the mobile cart (WM) scenario. Note that the mobile cart's height can be adjusted according to the height of the participant and this feature of height adjustment of the mobile cart can reduce the ratio of average lifting and lowering frequencies in the WM scenario relative to the WOM. The nature of the aforementioned stocking tasks can be seen from Figure 1 where (a), (b), (c), and (d) show conventional stocking tasks (WOM) and (e), (f) show the details of the mobile cart used in this study, with grocery items loaded onto it. It is interesting to observe that participants typically use their legs to support the package for shelving items as shown in Figures 1(a), 1(b) and 1(c).

[Insert Figure 1 here]

2.2. Data collection

During the stocking activities randomly alternating between two scenarios, amplified bio-potential signals were collected for 15-minute time intervals from 8 muscle groups of each participant - bilateral biceps, triceps, trapezius, and erector spinae using an 8-channel Bioradio 150® physiologic data acquisition system (Great Lakes Neurotechnologies, Cleveland OH). After wiping skin surfaces overlying target muscle groups with alcohol and allowing the alcohol to dry, two 1” by 1” MVAP-II electromyography (EMG) electrodes (MVAP Medical Supplies, Newbury Park CA) were placed over the belly of each muscle group and connected to the positive and negative input poles for each channel. An electrode was also attached to the right elbow and connected to the Ground input on the Bioradio® to complete the input circuit. The Biocapture data acquisition software package (Great Lakes Neurotechnologies, Cleveland OH) was used to capture and filter EMG data. Specifically, surface EMG (sEMG) data was captured at a sampling frequency of 256 Hz from each channel. Digital signal processing filters were applied to exclude low (<10 Hz) and high frequency (>127 Hz) signals at the time of data capture. While analyzing the signal in Matlab, noise filtering was also carried out in order that sEMG value is not affected by the wide-sense stationary assumption of EMG signals in muscle activity quantifications for spectral analysis, considering that for the dynamic and recursive tasks being performed by participants in this experiment, the changes in the positions of the electrodes, muscle length, and muscle force are infinitesimal (Frigo et al., 2004).

At the start of data collection, sEMG data was collected individually from each muscle group while the maximal voluntary isometric contraction of that muscle was elicited by an assistant providing resistance. In the design of experiments involving static work, raw forces data is typically analyzed in relation to each participant’s voluntarily exerted maximum strengths for specific muscle groups, specific postures, at specific points in time depending on the specific experiments being carried out, to derive a relative force value which is a percentage of the participant's maximum, referred to as maximum voluntary isometric contraction (MVC) (Frigo et al., 2004). The determination of the MVC for each of the muscle groups is important because absolute EMG values depend on many factors like the positioning of participants, fatigue and joint moments, which makes it difficult to determine actual muscle forces exerted without the isolation of these noise-inducing factors. The protocol used in this study to collect MVC data can be described as follows (Mirka, 1991):

(a) *Biceps (bilateral):* The designated participant, who was seated and stationary, was made to hold his/her forearm up at a 45^0 angle at the elbow with the palm supinated, and pull in an opposite direction of the force applied by an assistant (the same assistant did the force application for all of the MVC data collections). It should be noted that the same assistant was used applied maximum opposing forces during the MVC data collection for all of the muscle groups and for all of the participants, so as to ensure consistency and uniformity in the applied force;

(b) *Triceps (bilateral):* With the forearm still at a 45^0 angle, the participant pushed against an opposing force applied by an assistant. The participant was also in a sitting position and stationary;

(c) *Erector Spinae (bilateral):* While standing, the participant supported a given load behind the head at the level of his/her clavicle, while slightly arching the abdominal region forward. An assistant was positioned behind the participant to take the load off at the end of the data collection (which lasts for 4 seconds) and also provide any necessary aid so as to prevent excessive strain on the participant, and lower back injury;

(d) *Trapezius (bilateral):* An assistant applied downward pressure on the upper part of the deltoid while the participant applied force also, in the opposite direction.

Figure 2 shows the procedures used in this study to collect MVC data.

[Insert Figure 2 here]

There is also a large variation in muscle recruitment between individuals to achieve joint moments, thus making it important to have a relative measure of effort (%MVC) for each individual and each muscle group. The MVC data obtained according to the aforementioned protocol were used for the normalization of the muscle activation data collected from each of the participants' muscle groups, in other words for determining the %MVC values. In calculating %MVC, a percentage ratio was taken of the force applied on each of the muscle groups as follows:

$$\%MVC = 100\% * \{Force(\mu V)\} / MVC \tag{1}$$

Note that the calculation of %MVC in the above equation is one of the multiple ways that is widely accepted in the field of biomechanics and kinesiology. On account of the variability in participants' activities within the data collection time windows, it was necessary to also adopt analyses paradigms that would effectively capture each participant's throughput and have them compared between scenarios, with reference to %MVC. One of the measures adopted was the measurement of the distances travelled between shelves with and without the mobile cart by taking note of the number of shelf sections visited (workspace volume) per scenario, and the number of cases stacked up. Noting that each shelf section was 4 feet (ft.) wide, and thus workspace volume (measured in feet), *WV* was calculated as

$$WV = 4(ft) * S \tag{2}$$

where *S* represents number of sections visited by the participant per scenario. The estimation of the workspace volume using a single dimension of width is based on the assumption that the moment applied to the participant's spine is proportional to the horizontal distance the participant moves away from the body. With this assumption, the *WV* term in Equation 2 provides insight on workspace volume covered by participants for each scenario (with and without the mobile cart) and also provide a basis for throughput comparison**.** As a next step, percentage muscle activation per workspace volume, called MFM (muscle-force-metric), was determined in this study for each of the participants and compared between scenarios, so as to provide indications of activities that initiated relatively higher muscle activations. The MFM can be calculated using the following equation:

$$Muscle\ Force\ Metric\ (MFC) = \%MVC/WV \tag{3}$$

It should be pointed out here that due to the introduciton of the *Muscle-Force-Metric* (MFM) measured in %/feet, the levels of muscle forces that were applied in the same working conditions by the participants for both scenarios are represented in a relative sense to the number of shelves sections and aisles covered.

2.3. Ergonomic profile illustrator (EPI)

In the analysis of muscle activations, an entire set of data collected over a specified period of time is usually analyzed as one whole from the start of an experiment to its completion, thus obliterating important information on muscle activity for certain important sub-tasks. An example is the examination of muscle activity at points where participants are not involved in activities that form the core basis of a particular experiment. Strength of analysis is further enhanced if data collected can be subdivided into multiple time-segments for independent analysis, without having to restart the data acquisition device. A software tool was thus required to easily analyze significantly large sets of EMG data without compromise on depths of detail in the analysis. In this study, a software tool, called ergonomic profile illustrator (EPI), has been developed by the authors based on commercialized software (MATLAB), which was used for the simultaneous analysis of raw and normalized EMG and MFM values for different time segments.

The EPI is a user-friendly interface used for the simultaneous real-time analysis, normalization, and display of muscle activation data from eight distinct muscle groups. It has a compact graphical user interface as shown in Figure 3 that provides the user with various functions: (*a*) specify the range of EMG data to perform analysis on within an experiment’s time frame, (*b*) separate data from different muscle groups into multiple time segments (which can be varied at the user’s discretion), (*c*) perform multiple statistical analyses on the separated data, (*d*) specify normalization criteria, and (*e*) create user-specified plots and graphs from data. The EPI also provides visual cues to users after every action is performed, ensuring that there are no data-input errors.

[Insert Figure 3 here]

Thanks to the EPI, it was possible to further sub-divide data collected from both scenarios into value-added, and non-value-added activities, with the former being activities directly relating to stocking activity that includes retrieval of grocery items from cases, placement and arrangement of the items on shelves, re-arrangement of already stocked items, and breaking-up and disposal of empty cases. On the other hand, non-value-added activities include travels between shelves. In addition to the EMG-related data, EPI provides useful information of travel distances in both two scenarios.

3. ANALYSIS AND RESULTS

The various analyses performed in this section include normalized muscle activations, muscle-force-metrics for both value-adding and non-value-adding subtasks and travel distances. Note that sEMG data was used for most of analysis, together with video tape for travel distance analysis in the WM and WOM scenarios.

3.1. Normalized muscle activation (%MVC)

sEMG data collected from various muscle groups of the left biceps (LB), left triceps (LT), left erector spinae (LES), left trapezius (LTr), right biceps (RB), right triceps (RT), right erector spinae (RES), and the right trapezius (RTr) was analyzed in this section. Specifically, the normalized muscle activations (%MVCs) calculated by using Equation 1 for the eight muscles were compared in WM and WOM scenarios. The degree of exertions of individual muscle groups on either side of the body has been further compared to find out if the trend of activation is uniform or distinct. The results from this analysis are shown in Figure 4. First, the highest %MVCs was observed on the erector spinae for both the WM and WOM scenarios, indicating relatively greater deployment compared to other muscle groups during stocking. Second, on the left-hand portion of the body, the highest %MVC values were observed on the LES and LT muscle groups. Irrespective of the fact that these two muscle groups had mutually higher %MVC values recorded when compared to other muscle groups statistically significant disparities exists between them. In the WM scenario, a p-value of 0.0047 was recorded when comparing LES and LT, while in the WOM scenario for the same muscle groups, a p-value of 0.0016 was recorded. Similarly, on the right-hand portion, the highest %MVC values were observed on the RES and the RT muscle groups in both the WM and WOM scenarios with $p = 0.0055$ and $p = 0.0219$, respectively, thus indicating the bilateral erector spinae and triceps as the muscle groups that are recruited the most in stocking activities, with bilateral differences also existing between these two significantly activated muscle groups. Applying the same comparisons to the LES and RES and looking at the difference between the WM and WOM scenarios, no differences were observed, based on p-values of $p = 0.0920$ and $p = 0.0700$ respectively. The p-values are determined at 0.0500 level of significance. Relatively higher muscle activations on the triceps than biceps can be related to the nature of stocking tasks in which the participant's hands are pronated (not supinated) in general, which triggered the higher activation on the triceps.

[Insert Figure 4 here]

The sEMG data was further subdivided into value-added and non-value-added tasks to capture the fraction of total energy expended on useful work while carrying out the stocking activities and vice versa. More specifically, tasks performed for stocking activities, in other words physical placement of the grocery items on the shelves, breaking up of the boxes, and preparation of space to accommodate new items to be stocked, were termed as value-added. Other tasks such as engaging in conversations, walking between shelves, or pausing for long periods of time, were termed as non-value-added. Table 1 shows %MVC values for the value-added and non-value-added tasks. The values in the table were arranged according to muscle groups most utilized (the erector spinae) and least utilized (the right trapezius) during stocking activities, in both the WM and WOM scenarios. Total energy expended (based on %MVC values recorded in Table 1) on non-value added activities was higher than energy expended on value-added activities, in both the WOM and WM scenarios respectively. Data collection was done within fixed, equal time windows (15 minutes) in all scenarios. For the value-added activities, despite the lower values in total %MVC, the observed work output in terms of the total number of objects stacked on the shelves was higher with WM than without WOM. Note that in case of non-value–added activities, the participant must push or pull the mobile cart that is loaded with packages and items. Hence there is generally more energy expenditure in this latter case.

[Insert Table 1 here]

3.2. Muscle-force-metric (MFM)

By definition given in Equation 3, MFM values provide information on the relative effort applied to perform stocking tasks with reference to WV expressed in %MVC per unit feet. This presents baseline information about throughput in the WM and WOM scenarios. Figure 5 shows MFM values for the eight muscle groups.

[Insert Figure 5 here]

As shown in Figure 5, the LES and RES have the highest average MFM values in both scenarios. On the left-hand portion of the body, the next ranking muscle group to the LES is the LT with a statistically significant difference (of $p = 0.0539$ and $p = 0.0374$ for the WM and WOM scenarios, respectively). On the right-hand muscle groups, the RT is next to the RES with a statistically significant difference ($p = 0.0168$ and $p = 0.0389$ for the WM and WOM scenarios, respectively).

Figure 6 depicts MFM values for non-value-added activities and higher value for the erector spinae is observed from the figure. There exists in the WOM and WM scenario, statistically significant differences in MFM values of the LES and LT (p = 0.0179 and 0.0389 respectively), RES and RT ($p = 0.0368$ and $p = 0.0355$ respectively.

[Insert Figure 6 here]

Figure 7 illustrates MFM data got from value-added activities, and also show the LES and RES having the highest MFM values on both sides of the saggital plane. Remarkably, the LT is next in rank to the LES in MFM values ($p = 0.0070$ in WM, and $p = 0.0074$ in WOM scenarios respectively), while RES is followed by RT ($p = 0.0045$ in WM, and $p = 0.0439$ in WOM scenarios respectively).

[Insert Figure 7 here]

3.3. Travel distances

Table 2 summarizes several statistics of the travel distances that the participants made during stocking tasks in the WM and WOM scenarios. It is observed that WM is beneficial to the participants with improved statistics.

[Insert Table 2 here]

On the other hand, Figure 8 illustrates travel routes made by the participants in the form of a chart, called Spaghetti Chart. The travel routes shown in spaghetti charts are from three observation pairs, one from each participant. From these illustrations, it can be observed that there was increased movement in the WOM scenario for the same time frame allotted (15 minutes). In other words, the relative density of the routes in WM and WOM scenarios is clearly different such that the density of WM is lower than that of WOM. Importantly, the participants were able to transverse across more shelves with reduced number of trips, while being able to transport more cases at the same time with the aid of the mobile cart. It should be pointed out here that the reduced travel distance offered by using the mobile cart is traded off with extra energy by the participant to push, pull the cart which is loaded with items.

[Insert Figure 8 here]

3.4. Video based observations

From the video recordings made while performing the study, it was observed that the average number of cases treated in WOM scenario decreased by about 17% (with an approximately 21% decrease in the rate of cases treated per second). There was a 1% increase in single-handed motions at an increased average frequency of 189%, and a 46% decrease in two-handed motions with a decrease in frequency of 83%. It should be pointed out here that in addition to motions involving the placements of groceries on the shelves, the WM scenario also involves pulls/push between shelves, with multiple grocery packages stacked on the cart, further reducing travel distances.

4. DISCUSSION

The average %MVC and MFM values show higher muscle activation and utilization of both left and right erector spinae (LES and RES, respectively) followed by left and right triceps, relative to other muscle groups, during stocking activities. As expected, the low back was subject to higher applied load than other muscle groups. In addition, there was a substantial difference in total %MVC values between two scenarios of WOM and WM in case of the value-added tasks as shown in Table 1. Specifically, the total %MVC value decreases by 24.2% when mobile carts are used in case of value-added tasks. This shows that using the mobile cart can help the workers apply their energy to more useful activities in the WM scenario. Table 1 also shows in both scenarios, higher muscle activations when participants perform non-value-added tasks than when they perform value-added tasks. It is interesting to observe that there is not much difference in %MVC values of two scenarios in case of non-value-added tasks. This study may provide administrators of the local grocery store who deploy the mobile cart without comprehensive understanding of the ergonomic benefit that workers would receive, with baseline information about the ergonomic benefit of using mobile carts.

For non-value-added tasks performed without the mobile cart, there was little or no statistical difference between the force exerted on the erector spinae and that exerted on other muscle groups. On the other hand, while performing value-added tasks the differences in MFM for both the WM and WOM scenarios between the erector spinae and other muscle groups were significant. The reason for the highest stress applied on the erector spinae is based on the biomechanics. More specifically, it has been proved that L5/S1 is the location of the highest moment applied when the participant lifts up an object and thus erector spinae (left and right) play significant role to counteract the applied moment.

It is also interesting that the visual observations of the participants through video records revealed higher throughput and efficiency with the use of the mobile cart, in terms of the number of items stocked up on the shelves, the number of cases treated and the distances traveled. In other words, higher throughput and efficiency were observed with the use of the mobile cart than without it. It should be pointed here that the MFM has been developed in this study as a new tool to investigate the impact of using the mobile cart not only on ergonomic risks but also on work performance. The MFM analysis and the results further support the idea of using mobile carts for reduced ergonomic risks as well as improved work performance.

Even though the positive ergonomic and work-performance impact of using the mobile carts has been quantitatively investigated through this study, there are limitations of the study as well. One of the limitations is the number of participants tested. As described earlier, the data collection for this study was conducted during the holiday season to minimize the distractions to both employees and customers in the grocery store. The managers suggested collecting the data during the holiday break and this limited the number of the participants available for the study. In the future study, more participants are expected to be available.

5. CONCLUSION

The second-fastest growing workforce in the United States is retail salespeople with a projected increase by over one million in 2020 (Handbook, 2012). The need thus arises for the identification and subsequent elimination of potential causes of musculoskeletal accidents that would have huge financial implications for retail firms. This study presents new perspectives and approaches to the analysis of muscle activations data which can be applicable to occupational settings. Specifically, it focuses on the ergonomic impact of the use of assisting devices on workers at a regional grocery store in which a mobile cart was deployed recently to reduce musculoskeletal risks. The results of this study indicates that workers performing stocking activities using the deployed mobile cart experienced less stress, increased throughput, and higher efficiency. More specifically, the results show the following: First, muscle activations on erector spinae are higher when no mobile cart is used. The muscle groups with the highest values in terms of %MVC and MFM are the erector spinae and triceps. Tests showed statistically significant differences between %MVC and MFM values recorded for bilateral erector spinae, and bilateral triceps in both the WOM and WM scenarios. Third, muscle activations and MFM distribution for value-added subtasks and non-value-added subtasks are slightly different, with numerically greater values observed for non-value-added tasks. It should be pointed out that the observation from video recordings reveals higher work performance in terms of throughput and efficiency when the mobile cart is used. This study may provide administrators of the grocery stores with baseline information about the ergonomic benefit of the use of mobile carts for stocking tasks to employees. Furthermore, the identification of specific muscle groups experiencing relatively greater exertion provides direct pointers to what should be considered in designing more ergonomic mobile carts and other sundry assistive devices. Limitations of the study include the relatively small sample size of the participants, and the restriction of data collection to specific times of the day. Future study will consider influences of age, variations in years of experience, gender and working hours with WOM and WM scenarios on performance results.

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