XIII. VARIATION IN LIFTING BEHAVIOR DURING A HIGHLY REPETITIVE MANUAL MATERIAL TASK

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1. Introduction

Epidemiological studies have shown an association between manual material handling tasks and low back pain (LBP) (Macfarlane et al. 1997; Hughes et al. 1997; Vandergrift et al. 2012; Lavender et al. 2012). More specifically, manual handling tasks that involve repetitive bending, twisting, carrying or lifting movements have been associated with LBP (Marras et al. 1993; Hoogendoorn et al. 2002; Lotters et al. 2003; Heneweer et al. 2011; Mikkonen et al. 2012; Lavender et al. 2012). In addition, repetitive lifting during manual handling tasks has been associated with muscle fatigue (Dempsey 1998). However, the biomechanical mechanism linking muscle fatigue and back injury development has not been fully investigated. One theory is that muscle fatigue brings about altered behavioral strategies that changes an individual's exposure to biomechanical risk factors (National Academy Press 2001). Another theory is that momentary muscle substitution patterns result in more variable and less coordinated movements, while still maintaining the same overall behavioral strategy (National Academy Press 2001). With either of these theoretical views, there should be increased variability in biomechanical measures typically used to characterize lifting behavior Larger movement variability may also impose greater loads on the underlying structure.

The aim of the current research was to quantify the biomechanical variation experienced during repetitive asymmetric lifting as often observed in occupational lifting tasks (Marras et al. 1993). Specifically, over the course of a 60-minute repetitive asymmetric lifting task, the behavioral response measures (three-dimensional postural deviations, movement speeds, and spine moments) were hypothesized to exhibit larger peak values, suggestive of a mechanism for injury, as time progressed.

2. Methods

2.1 Overview
Research participants repetitively lifted a lightweight box, using a stoop posture, from a location directly in front of their feet and placed the box on a conveyor positioned to their left side at waist level. This task was performed at a rate of 10 lifts/minute for a 60-minute period. During this task, several behavioral measures were collected to assess changes in the movement patterns, and assess fatigue in the Erector Spinae (back) muscles.

2.2 Participants
Seventeen healthy volunteers, 11 males and six females between the ages of 19 and 44 (mean = 21.7 years, s.d.= 5.9 years) participated in the study. Mean height and weight of the participants were 1.75 m (s.d.= 0.09 m) and 79.7 kg (s.d.=19.1 kg). Participants had no prior history of musculoskeletal disorders of the back, neck, shoulder, arms and legs within the past six months. All participants were recruited from a university student population and had no experience in manual material handling jobs. All participants signed an institutional review board (IRB) approved consent document prior to participating.

2.3 Dependent Measures
Behavioral and biomechanical changes during the lifting task were assessed using measures of lift duration, three-dimensional spine kinematics between (T1 and S1), and three-dimensional spine moments computed using a dynamic linked-segment model. Three-dimensional spine motions were captured (at 120 Hz) using a magnetic motion capture system (The Motion Monitor ™, Chicago, IL). This system used data from two force plates under the participant's feet to obtain the ground reaction forces that provided input into a three-dimensional dynamic linked-segment model, within the Motion Monitor System, that predicts the three-dimensional moments acting at L5/S1. Fatigue was assessed using the Borg CR-10 scale (Borg 1982) and via changes in the oxygenated hemoglobin levels sampled from the Erector Spinae muscles using Near-Infrared Spectroscopy (NIRS).

2.4 Apparatus.
A passive conveyor structure was constructed to create a circular conveyor system so that each time the box was placed on the conveyor it returned to a position in front of the participant. The handles on the box were at a height of 0.25 m above the floor. The lifts terminated with the box handles 0.86 m above the floor. Given the participants were instructed not to move their feet, the destination conveyor provided approximately 90 degrees of lift asymmetry (to the participants left side). Electronic scales positioned beneath the conveyor system detected when the lifts were initiated and terminated. The

wooden box was 0.4 x 0.3 x 0.25 m and had cutout handles. The box was filled with reams of paper to adjust the weight. The weight of the box was adjusted to 15% of the participant's maximum lifting strength

2.5 Data Collection Protocol

Upon arrival, the participants were familiarized with the repetitive lifting task. They were then presented with an informed consent document that had been approved by the University's Institutional Review Board. The participant's isometric lifting strength was measured by having them pull up on a dynamometer positioned .25 m above the floor. This task was repeated, separated by two minutes of rest, until two maximum values were obtained that were within 10 percent of each other (Kroemer and Marras 1981). The strength data were used to adjust the box weight to 15% of maximum lifting strength as indicated by the largest exertion measured. On average, the box weighed 9.6 kg (s.d. = 3.1 kg).

Participants were given an opportunity to practice the lifting task before starting the first 10-minute block of lifts. During this time, participants selected a foot position that they were asked to use throughout the lifting session. Typically, this posture resulted in 10 degrees of lift asymmetry towards the participants' right side during the initial lift. Participants were also instructed not to move their feet during the lifting task. An experimenter informed the participants if they inadvertently changed their foot position.

The task was paced so that the participants performed 10 lifts/minute for 10 minutes. An audio signal, provided every six seconds, indicated when the lifts were to be initiated. At the end of each 10-minute lifting period, Borg scale rating was obtained, after which another 10-minute period of lifting was initiated. Participants lifted for a maximum of 60 minute period or until the participant indicated they were fatigued and were no longer able to continue. When participants decided to stop before the completion of the 60-minute lifting period, a final Borg rating was obtained.

2.6 Data Analysis

For each of the measures just described, the 95th percentile value was calculated for each 10-minute lifting period. To assess variations in lifting behavior, the trends in these 95th percentile values were evaluated for each participant by computing individualized regression functions. Trends were classified strong ($r^2 >= .67$), moderate ($.33 < r^2 < .67$), or weak ($r^2 <= .33$).

3. RESULTS

The ratings of perceived workload sampled at the completion of each 10-minute block of the repetitive asymmetric lifting task showed an average increase in rating of 0.64 units for every 10 minutes of repetitive lifting activity ($p<.001$). While most participants followed this general trend, there were a small number of individuals who reported very little change in their perceived workload ratings. The near-infrared spectroscopy data were used to quantify changes in the erector spinae muscle physiology. Overall, the slopes of the regression functions were significantly below zero ($p < 0.001$). On average, right erector spinae oxygenated hemoglobin dropped by about 40% towards the end of the repetitive asymmetric lifting task. The participants who were not able to complete the 60 minutes of repetitive lifting activity showed larger declines in their tissue oxygenation measure.

The analysis of the trends in the 95th percentile values for the trunk kinematics revealed some general trends, but also some large individual differences. The trends in the amount of forward bending are shown in figure 1. Each line in the figure represents the regression function computed for each participant's forward flexion; the data were normalized to the 95th percentile value from the first 10-minute block. Solid green lines represent those participants that had a strong linear trend across the 10-minute blocks of lifting. Participants showing moderate linear trends are represented by the blue dashed lines. The participants showing weak linear trends are represented by the gray dotted lines. Shorter lines indicated where participants terminated their lifting before the end of the 60-minute session. On average,

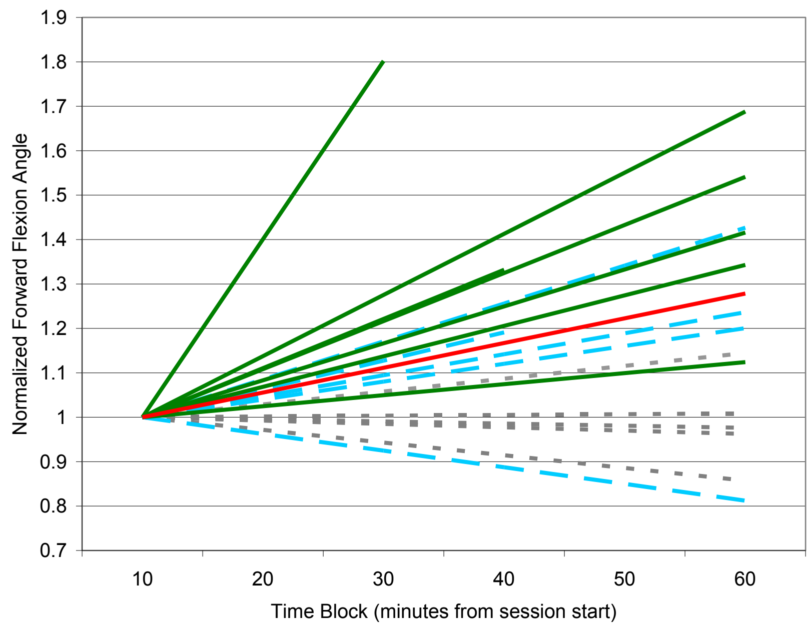

Figure 1. The trend lines for each participant for the 95th percentile forward flexion (bending) values over the 60-minutes of lifting. The red line shows the averaged 95th percentile value response across participants. The participants with strong, moderate, and weak linear trends are shown with solid green, dashed blue, and dotted gray lines, respectively.

the 95th percentile value for the amount of forward bending increased over time (red line in figure 1), therein indicating the forward bending became more extreme for several of the participants over time. These data show that the participants who had strongest trends in these 95th percentile values increased their forward bending over time.

Generally, the trends in the 95th percentile twisting and lateral bending postural deviations were weaker across participants. Only 4 participants showed strong linear trends in the 95th percentile twisting values. Of these, two were trending toward lower 95th percentile values and two were trending toward high 95th percentile values. Of the five participants that showed strong linear trends in the 95th percentile values for the amount of lateral bending, three had decreasing trends and two had increasing trends. However, the two that had strong increasing trends in their 95th percentile lateral bending values failed to complete the 60 minutes of lifting.

Figures 2, 3 and 4 show the trends in the 95th percentile values for the trunk extension, twisting, and lateral bending velocities, respectively. The extension velocity data (Figure 2) indicate that three-quarters of the participants had moderate to strong

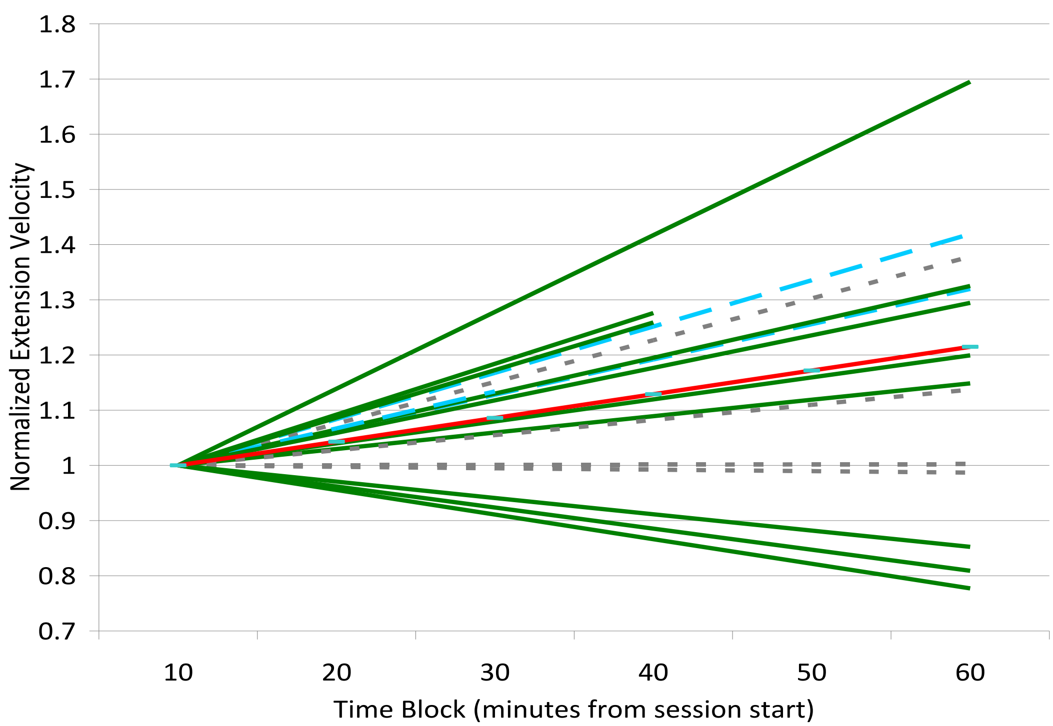

Figure 2. The trend lines for each participant for the 95th percentile extension velocity values over the 60-minutes of lifting. The solid red line show the averaged 95th percentile value response across participants. The participants with strong, moderate, and weak linear trends are shown with solid green, dashed blue, and dotted gray lines, respectively.

linear trends in their movement speeds over time. While the mean response (red line) and the majority of responses showed a trend towards faster trunk extension movements, three participants strongly trended towards slower movements over time. Most of the participants showed only weak trends in the 95th percentile twisting velocity values (Figure 3), however, three individuals showed strong increasing trends while to individuals showed strong decreasing trends. The 95th percentile lateral bending velocities, across participants showing moderate to strong trends, increased over the 60 minutes of lifting (Figure 4).

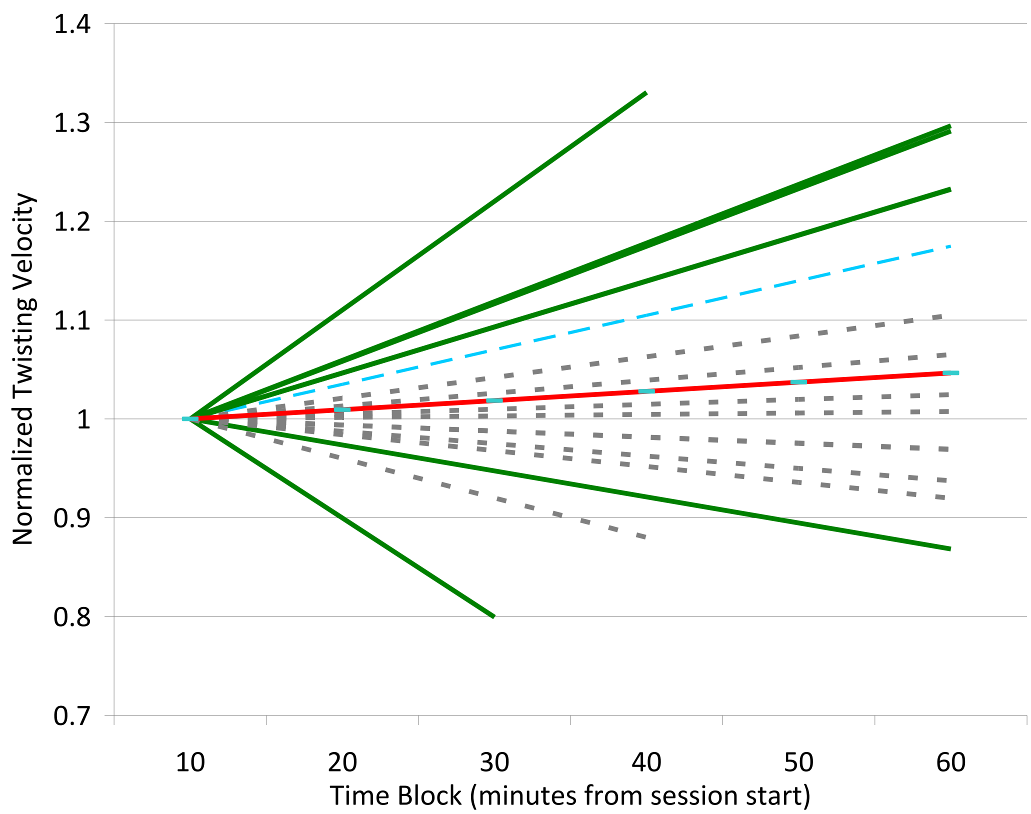

Figure 3. The trend lines for each participant for the 95th percentile twisting velocity values over the 60-minutes of lifting. The red lines show the averaged 95th percentile value response across participants. The participants with strong, moderate, and weak linear trends are shown with solid green, dashed blue, and dotted gray lines, respectively.

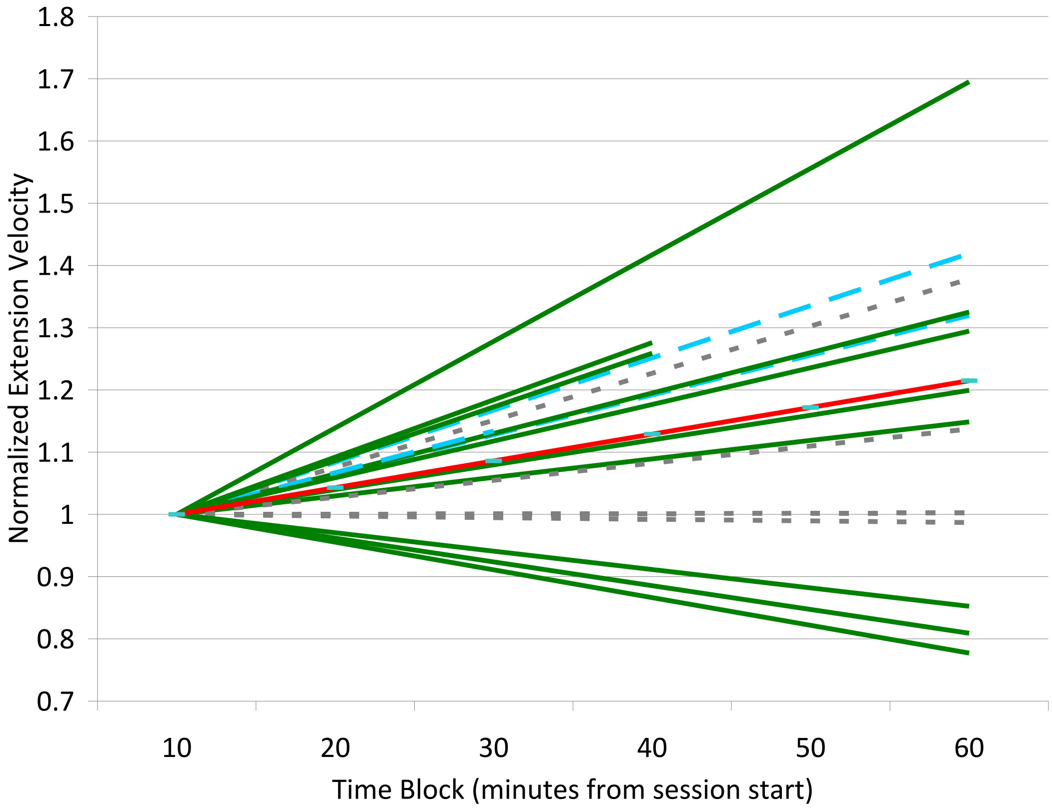

Figure 4. The trend lines for each participant for the 95th percentile lateral bending velocity values over the 60-minutes of lifting. The red lines show the averaged 95th percentile value response across participants. The participants with strong, moderate, and weak linear trends are shown with solid green, dashed blue, and dotted gray lines, respectively.

Overall, few participants showed strong trends in their 95th percentile forward bending or twisting spine moment values. Ten of the seventeen participants showed strong trends in their 95th percentile lateral bending moment values, with 9 out of 10 showing a decrease in their 95th percentile lateral bending moments over the 60 minutes of lifting.

4. DISCUSSION

Both the perceived physical effort and the oxygenation values confirm that these participants experienced physical fatigue over the 60 minutes of repetitive lifting. However, the data presented here suggest that there were considerable individual differences with regards to the behavioral adaptations in response to the fatigue. The increased forward flexion values suggest that many individuals reduced their neural muscular control during the eccentric portion of the task as they bent forward to reach the box. This suggest a movement strategy that may rely more on passive tissues in the spine to slow the descent rather than active muscle contraction. Such a strategy can lead to high localized loading of the these passive tissues. The lifting task, by design, limited participants ability to bend their knees when lifting the box. This was done to reduce the movement degrees of freedom and to simulate occupational material handling tasks where employees lift materials out of large bins.

As for the speed of the movements, some individuals displayed slower movements while, perhaps counter intuitively, several individuals displayed faster movements during the actual lifting phase. These faster movements occurred primarily in the sagittal and frontal planes (extension and lateral bending motions). This is suggestive of a ballistic lifting strategy which would result in larger muscle contractions early in the movement to quickly accelerate the body and the box being moved. Table 1 shows which of the 17 participants had strong trends of increasing or decreasing 95th percentile values in each plane over time. This table highlights that for many of the individuals showing faster (or slower) movements, these changes occurred in more than one plane of motion. Faster motions are associated with greater spine loads (Marras and Mirka, 1993). Three of the five variables in the injury risk model based on the lumbar motion monitor (Marras et al., 1993) are the degree of forward flexion, the twisting velocity, and the lateral bending velocity increases. Given, several participants showed increases in these

Table 1. Participants that showed "strong" trends in their 95th percentile movement speeds in trunk extension, twisting, and lateral bending are indicated with a "1" if the participant showed an increasing trend and with a "-1" if the participant showed a decreasing trend.

Particpant	Extension Velocity	Twisting Velocity	Lateral Bending Velocity
s01	1	1	1
s02			
s03	1		
s04	-1		
s05		1	
s06		1	
s07			
s08		1	1
s09	-1	-1	
s10			1
s11	1		
s12		-1	
s13	1		1
s14	1		1
s15	1		
s16	1		1
s17			1

quantities, the model would predict that these kinematic changes substantially increase injury risk as these individuals fatigued.

These results emphasize the need to carefully evaluate the design of highly repetitive manual lifting jobs. In many cases rate of lifting cannot be reduced as this is tied to production processes and overall productivity numbers and in many cases automation is not a viable option. In such cases it is particularly important to limit how much bending, reaching, and twisting is required. This can be accomplished with many different types of material handling equipment. However, before investing in any solution, those responsible for making process improvements should consider potential usability issues and engage the affected workers early in the solution development process to ensure the changes being considered will work well for everyone involved.

There are some limitations of this work that should be acknowledged. First, all the participants were inexperienced in repetitive manual material handling work. This was done to highlight changes associated with fatigue. It was theorized that experienced material handlers may show similar adaptations, however, they may take much more than 60 minutes to appear. Second, the instructions restricted movement of the feet and by design limited the bending of the knees. This was done to hasten the fatigue of the back muscles so that relevant adaptations could be observed within a reasonable time period. While this may seem contrived, there are many manual material handling situations that result in kinematic limitations. Third, the weight of the box was modest. The strength normalized weight was selected to minimize injury risk, was large enough to be a significant load for each person so as to provide external validity, and not be so heavy that it would severely restrict how it had to be moved. For example, a heavy load may reduce potential movement variability due to limitations in shoulder strength.

In summary, this study found that the 95th percentile kinematic values increased over time in several individual participants as they performed a fatiguing repetitive lifting task. The larger peak values suggest the tissues that support and move the spine are enduring greater biomechanical loads and are therefore more likely to be injured in repetitive manual material handling tasks that push individuals into a fatigued state.

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