The Effects of Job Rotation Parameters on Localized Muscle Fatigue and Performance: An Investigation of Rotation Frequency and Task Order

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Abstract

Work-related musculoskeletal disorders (WMSDs) remain a substantial problem in the workplace. Rotation, in which workers are rotated between tasks, is widely used as an administrative control, as it is considered to reduce WMSD risk through reducing physical exposures and increasing exposure variation. However, despite its widespread use, there is limited evidence that rotating between tasks is effective in reducing the risk of WMSDs. Inconsistencies in measured outcomes of rotation may be attributed to the variety of parameters involved in determining rotation schedules, including which tasks to include in a schedule, the rate at which workers rotate, and the order in which tasks are performed.

This research assessed the effects of rotation, specifically focusing on rotation frequency and task order, on muscle fatigue and performance when included tasks loaded the same muscle group. Twelve participants completed six experimental sessions in each of three studies, during which repetitive tasks were performed for one hour either with or without rotation. Each study simulated a different task, including static shoulder abduction, box lifting, and a light assembly task. Rotation occurred between lower and higher exertion levels, and each rotation schedule varied in both rotation frequency (rotating every 15 minutes vs. 30 minutes) and task order (starting with the lower vs. higher intensity task). Muscle fatigue was assessed through several measures, including electromyography, and ratings of perceived discomfort. Performance was assessed through the accuracy of shoulder moment output, the accuracy of box placement, or the speed of assembly completion.

As expected, rotation was effective in reducing fatigue compared to higher intensity tasks with no rotation, although it increased fatigue compared to the lower intensity with no rotation. While effects of rotation frequency and task order were seen on some measures, results across all three studies did not indicate consistent effects of either rotation frequency or task order on fatigue or performance. As such, the practical relevance of these rotation parameters and the likely impacts of rotation are not yet clear, and further assessments are needed. Such assessments should ideally involve longer durations, field studies, and/or more direct measures of injury or injury risk.

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Chapter 1: Introduction

Work-related musculoskeletal disorders (WMSDs) continue to be a substantial problem in the workplace, accounting for roughly 30% of injuries or illnesses that require days away from work (BLS, 2011). In the U.S. in 2010, the back was the most frequently injured body part, accounting for ~45% of all WMSD cases; the shoulder accounted for ~15% of these cases and involved the most severe injuries, requiring a median of 21 days away from work (BLS, 2011). Costs associated with occupational injuries have been estimated at up to \$150 billion in the US (Anderson & Budnick, 2009), and of these overexertion and repetitive motion cases account for around 30% (Liberty Mutual, 2011). Beyond days away from work, WMSDs can decrease productivity and work quality, as well as workers' overall quality of life (NIOSH, 1997).

Broadly, two strategies are used to control the risk of WMSDs: 1) engineering controls, through which risk is reduced or eliminated through redesign of the job, and 2) administrative controls, through which management practices are used to prevent or reduce exposures (NIOSH, 1997). Among alternative administrative control measures, rotation (aka "job rotation" or "task rotation"), in which workers are rotated between distinct tasks, is widely used and recommended to reduce WMSD risks. In the U.S. Midwest, more than 40% of manufacturing companies report using rotation to reduce physical exposures; these companies had used rotation for an average of 5 years, suggesting that it is often used as a permanent control, rather than a temporary fix while engineering controls are implemented (Jorgensen et al., 2005). Several studies have indicated positive psychosocial benefits of rotation, such as improved satisfaction (Dawal et al., 2009), improved worker motivation (Muramatsu et al., 1987), reduced monotony (Aptel et al., 2008), increased pride in work (Rissen et al., 2002), improved management outcomes such as increased employee flexibility (Eriksson & Ortega, 2006), and increased employee skill

(Jorgensen, et al., 2005). However, several researchers have indicated there is limited empirical evidence that job rotation is effective in reducing WMSD risk (Jorgensen, et al., 2005; Mathiassen, 2006; NIOSH, 2001; Wells et al., 2007). Efforts are thus needed to quantify the efficacy of rotation and thereby determine the potential effectiveness of this administrative control as an intervention to reduce WMSDs.

Only a few studies have formally analyzed the effects of rotation, primarily focusing on physical demands (e.g., kinematic and kinetic exposures) and physical exposure variation (e.g., temporal variability of physical demands), and these have led to inconsistent results. Rotation can reduce physical demands, for example reducing exposure to non-neutral working postures (Hinnen, 1992; Kuijer et al., 1999), cardiovascular load (Kuijer, et al., 1999), and muscle activation (Rissen, et al., 2002). Further, rotation can reduce muscle fatigue (Raina & Dickerson, 2009) and also increase physical exposure variation (Möller et al., 2004; Wells et al., 2010). In contrast, other evidence suggests that job rotation increases physical demands (Kuijer et al., 2005) and does not change physical exposure variation (Jonsson, 1988; Wells et al., 1989) or WMSD rates (Aptel, et al., 2008).

Some inconsistencies in the effectiveness of rotation can be attributed to how rotation schedules are designed, a process which requires determining several parameters. These parameters include which tasks are included in a schedule, the rate at which workers rotate, and the order in which the tasks are performed. In terms of task selection, a recommended approach is to include tasks with different physical exposures, which is thought to reduce WMSD risk (Mathiassen, 2006). However, existing evidence suggests that occupational tasks often involve similar physical exposures (Aptel, et al., 2008; Jonsson, 1988; Keir et al., 2011; Wells, et al., 1989). Therefore, there is a need to study the effects of rotation when included tasks have

limited exposure variation, such as tasks that load the same muscle(s), but this issue has not yet been thoroughly evaluated.

Further, there has been limited research on rotation frequency or task order. Though many workers rotate every 2 hours (Aptel, et al., 2008; Jorgensen, et al., 2005; Wells, et al., 1989), this has been suggested to be out of convenience (such as rotating at rest breaks), rather than based on ergonomic analysis (Jorgensen, et al., 2005). To the author's knowledge, only one study has analyzed specifically the effect of different rotation frequencies on physical demands. Using a mathematical model, the authors concluded that workers should rotate every 1 - 2 hours (Tharmmaphornphilas & Norman, 2004). Task order has been evaluated in a few lab-based studies, with inconsistent results. While one study showed that starting with a higher-exertion task leads to higher perceived exertion levels compared to starting with a lower exertion task (Raina & Dickerson, 2009), another study showed no effects of task order (Keir, et al., 2011). However, order has been considered when designing job rotation schedules, such as generating rotation schedules using algorithms to reduce the likelihood of a worker having backto-back tasks that require the same movement (Diego-Mas et al., 2009), or ensuring that no sequential tasks have high exposures (Henderson, 1992). Further, order effects have been found in exercise-based research (Simão et al., 2005; Spreuwenberg et al., 2006), suggesting there may be similar effects for occupational tasks.

The current research focused on rotation between tasks of different intensity levels, and manipulated rotation frequency and task order in controlled laboratory-based studies. The effects on WMSD risk were quantified indirectly using localized muscle fatigue as an outcome measure, and which was used due to its potential importance as a risk factor for WMSD development (Allison & Henry, 2002; Dugan & Frontera, 2000; Gorelick et al., 2003; Granata &

Gottipati, 2008; Weist et al., 2004; Winkel & Westgaard, 1992). Given the importance of quality and productivity assurance, the effect of job rotation on performance was also assessed. Thus, the main objective of this research was to determine the effects of rotation frequency and task order on fatigue and performance, and to do so for a range of simulated occupational tasks (static and dynamic, whole body, and upper extremity). Specific purposes were to: 1) determine if rotation is effective in reducing muscle fatigue when the included tasks load the same muscle(s); 2) evaluate the effects of rotation on task performance; and 3) identify the specific effects of rotation frequency and task order on fatigue and performance. The <u>overall hypotheses</u> were that rotating more frequently would reduce fatigue but have adverse effects on performance, that starting with the lower exertion task would be less fatiguing and have higher performance versus starting with the higher exertion task, and that these effects would be influenced by the type of task performed.

Three laboratory studies were completed to address these hypotheses. The first study investigated the effects of rotation during static shoulder exertions; the second focused on lifting tasks, and the third involved a simulated assembly task. These tasks were chosen as progressively less controlled and more representative of actual work tasks, as well as to reflect a range of task demands found occupationally. Further, demands were focused on commonly injured body parts, namely the upper extremity and back. In all three studies, several indicators of fatigue and performance were obtained.

This work addresses musculoskeletal disorders, which is a topic/strategic goal of most sectors within the current National Occupational Research Agenda (NIOSH, 2001). This research assessed the efficacy of job rotation under a variety of work conditions. As such, the results were intended to facilitate the development of guidelines for determining job rotation schedules

and to aid practitioners in evaluating the potential benefits of job rotation as an administrative control. This dissertation is organized with one chapter for each separate study, such that Chapter 2 describes the effects of rotation during shoulder abduction tasks, Chapter 3 describes effects during lifting tasks, and Chapter 4 describes effects during assembly tasks. A summary of these studies, the practical implications of the major findings, and suggestions for future research are provided in Chapter 5.

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Chapter 2: Effects of rotation frequency and task order on localized muscle fatigue and performance during repetitive static shoulder exertions

Abstract

Though widely considered to reduce physical exposures and increase exposure variation, there is limited evidence that rotating between tasks is effective in reducing the risk of work-related musculoskeletal disorders (WMSDs). The purpose of this study was to assess the effects of rotation, specifically focusing on rotation frequency and task order, on muscle fatigue and performance when included tasks loaded the same muscle group. Twelve participants completed six experimental sessions during which repetitive static shoulder abduction tasks were performed for one hour either with or without rotation. Where rotation occurred, it was between two exertion levels of the shoulder abduction task. As expected, rotation was effective in reducing fatigue compared to high intensity tasks with no rotation, although it increased fatigue compared to the low intensity tasks with no rotation. Increasing rotation frequency adversely affected peak errors, and task order had some influence on muscle fatigue. These parameters of rotation should be considered when implementing rotation in the workplace, as well as in future research.

Keywords: rotation frequency, task order, muscle fatigue, performance, shoulder

Introduction

Work-related musculoskeletal disorders (WMSDs) continue to be a substantial problem in the workplace, accounting for roughly 30% of injuries or illnesses that require days away from work (Bls 2011). The costs associated with occupational injuries have been estimated at up to \$150 billion in the US (Anderson and Budnick 2009), and of these overexertion and repetitive motion cases account for around 30% (Liberty Mutual 2011). Administrative controls, such as rotation (aka "job rotation" or "task rotation"), in which workers are rotated between a set of different tasks, are often adopted to reduce the prevalence of WMSDs. In a recent survey, more than 40% of manufacturing companies in the U.S. Midwest reported using rotation, with the primary motivation to reduce exposure to WMSD risk factors (Jorgensen et al. 2005). However, despite its widespread use, there is little evidence supporting the use of the rotation approach to reduce WMSD risk.

Existing research has shown inconsistent effects of rotation on physical demands (e.g., kinematic and kinetic exposures) and physical exposure variation (i.e., temporal variability of physical demands). Some implementations of rotation have led to decreases in physical demands, specifically reducing exposure to non-neutral working postures (Hinnen 1992, Kuijer et al. 1999), cardiovascular load (Kuijer et al. 1999), and decreasing muscle activation (Rissen et al. 2002). Rotation can also reduce muscle fatigue. For example, Raina and Dickerson (2009) reported that performing shoulder abduction alone was more fatiguing than rotating between shoulder abduction and flexion. An increase in physical exposure variation has been argued to be beneficial because while one muscle (or motor unit) is resting, other muscles can be loaded (Wells et al. 2010). In their study, Wells et al. (2010) found that rotating between functionally different grip tasks caused increased physical exposure variation when compared to performing only one gripping task. Further, Möller et al. (2004) assessed rotation at an

automotive plant and found increases in the variability of trapezius activity when workers rotated between tasks. In contrast to these beneficial effects, several studies conducted within actual work environments have found that implementing rotation increases physical demands (Kuijer et al. 2005) and has no effect on physical exposure variation (Wells et al. 1989, Jonsson 1988) or WMSD rates (Aptel et al. 2008).

The specific tasks included in a given rotation schedule may explain some of these inconsistencies. For example, when highly demanding tasks are included, rotation can increase the number of workers who experience peak loading from these tasks (Kuijer et al. 2004, Kuijer et al. 2005, Henderson 1992) as well as the likelihood of workers reporting low back pain (Frazer et al. 2003, Kuijer et al. 2005). As a specific example, Kuijer et al. (2004) found that rotating between truck driving and refuse collecting reduced physical demands for workers that previously only collected refuse, but increased physical demands and complaints of low back pain among workers that had solely performed truck driving. A recommended approach to task selection is to include tasks with different physical exposures, which in turn is thought to reduce WMSD risk (Mathiassen 2006). However, many occupational tasks involve comparable physical exposures (Jonsson 1988, Wells et al. 1989, Aptel et al. 2008, Keir et al. 2011). For example, Keir et al. (2011) found that when rotating between gripping and lifting tasks, the upper erector spinae and forearm musculature did not benefit from rotation, suggesting that even in tasks that seemed to use different muscle groups, there can be overlap in actual muscle loading between tasks. As such, there remains a need to assess the effects of rotating between tasks that have limited exposure variation, such as between tasks that load the same muscle(s). In addition to task selection, other parameters within a rotation scheme can be influential. Specifically, how frequently workers rotate and the order in which tasks are performed. To the authors' knowledge, only one study analyzed the effect of different rotation frequencies on

physical demands; this was performed using a mathematical modeling approach, with the conclusion that workers should rotate every 1 - 2 hours (Tharmmaphornphilas and Norman 2004). Workers on manufacturing assembly lines often rotate every two hours (Wells et al. 1989, Aptel et al. 2008, Jorgensen et al. 2005), though this may be due more to convenience (such as rotating at rest breaks) rather than based on any empirical evidence (Jorgensen et al. 2005). Similarly, some workers self-select to rotate between tasks every 1 to 1.5 hours (Muramatsu et al. 1987).

The effect of task order, or the sequence in which tasks are performed, is another important aspect of a rotation scheme. Raina and Dickerson (2009) examined rotating between repetitive shoulder flexion and abduction tasks. Though no significant effect of task order was found on objective fatigue measures, subjective exertion ratings were higher when starting with the more demanding task (shoulder abduction) compared to starting with shoulder flexion. Another study that assessed rotating between gripping and lifting tasks also found no effect of task order (Keir et al. 2011). Although the number of lab-based studies is limited and results are not yet conclusive, task order has been considered when implementing rotation in the workplace, for example ensuring no sequential tasks with high exposures (Henderson 1992), and in developing algorithms to generate rotation schedules, such as reducing the likelihood of a worker having back-to-back tasks that require the same movement (Diego-Mas et al. 2009). Further, order effects have been reported in exercise-based research (Simão et al. 2005, Spreuwenberg et al. 2006). The magnitude of performance decrement can depend on the sequence in which exercises are performed (Spreuwenberg et al. 2006), and performance (assessed through number of repetitions) has been found to be higher during exercises earlier in a sequence compared to those performed at the end (Simão et al. 2005). This suggests that there may be similar effects for occupational tasks. Though rotation is thought to improve employee skill

(Jorgensen et al. 2005), some evidence suggests that it can have a detrimental effect on task performance (Azizi et al. 2010, Allwood and Lee 2004, Kher et al. 1999). Given its importance with respect to quality and productivity, the effect of rotation on task performance needs more thorough evaluation.

The current study was conducted to provide additional information regarding the effects of rotation frequency and task order. A controlled laboratory study was used to isolate these effects, involving rotation between two simple static tasks that differed in the level of exertion. In addition, a compressed timeframe (performance period) was used, to facilitate implementation in a laboratory setting. Outcome measures emphasized localized muscle fatigue, due to its potential importance as a risk factor for WMSD development (Allison and Henry 2002, Weist et al. 2004, Gorelick et al. 2003, Granata and Gottipati 2008, Dugan and Frontera 2000, Winkel and Westgaard 1992) and task performance, due to its practical relevance. Specific purposes of this study were to: 1) determine if rotation is effective in reducing muscle fatigue when the included tasks load the same muscle(s); 2) evaluate the effects of rotation on task performance; and 3) identify the specific effects of rotation frequency and task order on fatigue and performance. It was hypothesized that rotating more frequently would reduce fatigue but have adverse effects on performance, and that starting with the lower exertion task would be less fatiguing and have higher performance versus starting with the higher exertion task.

Methods

Participants

A convenience sample of 12 participants (gender balanced) was recruited from the local community, whose respective mean (SD) age, stature, and body mass were 22.8 (1.7) years, 1.67 (0.13) m, and 66.5 (13.5) kg. All participants reported being physically active and having

no recent history of musculoskeletal injury, and all indicated being right-hand dominant. Participants completed an informed consent procedure approved by the Virginia Tech Institutional Review Board (Appendix A).

Experimental design

A full-factorial, repeated-measures design was used, in which participants completed repetitive, isometric shoulder abductions over 60-minute work periods in each of six conditions (Figure 1). Three levels of rotation frequency were used: 0 (no rotation), 15, and 30 minutes. Shoulder abductions were performed at two exertion levels, based on individual maximum voluntary contractions (MVCs, as described below). The two exertion levels were Lower (15% MVC) and Higher (30% MVC), and intended to represent low-moderate levels of occupational task demands. Where rotation occurred, it was between these two levels, and two task orders were evaluated: Lower to Higher, and Higher to Lower (hereafter denoted Start L and Start H, respectively). Participants completed a preliminary screening session followed by the six experimental sessions, all on separate days, with at least two days between each to minimize carryover effects (e.g., due to residual fatigue). During each experimental session participants completed one of the six experimental conditions, with the order of exposure counterbalanced using 6 x 6 balanced Latin squares (one for each gender).



Figure 1. Six experimental conditions ('L' denotes the lower exertion task, 'H' denotes the higher exertion task), involving all combinations of three levels of rotation frequency (shown on right) and two levels of task order (Start L vs. Start H).

Procedures and data collection

In the preliminary session, and following initial warm-up exercises, isometric MVCs of shoulder abduction were collected using a commercial dynamometer (System 3 Pro, Biodex Medical Systems, Shirley, New York). During MVCs, the right shoulder was abducted 90 degrees and the upper body and waist were secured to the dynamometer chair using padded straps (Figure 2: left). Participants were instructed to exert maximally against a padded fixture and were given non-threatening verbal encouragement. Outputs (i.e., moments) from the dynamometer were hardware low-pass filtered (15 Hz) and sampled at 1024 Hz. At least three MVCs were performed, with two minutes of rest between each, until peak moments were found to be non-increasing. After accounting for gravitational effects on the fixture and upper extremity mass, the largest shoulder moment across MVC efforts was recorded for later use





Figure 2. Posture used for shoulder abduction task (left) and visual feedback given during the task (right).

During each experimental session, participants initially performed 20 minutes of warm-up exercises and a practice session of the experimental tasks. After a brief rest, they completed three baseline 10-second static reference contractions at 22.5% MVC (midway between the Lower and Higher exertion levels) in the same posture as the MVCs. Participants then began the experimental tasks, which involved intermittent, repetitive static shoulder abductions were exerted against the dynamometer (also using the same posture as the MVCs) over a 60-minute work period. The tasks followed a 30s cycle time with a fixed duty cycle of 0.33 (10s work, 20s rest) at either the Lower or Higher exertion level. Over the 60-min work period, the exertion level changed (or didn't) as determined by the treatment condition (i.e., the specific combination of rotation frequency and task order; Figure 1). Visual feedback of the current moments and a square-wave pattern showing work and rest was provided (Figure 2: right); the appeared of the square-wave appeared the same between participants and exertion levels to reduce confounds in visual feedback guality, though the moment required to reach the top of the square wave was calibrated to the required exertion level (i.e., the y-axis scale changed according to the specific exertion level). During the resting portion of each cycle (indicated at the bottom of the square wave), participants lowered their arms into a hanging posture at their side.

During the 60-min work period, reference contractions, as described above, were completed every 15 minutes. During the reference contractions and the work period, shoulder moments were recorded continuously (as described above), along with electromyographic (EMG) activity of the middle deltoid. EMG was obtained using pre-gelled Ag/AgCl electrodes placed 2 cm apart on the belly of the muscle (Perotto 1994). Raw EMG was pre-amplified (Measurement Systems Inc., Ann Arbor, MI, USA), hardware band-pass filtered from 10 - 500 Hz, high-pass filtered with a 30 Hz cut-off, and sampled at 1024 Hz. Ratings of perceived discomfort (RPDs) were collected every 5 minutes during the work period for the right shoulder, upper arm, and upper back, using a 10-point scale (Borg, 1990; scale ranges from 0 = no discomfort to 10 = extremely strong, almost maximal discomfort) that was continuously visible to participants.

Data processing and dependent measures

Three EMG-based measures of fatigue were obtained from data collected during each exertion. Specifically, a 6-second window was extracted from each 10-second sustained abduction; the first three seconds and last second were removed to reduce transition effects. The first measure, EMG amplitude (Amp), was obtained after full-wave rectification, low-pass filtering (Butterworth, 3Hz cut-off, 4th-order, bidirectional), and correction of the EMG signal for resting amplitudes. The second, EMG mean power frequency (MnPF), was determined using a Fast Fourier transform of the EMG signal at each 1-second interval with a 50% overlapping Hamming window. The third, Dimitrov Spectral Index (DSI), was calculated from the raw EMG signal using Equation 1, where PS = power spectrum, f1 = 30 Hz, and f2 = 450 Hz (Gonzalez-Izal et al. 2010). For each experimental session, EMG Amp, MnPF, and DSI were normalized to the corresponding mean values obtained from the baseline reference contractions, and were averaged over the 6-second window extracted from each abduction. Increases in EMG Amp

and decreases MnPF were interpreted as being indicative of muscle fatigue (Krogh-Lund and Jørgensen 1991, Nussbaum 2001, Potvin and Bent 1997), and DSI values were expected to increase with fatigue (Dimitrov et al. 2006).

$$DSI = \frac{\int_{f_1}^{f_2} f^{-1} * PS(f) df}{\int_{f_1}^{f_2} f^{5} * PS(f) df}$$
(1)

Three measures of performance were derived, based on 6-sec windows (as above) of moments collected during each exertion. First, moment fluctuations (MF) were determined as the coefficient of variation (SD/mean) of the moment output (Christou and Carlton 2002, Tracy and Enoka 2002). Second, sample entropy (SampEn), a measure of the complexity of a signal (Richman 2000), was calculated using PhysioNet software (Goldberger et al. 2000) and based on SampEn(m,r,N), where m = 2, r = 0.2*SD, and N = the length of each window. A full description of this method can be found in Richman (2000), and the parameter values used were obtained from the literature (Svendsen and Madeleine 2010). Third, peak errors were calculated as the maximum difference between the generated and target moments. Increases in MF, SampEn, and PE were all considered to represent a decrease in task performance.

Specific dependent measures were: mean EMG Amp, MnPF, and DSI, mean and peak RPDs from each body part, and mean MF, SampEn, and PE. EMG and performance measures were available from both the work period (repetitive exertions) and the reference contractions. All dependent measures were calculated across the available data from a given condition (i.e., 60 min of repetitive abductions or four reference contractions). Mean values were used to represent the accumulation of fatigue (or the effects of fatigue); since each condition had the same duration, the integral of a measure over the work period is equivalent to the product of the measure and the duration.

Statistical analysis

One-way, repeated-measures analyses of variance (ANOVAs) were performed separately to assess the effects of condition (six levels) on each of the dependent measures. Gender and presentation order of the six conditions were included in these analyses as blocking variables. When there was a significant main effect of condition, post-hoc contrasts were used for several planned comparisons. In the following, "L" denotes the Lower exertion task, "H" denotes the Higher exertion task, and each letter represents one 15-minute period. Specific comparisons were made: 1) between no-rotation vs. all rotation conditions (LLLL vs. all rotation conditions and HHHH vs. all rotation conditions); 2) between the two no-rotation conditions (LLLL vs. HHHH); 3) between rotating every 15 vs. 30 minutes (rotation frequency); and 4) between Start L vs. Start H (task order). Significant interactions with gender were explored using simple effects analyses. Summary statistics are presented as means (SD). All statistical analyses were performed using JMP 9.0 (SAS Institute Inc., Cary, NC), and significance was concluded when p < 0.05.

Results

There were significant main effects of condition on many of the dependent measures (Table 1). Based on most measures, LLLL was less fatiguing than the rotation conditions (lower EMG Amp and DSI, higher EMG MnPF, lower RPDs), HHHH was more fatiguing than the rotation conditions (higher EMG Amp and DSI, lower EMG MnPF, higher RPDs), and LLLL was less fatiguing than HHHH (lower EMG Amp and DSI, higher EMG MnPF, lower RPDs). The effect of condition, however, was inconsistent for some measures. There was no effect of condition on EMG MnPF during the work period or EMG Amp during the reference contractions. Additionally, there was no difference between LLLL and the rotation conditions for mean RPDs for the upper back, though all other mean and peak RPDs showed significant differences between the no-

rotation and rotation conditions. LLLL and HHHH also showed better and worse performance, respectively, than the rotation conditions; this effect was seen through lower SampEn and PE for LLLL and higher SampEn and PE for HHHH during the work period compared to the rotation conditions. Further, LLLL had better performance than HHHH, evident as lower SampEn and PE. However, this difference was significant only during the work period; there were no main effects on any performance measure collected during the reference contractions.

Rotation frequency influenced some dependent measures. Rotating more frequently (every 15 minutes vs. every 30 minutes) resulted in significantly lower mean and peak RPDs for the upper back and there was a difference that approached significance (p = 0.064) indicating higher PEs when rotating more frequently. There were also several effects of task order that approached significance, in which Start H led to more substantial outcomes than Start L, and reflected in increased EMG DSI (p = 0.096) and increased mean discomfort ratings for the shoulder (p = 0.091) and upper arm (p = 0.076).

MF 0.42 Work SampEn <0.0001* 2.34(0.17) 2.07(0.11) <0.0001* 2.58(0.26) <0.0001* 2.34(0.17) 2.34(0.17) PE 0.039* 0.47(0.34) 0.31(0.23) 0.019* 0.51(0.34) 0.29 0.009* 0.53(0.39) 0.39(0.28) Performance MF 0.86 . <th>MF 0.42 Work SampEn <0.0001* 2.34(0.17) 2.07(0.11) <0.0001* 2.58(0.26) <0.0001* 2.34(0.17) 2.34(0.17) PE 0.039* 0.47(0.34) 0.31(0.23) 0.019* 0.51(0.34) 0.29 0.009* 0.53(0.39) 0.39(0.28) Performance</th> <th>MF 0.42 Work SampEn <0.0001* 2.34(0.17) 2.07(0.11) <0.0001* 2.58(0.26) <0.0001* <0.0001* 2.34(0.17) 2.34(0.17) PE 0.039* 0.47(0.34) 0.31(0.23) 0.019* 0.51(0.34) 0.29 0.009* 0.53(0.39) 0.39(0.28)</th> <th>MF 0.42 Work SampEn <0.0001* 2.34(0.17) 2.07(0.11) <0.0001* 2.58(0.26) <0.0001* <0.0001* 2.34(0.17) 2.34(0.17)</th> <th></th> <th>Upper Back 0.0056* 1.44(1.35) 0.70(0.87) 0.016* 2.04(1.09) 0.049* 0.0008* 1.15(1.14) 1.73(1.51)</th> <th>Peak Upper Arm <a> -0.0001* 2.44(1.91) 1.21(1.34) 0.0003* 3.65(1.80) 0.0004* -0.0001* 2.30(2.02) 2.57(1.82) </th> <th>Shoulder <2.0001* 2.97(2.01) 1.40(1.38) <0.0001* 3.74(1.95) 0.007* <0.0001* 2.90(2.07) 3.05(2.00)</th> <th>APDS .</th> <th>Upper Back 0.038* 0.58(0.60) 0.41(0.56) 0.25 0.93(0.53) 0.023* 0.008* 0.44(0.48) 0.73(0.59)</th> <th>Mean Upper Arm 0.0008* 1.29(1.15) 0.91(1.25) 0.038* 1.88(0.90) 0.0006* <0.0001* 1.22(1.26) 1.36(1.05)</th> <th>Shoulder 0.0002* 1.53(1.18) 0.98(1.11) 0.0038* 2.22(1.37) 0.001* <0.0001* 1.55(1.23) 1.51(1.16)</th> <th>DSI 0.012* 1.17(0.19) 1.08(0.15) 0.036* 1.28(0.19) 0.017* 0.0007* 1.20(0.22) 1.15(0.16)</th> <th>Reference MnPF 0.0089* 0.97(0.04) 0.99(0.04) 0.074 0.94(0.03) 0.0033* 0.0003* 0.97(0.04) 0.97(0.03)</th> <th>Amplitude 0.16</th> <th>EMG </th> <th>DSI 0.0059* 1.17(0.17) 1.09(0.16) 0.0835 1.30(0.24) 0.005* 0.0005* 1.19(0.19) 1.15(0.14)</th> <th>Work MnPF 0.23</th> <th>Amplitude <0.0001* 0.96(0.18) 0.65(0.10) <0.0001* 1.24(0.21) <0.0001* <0.0001* 0.98(0.19) 0.94(0.17)</th> <th>Measure Condition Rotation LLLL <i>p</i> HHHH <i>p p</i> Rotate 15 Rotate 30</th> <th>LLLL vs. Rotation HHHH vs. Rotation LLLL vs. Rotation Frequency</th> <th>are indicated by the symbol ".</th>	MF 0.42 Work SampEn <0.0001* 2.34(0.17) 2.07(0.11) <0.0001* 2.58(0.26) <0.0001* 2.34(0.17) 2.34(0.17) PE 0.039* 0.47(0.34) 0.31(0.23) 0.019* 0.51(0.34) 0.29 0.009* 0.53(0.39) 0.39(0.28) Performance	MF 0.42 Work SampEn <0.0001* 2.34(0.17) 2.07(0.11) <0.0001* 2.58(0.26) <0.0001* <0.0001* 2.34(0.17) 2.34(0.17) PE 0.039* 0.47(0.34) 0.31(0.23) 0.019* 0.51(0.34) 0.29 0.009* 0.53(0.39) 0.39(0.28)	MF 0.42 Work SampEn <0.0001* 2.34(0.17) 2.07(0.11) <0.0001* 2.58(0.26) <0.0001* <0.0001* 2.34(0.17) 2.34(0.17)		Upper Back 0.0056* 1.44(1.35) 0.70(0.87) 0.016* 2.04(1.09) 0.049* 0.0008* 1.15(1.14) 1.73(1.51)	Peak Upper Arm <a> -0.0001* 2.44(1.91) 1.21(1.34) 0.0003* 3.65(1.80) 0.0004* -0.0001* 2.30(2.02) 2.57(1.82)	Shoulder <2.0001* 2.97(2.01) 1.40(1.38) <0.0001* 3.74(1.95) 0.007* <0.0001* 2.90(2.07) 3.05(2.00)	APDS .	Upper Back 0.038* 0.58(0.60) 0.41(0.56) 0.25 0.93(0.53) 0.023* 0.008* 0.44(0.48) 0.73(0.59)	Mean Upper Arm 0.0008* 1.29(1.15) 0.91(1.25) 0.038* 1.88(0.90) 0.0006* <0.0001* 1.22(1.26) 1.36(1.05)	Shoulder 0.0002* 1.53(1.18) 0.98(1.11) 0.0038* 2.22(1.37) 0.001* <0.0001* 1.55(1.23) 1.51(1.16)	DSI 0.012* 1.17(0.19) 1.08(0.15) 0.036* 1.28(0.19) 0.017* 0.0007* 1.20(0.22) 1.15(0.16)	Reference MnPF 0.0089* 0.97(0.04) 0.99(0.04) 0.074 0.94(0.03) 0.0033* 0.0003* 0.97(0.04) 0.97(0.03)	Amplitude 0.16	EMG	DSI 0.0059* 1.17(0.17) 1.09(0.16) 0.0835 1.30(0.24) 0.005* 0.0005* 1.19(0.19) 1.15(0.14)	Work MnPF 0.23	Amplitude <0.0001* 0.96(0.18) 0.65(0.10) <0.0001* 1.24(0.21) <0.0001* <0.0001* 0.98(0.19) 0.94(0.17)	Measure Condition Rotation LLLL <i>p</i> HHHH <i>p p</i> Rotate 15 Rotate 30	LLLL vs. Rotation HHHH vs. Rotation LLLL vs. Rotation Frequency	are indicated by the symbol ".
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1. Summary of the main effects of condition on each dependent measure. Where this main effect was significa	nt,
ponding mean (SD) values are shown for distinct conditions along with results from post-hoc comparisons. Sig	nificant effects
icated by the symbol *.	

Gender had a significant main effect on EMG Amp during the work period, suggesting less fatigue for females. EMG Amp was lower among females in both the work period (p = 0.021) and reference contractions (p = 0.078), though the latter only approached significance. Gender differences for EMP Amp during the reference contractions, however, were not consistent across conditions. Simple effects testing showed that EMG Amp was lower for HHHH than the rotation conditions or LLLL for males, whereas for females EMG Amp was higher during LLLL compared to the rotation conditions (Figure 3). The effect of task order also differed between genders (Figure 4). For females Start L resulted in higher EMG Amp, an effect that was not present among males. Testing of gender effects in this interaction showed that, overall, males had higher EMG Amp during the reference contractions than females during the rotation conditions (p = 0.011), but this effect was not consistent for all contrast levels. Males had higher EMG Amp during Start H conditions (p = 0.0014) and for rotating every 15 (p = 0.016) and every 30 minutes (p = 0.029), but a gender difference was not present for Start L conditions. Further, there was no difference between genders in either of the no-rotation conditions for this measure.



Figure 3. Gender differences in the effects of rotation vs. no-rotation on normalized EMG Amplitude (Amp) during the reference contractions. Within each gender, values not having the same letter are significantly different. Error bars indicate SDs.



Figure 4. Gender differences in the effect of task order on normalized EMG Amplitude (Amp) during the reference contractions. Within each gender, values not having the same letter are significantly different. Error bars indicate SDs.

Through not significant (p = 0.072), mean RPDs from the shoulder were higher among males than females, with respective values of 2.10(1.20) and 0.98(1.00), also suggesting less fatigue among females. In terms of task performance, there were main effects of gender such that females had significantly lower SampEn and PEs, but higher MFs. These gender differences were generally consistent between the work and reference contractions. Gender differences in MFs, though, were not consistent between conditions (Figure 5). Among males, MFs were higher during HHHH compared to the rotation conditions and LLLL, but among females MFs were higher during LLLL compared to the rotation conditions and HHHH.



Figure 5. Gender differences in the effects of rotation vs. no-rotation on moment fluctuations (MFs) during the work period. Within each gender, values not having the same letter are significantly different. Error bars indicate SDs.

Discussion

In this study we investigated the effects of rotation, specifically rotation frequency and task order, on localized muscle fatigue and performance during repetitive static loading of the shoulder at two different exertion levels. As expected, rotating between the tasks resulted in reduced fatigue and improved performance compared to only performing the higher intensity task, and increased fatigue and reduced performance compared to only performing the lower intensity task. These effects were evident through both objective and subjective measures of fatigue, and similar effects have been reported in prior studies on rotation (Raina and Dickerson 2009, Kuijer et al. 2004). Further, these results demonstrate that the two task conditions involved distinct physical workload levels.

We expected that rotating between tasks more frequently would be beneficial in reducing accumulated fatigue. Low intensity exertion efforts can serve as periods of active recovery, which previous research has shown to increase blood flow (Bogdanis et al. 1996, Bond et al. 1991, Sairyo et al. 2003). This allows for increased dispersal of H⁺ ions that accumulate with the breakdown of lactic acid, thereby reducing fatigue. As such, more frequently occurring periods of low intensity loading (i.e., every 15 minutes vs. every 30 minutes) could result in increased periods of active recovery and reduced fatigue. Here, however, this expected effect was only seen in discomfort ratings from the upper back. In addition to effects on fatigue, it was expected that increased rotation frequency would decrease task performance. Previous evidence suggests an adverse effect of rotation frequency on task performance due to learning/forgetting effects (Kher et al. 1999, Allwood and Lee 2004). Consistent with this, peak errors were higher in the more rapid 15-minute rotation conditions, though similar effects were not seen for the other performance measures. As such, strong conclusions regarding the effects of rotation frequency on fatigue or performance cannot be made based on the current results.

Several measures indicated a potential effect of task order on fatigue, suggesting that starting with the more demanding task resulted in more fatigue than starting with the less demanding task, though these effects only approached significance. This was seen in both EMG DSI and

subjective ratings of discomfort, and is consistent with results from a previous study, in which subjective ratings of perceived exertion were higher when starting with the more demanding task (Raina and Dickerson 2009). A possible explanation for this effect is that warm-up exercises can improve performance during demanding tasks and increase endurance time (Bishop 2003). Hence, a low intensity-task at the beginning of a work shift may serve as a prolonged warm-up period.

There were several measures assessed here that provided inconsistent results, particularly EMG measures from the work period compared to the reference contractions. Overall, these EMG measures may not be the best indicators of fatigue for the tasks used in the present study. Exertions levels were typically below 30% MVC, for which EMG may not be sufficiently sensitive to fatigue (Yassierli and Nussbaum 2008, Movahed et al. 2011, Oberg 1994, Sood et al. 2007). This lack of sensitivity can be due to rotation of motor units, changing in firing rates, decruitment of motor units, and additional motor unit recruitment (Westgaard and De Luca 1999, Kamo 2002). Further, although postures were controlled for each exertion, it is possible that as participants raised/lowered their arm before/after each exertion their postures changed between each abduction effort. Such changes could have affected muscle activation (De Luca 1997) and thereby masked subtle changes occurring due to fatigue. Changes in levels of agonistic and antagonistic co-contraction may also have occurred, though as only the middle deltoid was monitored here such changes could not be evaluated. Among EMG-based measures, the DSI appeared to be the most sensitive in terms of detecting differences between the conditions, based on values in both work periods and reference contractions, consistent with evidence that it is relatively insensitive to changes in posture and motor unit firing rates (Dimitrov et al. 2006, Gonzalez-Izal et al. 2010). Overall, our results suggest that subjective ratings were more

sensitive to fatigue development than were EMG measures, as is consistent with prior research (Nussbaum et al., 2001; Sood, et al., 2007).

There were several main effects of gender indicating that males were less fatigued and had poorer task performance than females overall. This is consistent with prior research, which showed greater fatigue resistance among females when performing upper extremity tasks at comparable levels of effort relative to capacity (Hicks 2001, Nussbaum et al. 2001, Avin et al. 2010). Further, females overall had better performance compared to males, likely a result of reduced fatigue, seen in this study through reduced peak errors and sample entropy. This also supports previous research, in which females have exhibited better motor control than males (Endo and Kawahara 2011). Gender differences in performance, though, were not consistent across measures, in that males had lower levels of moment fluctuations. Earlier work has shown greater steadiness in force output (lower force fluctuations) for males than females (Brown et al. 2010), a difference which these authors suggested may be due to a difference in absolute strength between genders; since strength and steadiness are related, such higher strength may allow for greater motor control. Here, males were roughly twice as strong as females in shoulder abduction, accounting as least in part for the difference in moment fluctuations.

Males and females also responded differently to the experimental conditions in terms of moment fluctuations during the abduction tasks. For males, the largest fluctuations were found during the conditions involving the higher exertion without rotation. This was likely a direct result of higher levels of fatigue being developed in this condition, since with fatigue the rates of discharge and recruitment of motor units change, in turn causing increased fluctuations in motor output (Hunter et al. 2004, Enoka and Stuart 1992). For females, in contrast, fluctuations were

highest during the condition involving the lower exertion task without rotation, the least fatiguing task condition. Fluctuations are lowest at moderate exertions levels, on the order of 25% MVC, and higher for lower levels of exertion (Taylor et al. 2003, Mehta and Agnew 2011, Brown et al. 2010). This relationship, and the relatively lower level of fatigue development, may account for the observed results among females (since fluctuations for them were larger during the 15% vs. the 30% MVC tasks). Additional analyses of the performance measures were explored, including emphasizing the transitions (between exertions levels) and the proportion of each exertion within a fixed tolerance band. These analyses did not provide any information beyond what has been presented above.

Several limitations were present in this study that should be noted. A controlled, static task was performed in a laboratory setting, and the results obtained may thus not be broadly applicable. While many occupational tasks can be characterized as roughly static (e.g., light assembly), fatigue development during static and dynamic tasks can differ (Masuda et al. 1999, Bakke et al. 1996). Another possible limitation is that our measures of performance may have been affected by participant motivation, which likely was lower than that of actual workers. Also, while our measures of performance likely reflected aspects of motor control ability, it is not clear if the results can be generalized to performance on more complex occupational tasks. Hence, generalizing the current results to actual work environment requires some caution. A limited small sample of young, healthy adults was included in this study, and it is unclear if similar outcomes would be found among older workers, who may differ in their responses to fatiguing tasks (Yassierli et al. 2007, Kent-Braun et al. 2002, Deschenes 2004, Merletti et al. 2002, Avin and Frey Law 2011). The current study, due to the sample size, may also have been underpowered to detect what may be relatively small effect sizes on some outcome measures related to rotation frequency and task order. To facilitate an efficient experiment, a

"compressed" work period of 1 hour was used, and fatigue induced over this period may not be representative of fatigue experienced by workers during a longer and more typical shift. Finally, the current focus was on acute fatigue and the effects of such fatigue, and did not consider any cumulative effects (i.e., across multiple days) that could contribute to WMSD risks.

In summary, the current results indicate, as expected and consistent with earlier evidence, that rotating between tasks involving different levels of exertion can reduce/increase fatigue compared to performing only a higher/lower intensity task. For the specific task and exertion levels examined, no benefits of increasing rotation frequency were evident in terms of fatigue, though increased frequency may have a detrimental effect of task performance. Some evidence suggests a possible effect of task order on fatigue development, supporting the practical recommendation that starting a work shift with a low-intensity task may reduce fatigue accumulation over the shift. Though not always consistent, results indicated that gender can modify the effects of different rotation schemes on fatigue and performance. The current findings overall provided some evidence that specific aspects of a rotation scheme may be influential in terms of fatigue and performance, though further work is needed to assess these effects under more realistic situations, among a more diverse sample, and to obtain more direct measures of injury risks.
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Chapter 3: Effects of rotation frequency and task order on localized muscle fatigue and performance during lifting tasks

Abstract

Though widely considered to reduce physical exposures and increase exposure variation, there is limited evidence that rotating between tasks is effective in reducing the risk of work-related musculoskeletal disorders. The purpose of this study was to assess the effects of rotation, specifically focusing on rotation frequency and task order, on muscle fatigue and performance when included tasks involved the same functional demands and goal. Twelve participants completed six experimental sessions during which repetitive box lifting tasks were performed for one hour either with or without rotation. Where rotation occurred, it was between two intensity levels based on box weight. As expected, rotation reduced fatigue compared to the high intensity with no rotation, and increased fatigue compared to the low intensity with no rotation. Neither rotation frequency nor task order had definitive effects, though peak discomfort ratings were higher when starting with the lower intensity task. These parameters of rotation should be further evaluated under more realistic task conditions.

Keywords: rotation frequency, task order, muscle fatigue, performance, lifting

Introduction

Work-related musculoskeletal disorders (WMSDs), particularly those involving the back and upper extremities, are a considerable problem in the workplace. In 2010, the back was the most frequently injured body part, accounting for ~45% of all WMSD cases, and the shoulder accounted for ~15% of these cases (BLS, 2011). Further, lifting tasks accounted for nearly 50% of overexertion cases (BLS, 2011). Costs associated with occupational injuries have been estimated at up to \$150 billion (Anderson & Budnick, 2009), and of these overexertion and repetitive motion-type cases account for ~30% (Liberty Mutual, 2011). Rotation (aka "job rotation" or "task rotation") is a commonly used administrative control in which workers rotate between a set of different tasks, following an underlying assumption that its use will reduce the risk of WMSDs. More than 40% of manufacturing companies in the U.S. Midwest reported using job rotation in a recent survey (Jorgensen et al., 2005). There is limited evidence, however, supporting the use of rotation to reduce WMSD risk, despite its widespread use.

Previous investigations of job rotation have primarily focused on outcomes related to physical demands (e.g., kinematic and kinetic exposures) and physical exposure variation (e.g., temporal variability of physical demands), and reported outcomes have been inconsistent. A few studies have focused on the implementation of rotation in occupational environments, and have shown decreases in physical demands. For example, rotation can reduce exposure to non-neutral working postures (Hinnen, 1992; Kuijer et al., 1999) cardiovascular load (Kuijer, et al., 1999) and muscle activation (Rissen et al., 2002). In addition, rotation can also reduce muscle fatigue. Raina and Dickerson (2009) demonstrated, through a lab-based study, that performing shoulder abduction alone can be more fatiguing than rotating between shoulder abduction and flexion. It has also been argued that increasing physical exposure variation can be beneficial because while one muscle is loaded, another muscle (or motor unit) can rest (Wells et al., 2010).

Specifically, Wells et al. (2010), found that physical exposure variation was increased when rotating between two different grip tasks compared to performing a single gripping task. Further, increased variability in trapezius activity has been observed with rotation (Möller et al., 2004). In contrast, however, several studies have implemented rotation in occupational environments, and seen increases in physical demands (Kuijer et al., 2005) or no changes in physical exposure variation (Jonsson, 1988; Wells et al., 1989) or WMSD rates (Aptel et al., 2008).

Contrasting effects of rotation could be ascribed to the tasks included in a rotation schedule. For example, tasks with high physical demands can, when included in a rotation schedule, expose more workers to the peak exposures associated with these tasks (Henderson, 1992; Kuijer et al., 2004; Kuijer, et al., 2005), and can increase the likelihood of workers reporting low back pain (Frazer et al., 2003; Kuijer, et al., 2005). For example, rotating between truck driving and refuse collecting can reduce physical demands for workers that previously did only refuse collecting, but an opposite effect was observed for workers that had previously only performed truck driving (Kuijer, et al., 2004). Including tasks with different physical exposures is a recommended approach to task selection for rotation schedules, which is thought to reduce WMSD risk (Mathiassen, 2006). However, this may be difficult to implement in practice, since several studies have shown that many occupational tasks involve similar physical exposures (Aptel, et al., 2008; Jonsson, 1988; Keir et al., 2011; Wells, et al., 1989). For example, Keir et al. (2011) found that the upper erector spinae and forearm muscles did not benefit from rotating between gripping and lifting tasks. This emphasizes a need to assess the effects of rotation when the included tasks have limited exposure variation.

There are other parameters of rotation that may influence its effectiveness in reducing WMSD risks, specifically how frequently workers rotate and the order in which tasks are performed. To

date, neither parameter has been comprehensively evaluated. Workers on manufacturing assembly lines often rotate every two hours (Aptel, et al., 2008; Jorgensen, et al., 2005; Wells, et al., 1989), though it has been suggested this is more so out of convenience (e.g., rotating at rest breaks) (Jorgensen, et al., 2005). Similarly, when given the opportunity to select how frequently to rotate between tasks, some workers choose to rotate every 1 to 1.5 hours (Muramatsu et al., 1987). A study based on mathematical modeling of rotation schedules and effects on physical demands concluded that workers should rotate every 1 - 2 hours (Tharmmaphornphilas & Norman, 2004). However, in our first study (Chapter 2), we analyzed the effect of rotation frequency on demands during static shoulder abduction tasks of two intensity levels, and found no benefit to increased rotation frequency on reduction of muscle fatigue. A recently developed method from the National Institute for Occupational Safety and Health (NIOSH) for assessing sequential lifting tasks, the sequential lifting index (SLI), assumes that there are effects of rotation frequency on overall risk (Waters et al., 2007), in that more frequently rotating between tasks reduces overall physical demands. The frequency effect here is based on the lifting duration component of the frequency multiplier found in the revised NIOSH lifting index, which results in greater risk values for tasks of longer duration (Waters et al., 1994).

Task order, or the sequence in which tasks are performed, also may be influential in the effectiveness of rotation. A limited number of lab-based studies have analyzed task order, and have found inconsistent results. Raina and Dickerson (2009) examined rotating between repetitive shoulder flexion and abduction tasks, and found subjective ratings of exertion were higher when starting with the more demanding task (shoulder abduction), compared to starting with the less demanding task, shoulder flexion; however, these results were not confirmed through objective fatigue measures. Similar results were seen in our first study (Chapter 2), in

which discomfort ratings were higher when starting with the higher exertion shoulder abduction task compared to starting with the lower exertion abduction task. However, another study found no effect of task order when rotating between gripping and lifting tasks (Keir, et al., 2011), as well the NIOSH SLI does not assume effects of task order (Waters, et al., 2007).

Despite the inconclusiveness of these results, task order has been considered when implementing rotation schedules in the workplace, such as generating rotation schedules using algorithms which reduce the likelihood of a worker having back-to-back tasks that require the same movement (Diego-Mas et al., 2009) or ensuring no sequential tasks have high exposures (Henderson, 1992). Order effects have also been found in exercise-based research (Simão et al., 2005; Spreuwenberg et al., 2006). The sequence in which exercises are performed can affect the magnitude of performance decline over the sequence (Spreuwenberg, et al., 2006). Further, the number of repetitions performed is higher for exercises performed earlier compared to later in a sequence (Simão, et al., 2005). These results suggest that there may be similar effects for occupational tasks. Another important consideration when designing rotation schedules is the effect of rotation, and these parameters, on task performance, particularly given its importance related to quality and productivity. Though rotation is thought to improve employee skill level (Jorgensen, et al., 2005), some evidence suggests that it can have a detrimental effect on task performance (Allwood & Lee, 2004; Azizi et al., 2010; Kher et al., 1999). As such, the effect of rotation on task performance needs more thorough evaluation.

The overall purpose of the current study was to further understanding of the effects of rotation frequency and task order. In our first study, we analyzed these effects during static shoulder abduction tasks. Here, we expanded our work to implement more realistic simulations of occupational tasks involving box lifting. We used a controlled laboratory study to isolate the

effects of rotation frequency and task order using two dynamic box lifting tasks that differed in the level of exertion; a compressed time period of one hour was used to facilitate implementation in a laboratory setting. Outcome measures emphasized localized muscle fatigue, due to its potential importance as a risk factor for WMSD development (Allison & Henry, 2002; Dugan & Frontera, 2000; Gorelick et al., 2003; Granata & Gottipati, 2008; Weist et al., 2004; Winkel & Westgaard, 1992); cardiovascular demand, due to its relationship with physical workload levels; and task performance, due to its practical relevance. Specific purposes of this study were to: 1) determine if rotation is effective in reducing muscle fatigue when the included tasks load the same muscle(s); 2) evaluate the effects of rotation on task performance; and 3) identify the specific effects of rotation frequency and task order on fatigue and performance. It was hypothesized that rotating more frequently would reduce fatigue but have adverse effects on performance, and that starting with the lower exertion task would be less fatiguing and have higher performance versus starting with the higher exertion task.

Methods

Participants

Twelve participants (gender balanced) were recruited from the local community using convenience sampling. Mean (SD) age, stature, and body mass were of 21.9 (1.9) years, 1.74 (0.11) m, and 63.4 (12.0) kg. All participants reported being right-hand dominant and physically active, and having no recent history of musculoskeletal injury. Participants completed an informed consent procedure approved by the Virginia Tech Institutional Review Board (Appendix A).

Experimental design

A full-factorial, repeated-measures design was used, in which participants completed each of six experimental conditions (Figure 6). During each condition, participants completed repetitive box lifting over a 60-minute work period. Independent variables included three levels of rotation frequency and two levels of task order. Rotation frequencies included 0 (no rotation), 15, and 30 minutes. Two exertion levels were used for the box lifting tasks, each based on participants' body weight (BW): Lower (10% BW) and Higher (20% BW); these levels were intended to represent low to moderate levels of occupational task demands and were pilot tested to ensure levels were sufficiently high enough to induce perceived fatigue, and sufficiently low enough for participants to complete the task for the one-hour sessions. Rotation occurred between these two levels, and two task orders were evaluated: Lower to Higher, and Higher to Lower (hereafter denoted Start L and Start H, respectively). Participants completed a screening session followed by six experimental sessions. All sessions occurred on separate days and there were at least two days between each to minimize carryover effects (e.g., due to residual fatigue). During each experimental session, participants completed one of the six experimental conditions. The order of exposure to the conditions was counterbalanced using one 6 x 6 balanced Latin square for each gender.



Figure 6. Six experimental conditions ('L' denotes the lower exertion task, 'H' denotes the higher exertion task), involving all combinations of three levels of rotation frequency (shown on right) and two levels of task order (Start L vs. Start H).

Procedures and data collection

During the preliminary session, and following warm-up exercises, static maximum voluntary contractions (MVCs) of torso extension were collected using a standardized lifting posture (Figure 7: left). Specifically, participants were asked to maximally exert by grasping a handle and pulling up against a chain attached to the floor; a uniaxial load cell (Interface, Inc., Model SM-500, Scottsdale, Az) was mounted in series with the chain and participants were given non-threatening verbal encouragement during each exertion. The length of the chain was adjusted to ensure forward torso flexion of 45 degrees with arms perpendicular to the floor; participants were asked to keep their back flat, knees straight, and stand with their feet at hip width during the exertion. Force data from the load-cell were sampled at 1024 Hz and low-pass filtered using a 3 Hz cutoff (Butterworth filter, 2nd order, bidirectional). At least three MVCs were performed, with two minutes of rest between each, until peak forces were non-increasing; the largest force output was recorded as the participants MVC.



Figure 7. Posture used for torso reference contraction and MVCs (left) and arm reference contraction (right).

During each experimental session, participants performed 20-minutes of warm-up exercises and practice of the tasks. After resting briefly, participants performed three baseline reference contractions in each of two postures (Figure 7). The first posture isolated the lower back muscles, and was performed in the same posture as the MVCs. This posture involved a 10-s sustained static contraction equivalent to 15% BW (mid-way between the Lower and Higher exertion levels). Participants were asked to pull upwards on the chain to match a target force value and were given continuous visual feedback of their current and target force. The second posture isolated the arm muscles, and involved a 10-s sustained posture holding a box weighted at 15% BW (mid-way between the Lower and Higher exertion levels), with the shoulders flexed 20 degrees from vertical. Participants were asked to stand upright with their feet at hip width, elbows straight, and look forward during each exertion. Foot placement during both postures was controlled using poster board placed on the floor. The postures for the torso and arm

reference contractions were intended to represent the middle of the range of motion for the task, in which the torso extended from 0 (parallel to floor) to 90 degrees (upright standing), and the shoulder moved from 0 to 40 degrees forward flexion.

Participants then began the experimental tasks, which involved repetitive box lifting at a pace of 12 lifts/lowers per minute for a 60-minute work period. The box was lifted from a platform 6 inches from the floor to a table that was set to each participant's mid-thigh height (Figure 8). During each lift/lower, participants were asked to keep their feet at shoulder width and knees straight (i.e., stoop lift); foot placement was controlled using poster board placed on the floor. The lifting/lowering pace was controlled by a metronome and the box was weighted to be either 10 or 20% BW (the Lower or Higher exertion level). Over the 60-minute work period, the exertion level changed (or didn't) as determined by the treatment condition (Figure 6). Between each lift/lower of the box, participants were asked to return to neutral standing (standing upright, looking forward). Also, during each lift, participants were asked to place the box such that a pointer attached to the middle of the front of the box (away from the participant) lined up as closely as possible to the center of two lines drawn on the backboard of the table, and that the box was aligned parallel to the face of the backboard (Figure 9). Although not intended to exactly replicate an occupational task, the box placement task was designed to assess gross motor control, a common component of many occupational tasks.



Figure 8. Postures used for the lifting task: bottom of lift (left) and top of lift (right).



Figure 9. Box placement task: Participants were asked to place the pointer (on front of box) against the backboard such that the pointer lined up with the middle of two vertical lines and the box was parallel to the backboard.

During the work period, reference contractions, as described above, were completed every 15 minutes. Electromyographic (EMG) activity was collected continuously during the reference contractions from the anterior deltoid (AD), middle deltoid (MD), bicep brachii (BI), trapezius (TR), and erector spinae at the L1 and L3 levels (denoted L1 and L3 hereafter), all on the right side. EMG was obtained using pre-gelled Ag/AgCl electrodes placed 2cm apart on the belly of the muscle (Perotto, 1994). Raw EMG were pre-amplified (Measurement Systems Inc., Ann

Arbor, MI, USA), hardware band-pass filtered (10 - 500 Hz), high-pass filtered with a 30 Hz cutoff, and sampled at 1024 Hz. Ratings of perceived discomfort (RPDs) were collected every 5 minutes during the work period from the right shoulder, upper arm, upper back, and lower back, using a 10-point scale (Borg, 1990; scale ranges from 0 = no discomfort to 10 = extremely strong, almost maximal discomfort) that was visible continuously to participants. Cardiovascular demand was monitored continuously during the work period using a Polar heart rate monitor (Model RS800, Polar USA, Lake Success, NY) and data collected as inter-beat (RR) intervals. Performance of the box placement task was monitored using a 7-camera motion capture system (Vicon MX, Vicon motion systems Inc., Denver, CO, US), which involved markers placed on the box as well as on the backboard. Marker data were sampled at 60 Hz.

Data processing and dependent measures

Three EMG-based measures of fatigue were obtained from a 6-second window during each 10second reference contraction; the first three seconds and last second were removed to reduce transition effects. Each of the following measures was averaged over the 6-second window from each reference contraction. The first measure, *EMG amplitude (Amp)*, was obtained after full-wave rectification, low-pass filtering (Butterworth, 3Hz cut-off, 4th-order, bidirectional), and correction of the EMG signal for resting amplitudes. The second, *EMG mean power frequency (MnPF)*, was determined using a Fast Fourier transform of the EMG signal at each 1-second interval with a 50% overlapping Hamming window. The third, *Dimitrov Spectral Index (DSI)*, was calculated from the raw EMG as in Equation 1, where *PS* = power spectrum, *f*₁ = 30 Hz, and *f*₂ = 450 Hz (Gonzalez-Izal et al., 2010). For each experimental session, EMG measures were normalized to mean values determined from the baseline reference contractions. Increases in EMG Amp and decreases MnPF were interpreted as indicating muscle fatigue

(Krogh-Lund & Jørgensen, 1991; Nussbaum, 2001; Potvin & Bent, 1997), and DSI values were expected to increase with fatigue (Dimitrov et al., 2006).

$$DSI = \frac{\int_{f_1}^{f_2} f^{-1} * PS(f) df}{\int_{f_1}^{f_2} f^{5} * PS(f) df}$$
(1)

Heart rate was analyzed using percentage of HR reserve (%HRR), which is calculated using Equation 2, where $HR_{average}$ = average HR across the four 15-minute work periods. HR_{max} = 220 – age (Fox & Haskell, 1970; Strath, 2000), HR_{rest} was determined using a 6-minute rest period in a supine posture; the last minute of this trial was averaged to determine HR_{rest} (Jouven et al., 2001). Higher %HRR values were considered to represent increased cardiovascular demand (Garet et al., 2005), and to indirectly represent increased physical workload (Kuijer, et al., 1999).

$$\% HRR = \left(\frac{HR_{average} - HR_{rest}}{HR_{max} - HR_{rest}}\right) * 100$$
⁽²⁾

Two measures of performance were derived: box Distance and Angle. Distance was calculated as the absolute distance from the pointer to the center of the two vertical target lines at the end of each lift (along the x-axis; Figure 9). Absolute Angle was calculated using Equation 3, where θ = the angle between the platform and the box, a = the (x, y) vector of the edge of the box, and b = the (x, y) vector of the platform. Increased Distance and Angle were interpreted as indicating decreased task performance.

$$\theta = \arccos\left(\frac{a \cdot b}{\|a\| \|b\|}\right) \tag{3}$$

Specific dependent measures were: mean EMG Amp, MnPF, and DSI from each of the muscles tested, mean and peak RPDs from each body part, %HRR, and mean and peak box Distance and Angle. EMG was available from the reference contractions, while performance and heart rate were available continuously during the work period. All dependent measures were calculated across the available data from a given condition (i.e., 60 min of repetitive lifting or four reference contractions). Mean values were used to represent the accumulation of fatigue (or the effects of fatigue); since each condition had the same duration, the integral of a measure over the work period is equivalent to the product of the mean of the measure and the duration.

Statistical analysis

One-way, repeated-measures analyses of variance (ANOVAs) were performed separately to assess the effects of condition (six levels) on each of the dependent measures, with gender and presentation order of the six conditions included as blocking variables. When there was a significant main effect of condition, post-hoc contrasts were used for several planned comparisons; in the following, "L" denotes the Lower exertion task, "H" denotes the Higher exertion task, and each letter represents one 15-minute period. Planned comparisons included: 1) between no-rotation and rotation conditions (LLLL vs. all rotation conditions and HHHH vs. all rotation conditions); 2) between the two no-rotation conditions (LLLL vs. HHHH); 3) between rotating every 15 vs. 30 minutes (rotation frequency); and 4) between Start L vs. Start H (task order). Simple effects analysis was used to explore significant interactions between gender and condition. All statistical analyses were performed using JMP 9.0 (SAS Institute Inc., Cary, NC), and significance was concluded when p < 0.05. Summary statistics are presented as means (SD).

Results

There were significant main effects of condition on many of the dependent measures. From the EMG data, there were several measures indicating less fatigue for LLLL compared to the rotation conditions, and more fatigue for HHHH than the rotation conditions; however these effects were seen for very few of the muscles and measures tested and were sometimes inconsistent. There was a main effect of condition on AD MnPF (p = 0.031) showing that the MnPF during HHHH (1.00(0.02)) was lower than that of the rotation conditions (1.02(0.03); p =0.047). However, there were also main effects of condition on AD DSI (p = 0.029), and BI DSI (p = 0.015) which indicated more fatigue for LLLL compared to the rotation conditions; DSI values were higher for LLLL (1.05(0.17) and 1.08(0.14), respectively) compared to the rotation conditions (0.93(0.14); p = 0.006 and (0.96(0.15); p = 0.011, respectively). There were several significant interactive effects between gender and condition, specifically EMG Amp from the BI (p = 0.0017), L1 (p = 0.016), and L3 (p = 0.024). For the BI, Amp was higher for HHHH than the rotation conditions for males (p = 0.067); a similar effect was seen for L1 Amp for females (p =0.063). Further, for the L3, Amp was lower for LLLL compared to the rotation conditions (p =0.067) and higher for HHHH compared to the rotation conditions (p = 0.026), though this effect was only seen for males.

Several measures indicated effects of rotation frequency and task order, however these effects were inconsistent between muscles and genders. Regarding rotation frequency, there was a main effect of condition for TR Amp (p = 0.032), and post-hoc testing showed that TR Amp was higher for Rotate 15 (1.43(0.71)) than Rotate 30 (1.08(0.13); p = 0.011). However, the interaction effect between gender and condition for BI Amp indicated that for males, Rotate 15 resulted in lower BI Amp than Rotate 30 (p = 0.0002; Figure 10); no similar effects were seen for females. Similar effects were seen for the BI DSI, in which DSI was higher for Rotate 30

(1.01(0.13) compared to Rotate 15 (0.91(0.15); p = 0.023). Effects of task order were seen through both AD DSI and BI DSI, which were higher for Start L (0.97(0.14) and 0.99(0.12), respectively) compared to Start H (0.90(0.12); p = 0.066 and 0.92(0.17); p = 0.098, respectively), though these effects only approached significance. Further, the interactive effect between gender and condition for L3 Amp showed effects of task order that approached significance for both genders, however the effect was inconsistent between genders. For males, Start L had lower L3 Amp than Start H (p = 0.061), while the opposite occurred for females (p = 0.088; Figure 11).

There were also several effects of gender from the EMG measures. Males had lower Amp for the AD (p = 0.026) and trended towards lower MnPF for the MD (p = 0.063). Further, testing of gender effects in the interactions indicated males had lower BI Amp for HHHH (p = 0.074), though this only approached significance. Males also had higher BI Amp for Rotate 30 (p = 0.017), higher L3 Amp for Rotate 15 (p = 0.056), and higher L3 Amp for Start H (p = 0.015).



Figure 10. Gender differences in the effect of rotation frequency on EMG Amp from the BI. Within each gender, values not having the same letter are significantly different. Error bars indicate SDs.



Figure 11. Gender differences in the effect of task order on EMG Amp from the L3. Within each gender, values not having the same letter are significantly different. Error bars indicate SDs.

There was also a main effect of condition on %HRR, which showed LLLL was less demanding on the cardiovascular system than the rotation conditions, and HHHH was more demanding than the rotation conditions (Table 2). Metabolic equivalent (MET) calculations were performed using the heart rate data, and based on estimated metabolic demands of the task (Garg et al., 1978) and basal metabolic rates for each participant (International Organization for Standardization, 1990); equations are shown in Appendix B. Results indicated an average MET (across genders) of 6.23 for condition LLLL, 6.71 for the rotation conditions, and 7.19 for HHHH. Figures of %HRR data are shown in Appendix C.

All Mean and Peak RPDs showed significant main effects of condition (Table 2), suggesting that LLLL was less fatiguing than the rotation conditions and HHHH was more fatiguing than the rotation conditions. However, there were also significant interactive effects between gender and condition for several RPDs, including mean ratings from the Shoulder (p = 0.0010) and Upper Arm (p = 0.021), as well as peak ratings from the Shoulder (0.041). For mean RPDs from the Shoulder and Upper Arm and peak RPDs from the Shoulder, females showed lower ratings for LLLL compared to the rotation conditions (p = 0.026, 0.049, and 0.002, respectively) and higher ratings for HHHH compared to the rotation conditions (p < 0.0001 for all). For males, mean ratings from the Shoulder and Upper Arm and peak ratings from the Shoulder were lower for LLLL compared to the rotation conditions (p = 0.095, 0.083, and 0.030, respectively); mean ratings here only approached significance. Further, both mean Upper Arm and peak Shoulder ratings were lower for LLLL compared to HHHH for males (p = 0.041 and 0.011, respectively). Testing of gender effects in these interactions showed that mean RPDs from the upper arm were lower for males than females for HHHH (p = 0.065), though this only approached significance and this effect was not present for any other body part. Additionally, all peak RPDs showed effects of task order, in which Start L had higher ratings than Start H, though ratings

from the Upper Back and Shoulder were only approaching significance (p = 0.12 and 0.053, respectively).

				LLLL vs.	Rotation	HHHH vs.	Rotation	LLLL vs. HHHH	Rot	ation Frequenc	Ŷ		Task Order	
Measur	æ	Condition	Rotation		q	НННН	q	q	Rotate 15	Rotate 30	q	Start L	Start H	q
Heart Rate	%HRR	<0.0001*	37.2(9.09)	31.3(7.70)	0.0002*	45.0(9.83)	<0.0001*	<0.0001*	37.3(9.02)	37.1(9.36)	0.90	37.3(10.2)	37.2(8.11)	0.96
RPDs Mean	Lower Back	<0.0001*	1.15(0.88)	0.88(0.88)	0.0061*	1.78(1.18)	<0.0001*	<0.0001*	1.12(0.93)	1.17(0.84)	0.58	1.17(0.87)	1.13(0.91)	0.66
	Upper Back	0.0003*	1.05(1.00)	0.89(1.06)	0.14	1.57(1.43)	<0.0001*	<0.0001*	1.03(0.99)	1.08(1.04)	0.61	1.05(1.04)	1.05(0.99)	0.97
	Shoulder	0.0005*	0.89(0.75)	0.64(0.72)	0.0067*	1.14(0.93)	0.0005*	<0.0001*	0.87(0.80)	0.90(0.71)	0.73	0.87(0.72)	0.91(0.79)	0.62
	Upper Arm	<0.0001*	0.86(0.72)	0.56(0.54)	0.010*	1.41(1.21)	<0.0001*	<0.0001*	0.83(0.78)	0.90(0.66)	0.53	0.85(0.69)	0.88(0.76)	0.82
Peak	Lower Back	<0.0001*	2.36(1.43)	1.48(1.22)	0.0001*	3.23(1.67)	0.0004*	<0.0001*	2.38(1.43)	2.33(1.46)	0.85	2.57(1.46)	2.15(1.40)	0.014*
	Upper Back	<0.0001*	2.00(1.59)	1.43(1.43)	0.012*	2.92(2.08)	0.0001*	<0.0001*	1.85(1.45)	2.15(1.75)	0.13	2.16(1.71)	1.85(1.48)	0.12
	Shoulder	<0.0001*	1.80(1.20)	1.10(1.18)	0.0003*	2.63(1.92)	<0.0001*	<0.0001*	1.71(1.19)	1.89(1.22)	0.26	1.96(1.28)	1.64(1.11)	0.053
	Upper Arm	<0.0001*	1.78(1.16)	0.93(0.87)	<0.0001*	2.60(1.81)	0.0001*	<0.0001*	1.67(1.17)	1.90(1.16)	0.16	1.95(1.27)	1.62(1.04)	0.045*

conditions along with results from post-hoc comparisons.	Fable 2. Summary of the main effects of condition on HR
Significant effects are indicated by the symbol *.	and RPDs. Corresponding mean (SD) values are shown for distinct

In terms of task performance, though there were no main effects of condition on any performance measure, there were main effects of gender and interactive effects of gender and condition for mean and peak Distance (p = 0.034 and 0.046, respectively). These results indicated that, overall, performance was better for LLLL and worse for HHHH, but males and females responded different to the rotation conditions. Specifically, simple effects testing of the interactions showed that for males mean Distance was lower for both LLLL and HHHH compared to the rotation conditions (p = 0.026 and 0.064, respectively; Figure 12), suggesting that rotation overall had a detrimental effect on task performance. Females, however, showed only lower mean Distance for LLLL compared to HHHH, and this effect only approached significance (p = 0.069). Further, peak Distance for males was lower for LLLL than both the rotation conditions (p = 0.0052) and HHHH (p = 0.063), again suggesting that for males, rotating had a detrimental effect on task performance. For females, however, peak Distance was lower for both LLLL (p = 0.041) and the rotation conditions (p = 0.020) compared to HHHH (Figure 13). Main effects of gender showed that overall both mean and peak Distance were higher for males (p = 0.061 and 0.045, respectively) than females. However, testing of gender effects in the interactions showed that, while this relationship was present for all contrast levels representing the rotation conditions (Rotate 15, Rotate 30, Start L, and Start H), there were no differences in performance between genders for either no-rotation conditions.



Figure 12. Gender differences in the effects of rotation vs. no-rotation on mean Distance. Within each gender, values not having the same letter are significantly different. Error bars indicate SDs.



Figure 13. Gender differences in the effects of rotation vs. no-rotation on peak Distance. Within each gender, values not having the same letter are significantly different. Error bars indicate SDs.

Discussion

In this study we investigated the effects of rotation, specifically rotation frequency and task order, on localized muscle fatigue, cardiovascular demand, and performance during repetitive box lifting at two different exertion levels. As expected, rotation resulted in reduced fatigue and cardiovascular demand compared to only performing the higher intensity task, and increased fatigue and cardiovascular demand compared to only performing the lower intensity task. These effects were evident primarily through subjective measures of fatigue and heart rate, and similar effects have been reported in prior studies on rotation (Kuijer, et al., 2004; Raina & Dickerson, 2009). These effects were also seen through some EMG measures, however EMG effects were fairly inconsistent across muscles tested and between genders, and were largely nonsignificant. Overall, the rotation vs. no rotation effects demonstrate that the two task conditions included were distinct in terms of their physical workload. Task performance was overall better for the low exertion task without rotation, and worse for the high exertion task without rotation. However, males and females responded differently to the rotation conditions in terms of performance on the task. Specifically, results suggested that rotation had a detrimental effect on task performance for males, yet this effect was not seen for females. This supports some previous research, which suggests that rotation can detrimentally affect task performance (Allwood & Lee, 2004; Azizi, et al., 2010; Kher, et al., 1999), and supports results from our first study (Chapter 2). Further, males overall had lower performance than females, supporting previous research that females have greater motor control than males (Endo & Kawahara, 2011).

We expected that rotating between tasks more frequently would be beneficial in reducing accumulated fatigue. Low intensity loads can allow for increased blood flow (Bogdanis et al.,

1996; Bond et al., 1991; Sairyo et al., 2003), which can reduce the concentration of H⁺ that results from the breakdown of lactic acid, and therefore reduce fatigue. Further, prior work on sequential lifting tasks, namely the NIOSH SLI, implicitly assumes an effect of rotation frequency, in that rotation sequences containing longer duration tasks are given higher risk values (Waters, et al., 2007). As such, we expected that more frequently occurring periods of low intensity loading would reduce accumulated fatigue. Though there were some effects of rotation frequency in the EMG data, the direction of the effects was inconsistent. Further, no effects of rotation frequency were seen in any other measure, so interpretation of the effects on the EMG measures is limited. Therefore, it is likely that the low intensity loading periods (i.e., lower box weight) did not allow for recovery from the higher intensity loads. These results also are in agreement with results from our first study (see Chapter 2), which showed no effect of rotation frequency on fatigue.

We also expected that starting with the lower intensity task would reduce fatigue compared to starting with the higher intensity task, possibly due to the lower intensity task serving as a prolonged warm-up period, which can improve performance and increase endurance time (Bishop, 2003). This effect was observed from one EMG measure, though opposing effects were also seen from the discomfort ratings and some EMG measures. Though not always significant, peak discomfort ratings were consistently higher when starting with the lower intensity task; this effect, however, was not seen for mean discomfort ratings. The observed effect for peak ratings opposes some prior research on rotation, including the results from our first study (Chapter 2), in which ratings were lower when starting with the lesser demanding task (Raina & Dickerson, 2009), and in which there were no effects of task order (Keir, et al., 2011). The latter work, however, agrees with most measures, which showed no consistent effects of

task order. Further, the NIOSH SLI assumes no effect of task order; Table 3 shows a ranking of the conditions from our results (based on RPD and HR measures), as well as suggested ranking according to the SLI. The ranks shown using the SLI are based on sample calculations shown in Waters et al. (2007).

Table 3. Ranked conditions according to our results and the SLI estimated risk. A lower rank indicates lower risk; ranks of tied conditions are shown as the mean of the tied positions.

	RPDs	HR	SLI
LLLL	1	1	1
LHLH	3.5	3.5	2.5
HLHL	3.5	3.5	2.5
LLHH	3.5	3.5	4.5
HHLL	3.5	3.5	4.5
HHHH	6	6	6

Though some EMG measures showed changes due to fatigue, overall these measures were inconsistent and contributed little information towards the results of this study. EMG was only available during the reference contractions, which were on average ~19% MVC for the torso reference contraction (relative to upward pull MVCs) for all participants, levels for which EMG may not be sensitive to fatigue (Movahed et al., 2011; Oberg, 1994; Sood et al., 2007; Yassierli & Nussbaum, 2008). Possible reasons for insensitivity at these levels include rotation of motor units, changing in firing rates, decruitment of motor units, and additional motor unit recruitment (Kamo, 2002; Westgaard & de Luca, 1999). Further, although posture was controlled in the reference contractions, it is likely that there were slight changes in position that could have affected muscle activation levels and masked changes occurring due to fatigue (De Luca, 1997). Further, increases in muscle temperature over the work periods could have masked fatigue

effects (Madigan & Pidcoe, 2002), by increasing MnPF in opposition to the typical decrease expected with fatigue.

Several limitations of this study should be acknowledged. This study involved a controlled lifting task performed in a laboratory setting. Though lifting is a common occupational task, the constrained, symmetric, stoop-style lift used in this study may not be representative of the type of lifting performed in real work environments. Further, a small sample of healthy young adults was used, who may differ in their responses to fatiguing tasks (Avin & Frey Law, 2011; Deschenes, 2004; Kent-Braun et al., 2002; Merletti et al., 2002; Yassierli et al., 2007) compared to older workers, and also may differ in their motivation towards performing the tasks. In addition, the small sample size used here may have been underpowered to detect subtle changes related to rotation frequency and task order. To facilitate implementation in a laboratory setting, several constraints were placed on the tasks that may affect their generalizability to actual work environments. A compressed time period of one hour was used and only within-session effects of fatigue were evaluated; a longer duration task and/or consideration of cumulative effects of day-to-day work may be more representative of fatigue experienced in actual work environments.

In summary, rotation between lifting tasks that vary in exertion level can reduce/increase fatigue compared to performing only a higher/lower intensity task. For the tasks examined here, there were not any consistent effects of either rotation frequency or task order across measures. There was some evidence, though the effect differed between genders, that rotation overall had a detrimental effect on task performance. Overall these findings do not provide conclusive information regarding the effects of rotation frequency or task order on fatigue or performance.

If there are effects of these parameters of rotation, the effects may be relatively small and were not detected using the constrained task in this study. Therefore, further work is needed under more realistic task conditions, such as with a longer duration exposure, and with a more diverse sample to further explore these parameters.

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Chapter 4: Effects of rotation frequency and task order on localized muscle fatigue and performance during simulated assembly work

Abstract

Rotating between tasks is widely used and considered to reduce the risk of work-related musculoskeletal disorders (WMSDs), though there is limited evidence that it is effective in doing so. The purpose of this study was to assess the effects of rotation, specifically focusing on rotation frequency and task order, on muscle fatigue and performance when included tasks loaded the same muscle group. Twelve participants completed six experimental sessions during which repetitive assembly tasks were performed for one hour either with or without rotation. When rotation occurred, it was between two intensity levels that corresponded with two working heights. As expected, rotating between the tasks reduced fatigue compared to only performing the high intensity task, and increased fatigue compared to only performing the low intensity task. Neither rotation frequency nor task order had significant effects on fatigue or performance, though these effects should be considered in studies of rotation under more realistic task conditions.

Keywords: rotation frequency, task order, muscle fatigue, performance
Introduction

Work-related musculoskeletal disorders (WMSDs) continue to be a substantial problem in the workplace. The costs associated with occupational injuries have been estimated at up to \$150 billion in the US (Anderson & Budnick, 2009). WMSDs account for roughly 30% of injuries or illnesses that require days away from work (BLS, 2011), and of these, the shoulder accounts for around ~15% of the total cases and involved the most severe injures, requiring a median of 21 days away from work (BLS, 2011). To reduce the prevalence of WMSDs, administrative controls, such as rotation (aka "job rotation" or "task rotation"), are often adopted. Rotation involves workers rotating between a set of different tasks, and is used by more than 40% of manufacturing companies in the U.S. Midwest, with the primary motivation to reduce exposure to WMSD risk factors (Jorgensen et al., 2005). However, there is little evidence supporting the use of the rotation approach to reduce WMSD risk, despite its widespread use.

Much of the focus of rotation research has been on the effects on physical demands (e.g., kinematic and kinetic exposures) and physical exposure variation (i.e., temporal variability of physical demands). However, existing evidence has shown inconsistent effects. Some implementations of rotation have led to decreases in physical demands, specifically reducing exposure to non-neutral working postures (Hinnen, 1992; Kuijer et al., 1999), cardiovascular load (Kuijer, et al., 1999), and muscle activation (Rissen et al., 2002). Raina and Dickerson (2009) demonstrated that rotation can also reduce muscle fatigue; in their study, performing shoulder abduction alone was more fatiguing than rotating between shoulder abduction and flexion. Regarding physical exposure variation, increases are thought to be beneficial because while one muscle (or motor unit) is resting other muscles can be loaded (Wells et al., 2010). In their study, Wells et al. (2010) found that physical exposure variation can be increased when

rotating between different grip tasks compared to performing only one grip task. Further, rotation at an automotive plant increased variability of the trapezius muscle activity (Möller et al., 2004). However, and in contrast, several studies have implemented rotation in work environments and found increases physical demands (Kuijer et al., 2005), no effects on physical exposure variation (Jonsson, 1988; Wells et al., 1989), and no change in WMSD rates (Aptel et al., 2008).

There are many parameters of rotation that need to be specified when developing rotation schedules and that may explain some of these inconsistencies, such as which tasks to include in a given rotation schedule, how frequently workers rotate between tasks, and in which order the tasks are performed. In terms of task selection, a common problem with rotation is that when highly-demanding tasks are included, rotation can increase the number of workers who experience peak loading from these tasks (Henderson, 1992; Kuijer et al., 2004; Kuijer, et al., 2005) as well as the likelihood of workers reporting low back pain (Frazer et al., 2003; Kuijer, et al., 2005). For example, when workers rotated between refuse collecting and truck driving, Kuijer et al. (2004) found that rotating reduced physical demands for workers that previously only collected refuse, but increased physical demands among workers that had previously only performed truck driving. Another complexity with task selection for rotation schedules is that a recommended approach is to include tasks with different physical exposures, which in turn is thought to reduce WMSD risk (Mathiassen, 2006). However, many occupational tasks involve comparable physical exposures (Aptel, et al., 2008; Jonsson, 1988; Keir et al., 2011; Wells, et al., 1989). For example, Keir et al. (2011) found that the upper erector spinae and forearm muscles did not benefit from rotating between gripping and lifting tasks. Therefore, there

remains a need to assess the effects of rotation when the included tasks have limited exposure variation, such as between tasks that load the same muscle(s).

How frequently workers should rotate between tasks, i.e., rotation frequency, also may be influential. Few analyses have been done of effects of rotation frequency on physical demands. A study based on mathematical modeling of rotation schedules and effects on physical demands concluded that workers should rotate every 1 – 2 hours (Tharmmaphornphilas & Norman, 2004). However, in our prior two studies (see Chapters 2 and 3), we analyzed the effect of rotation frequency on demands during static shoulder abduction and box lifting tasks, and found no benefit to increased rotation frequency in terms of reducing muscle fatigue. Workers on manufacturing assembly lines often rotate every two hours (Aptel, et al., 2008; Jorgensen, et al., 2005; Wells, et al., 1989), though it has been suggested this is out of convenience (e.g., rotating at rest breaks) rather than based on empirical evidence (Jorgensen, et al., 2005). Similarly, some workers self-select rotating between tasks every 1 to 1.5 hours (Muramatsu et al., 1987).

The effect of task order, or the sequence in which tasks are performed, is another important aspect of rotation schedules. A few lab-based studies have analyzed task order, and found inconsistent results. Raina and Dickerson (2009) examined rotating between repetitive shoulder flexion and abduction tasks. Though no significant effect of task order was found on objective fatigue measures, subjective exertion ratings were higher when starting with the more demanding task (shoulder abduction) compared to starting with shoulder flexion. This effect was also found in our first study (Chapter 2), which involved rotating between static shoulder abduction at two intensity levels; higher discomfort ratings resulted when starting with the higher

intensity level compared to the lower intensity level. However, other studies have shown no effects of task order. For example, Keir et al. (2011) found no effects of task order when rotating between gripping and lifting tasks. Further, in our second study (Chapter 3), we found no consistent effects of task order when rotating between lifting tasks of different intensity levels. Although the number of lab-based studies is limited and results are not yet conclusive, task order has been considered when implementing rotation in the workplace. For example, rotation schedules have been designed such that no sequential tasks have high exposures (Henderson, 1992), and using algorithms which reduce the likelihood of a worker having back-to-back tasks that require the same movement (Diego-Mas et al., 2009). Order effects have also been reported in exercise-based research (Simão et al., 2005; Spreuwenberg et al., 2006), suggesting there may be similar effects for occupational tasks. The magnitude of performance decrements can depend on the sequence in which exercises are performed (Spreuwenberg, et al., 2006), and performance (assessed through number of repetitions) can be higher during exercises performed earlier in a sequence compared to those at the end (Simão, et al., 2005).

Another consideration for using rotation is its effect on task performance. Though rotation is thought to improve employee skill (Jorgensen, et al., 2005), some evidence suggests that it can have a detrimental effect on task performance (Allwood & Lee, 2004; Azizi et al., 2010; Kher et al., 1999). In our first study (Chapter 2), we found that a higher rotation frequency (rotating every 15 minutes vs. every 30 minutes) resulted in higher peak errors made during the task, and results from our second study (Chapter 3) suggested that rotation overall resulted in worse performance compared to not rotating. Given the potential impact of rotation schemes with respect to quality and productivity, the effect of rotation on task performance needs more thorough evaluation.

The purpose of the current study was to provide additional information regarding the effects of rotation frequency and task order. A controlled laboratory study was used to isolate these effects, involving rotation between two simulated assembly tasks that differed in the level of exertion. As previously, a compressed timeframe was used to facilitate implementation in a laboratory setting. A Purdue Pegboard Test was used to simulate the assembly tasks; this test was chosen as it requires fine motor control (Tiffin & Asher, 1948), and to simulate a complex, dynamic task requiring commonly found demands in occupational work. Outcome measures included localized muscle fatigue, due to its potential importance as a risk factor for WMSD development (Allison & Henry, 2002; Dugan & Frontera, 2000; Gorelick et al., 2003; Granata & Gottipati, 2008; Weist et al., 2004; Winkel & Westgaard, 1992); cardiovascular demand, due to its relationship with physical workload levels; and task performance, due to its practical relevance. Specific purposes of this study were to: 1) determine if rotation is effective in reducing muscle fatigue when the included tasks load the same muscle(s); 2) evaluate the effects of rotation on task performance; and 3) identify the specific effects of rotation frequency and task order on fatigue and performance. It was hypothesized that rotating more frequently would reduce fatigue but have adverse effects on performance, and that starting with the lower exertion task would be less fatiguing and have higher performance versus starting with the higher exertion task.

Methods

Participants

Twelve participants (gender balanced) were recruited from the local community using convenience sampling, whose respective mean (SD) age, stature, and body mass were 22.3 (1.9) years 1.69 (0.10) m, and 64.7 (10.1) kg. All participants reported being physically active

and having no recent history of musculoskeletal injury, and all indicated being right-hand dominant. Participants completed an informed consent procedure approved by the Virginia Tech Institutional Review Board (Appendix A).

Experimental design

A full-factorial, repeated-measures design was used in which participants completed each of six experimental conditions (Figure 14); during each condition participants performed repetitive assembly tasks over a 60-minute work period. Three levels of *rotation frequency* were used: 0 (no rotation), 15, and 30 minutes. Assembly tasks were performed at two exertion levels, based on working height, which was based on each individual participant's height. The two exertion levels were Lower (waist height) and Higher (shoulder height). Where rotation occurred, it was between these two levels, and two *task orders* were evaluated: Lower to Higher, and Higher to Lower (hereafter denoted Start L and Start H, respectively). Participants completed a screening session followed by six experimental sessions; all sessions occurred on separate days and there were at least two days between each to minimize carryover effects (e.g., due to residual fatigue). During each experimental session, participants completed one of the six experimental conditions. The order of exposure to the conditions was counterbalanced using one 6 x 6 balanced Latin square for each gender.



Figure 14. Six experimental conditions ('L' denotes the lower exertion task, 'H' denotes the higher exertion task), involving all combinations of three levels of rotation frequency (shown on right) and two levels of task order (Start L vs. Start H).

Procedures and data collection

In the preliminary session, and following initial warm-up exercises, isometric MVCs of shoulder flexion were collected using a commercial dynamometer (System 3 Pro, Biodex Medical Systems, Shirley, New York). During MVCs, the right shoulder was flexed 90 degrees and the upper body and waist were secured to the dynamometer chair using padded straps. Participants were instructed to exert maximally against a padded fixture and were given non-threatening verbal encouragement. Moments output by the dynamometer were hardware low-pass filtered (15 Hz) and sampled at 1024 Hz. At least three MVCs were performed, with two minutes of rest between each, until peak moments were non-increasing. After accounting for gravitational effects on the fixture and upper extremity mass, the largest shoulder moment across MVC efforts was recorded.

During each experimental session, participants performed a 20-minute period of warm-up exercises and practice of the tasks. After resting briefly, participants performed three baseline reference contractions in each of two postures (Figure 15). The first posture partially isolated the anterior part of the deltoid muscle, and involved a 10-s sustained static posture with the shoulder flexed 90 degrees (Figure 15: left). The second posture partially isolated the middle deltoid and trapezius (Figure 15: right), and involved a 10-s sustained posture with the shoulder abducted 90 degrees, and the elbow flexed 90 degrees. Vertically-oriented boards were attached to a table in front of participants, on which a mark was placed giving participants a target with which to line their hand up for each posture; this was done to ensure consistent positioning between each reference contraction.





Figure 15. Posture used for the first reference contraction isolating the AD (left) and the second isolating the deltoid and trapezius (right).

Participants then began the experimental task, which involved repetitive assembly over a 60minute work period. The tasks followed a 3:50 minute cycle time, with 3:30 minutes of work and 20-s rest, and were performed using a Purdue Pegboard Test (Figure 16). The pegboard was placed at waist or shoulder height (Figure 17), corresponding to the Lower and Higher exertion levels, respectively. When placed at shoulder height, the pegboard was angled 45 degrees to ensure the entire board could be reached. This task involved placing four pieces (one pin, two washers, and one collar) in holes on the pegboard. Participants were instructed to place the pieces in a specific order, beginning with one pin placed in the pegboard (right hand), followed by one washer (left hand), one collar (right hand), and one washer (left hand), each placed over the pin. Participants were asked to complete the assemblies as quickly as possible without making any mistakes, and to keep their feet on the floor at shoulder width and back vertical during the tasks. Over the 60-minute work period, the exertion level (i.e., working height) changed (or didn't) as determined by the treatment condition (Figure 14).





Figure 16. Purdue pegboard: Participants were asked to assemble pieces (left) into holes in a pegboard (right).





Figure 17. Exertion levels for assembly task: waist height (left) and shoulder height (right).

During the work period, reference contractions, as described above, were completed every 15 minutes. Electromyographic (EMG) activity was collected continuously during the reference contractions from the anterior deltoid, middle deltoid, posterior deltoid, and trapezius (hereafter denoted AD, MD, PD, and TR respectively), all on the right side. EMG was obtained using pre-gelled Ag/AgCl electrodes placed 2 cm apart at locations described earlier (Perotto, 1994). Raw EMG from the muscles were pre-amplified (Measurement Systems Inc., Ann Arbor, MI, USA), hardware band-pass filtered (30 - 1000 Hz), and sampled at 1024 Hz. Ratings of perceived discomfort (RPDs) were collected every 3.5 minutes during the work period from the right shoulder, upper arm, and upper back, using a 10-point scale (Borg, 1990; scale ranges from 0 = no discomfort to 10 = extremely strong, almost maximal discomfort) that was visible continuously to participants. Cardiovascular demand was monitored continuously during the work period using a Polar heart rate monitor (Model RS800, Polar USA, Lake Success, NY) and

data collected as RR intervals. Performance at the assembly task was monitored through quantification of the completed number of assemblies during each 3:50 minute work cycle.

Data processing and dependent measures

Three EMG-based measures of fatigue were obtained from data collected from each muscle during each reference contraction. Specifically, a 6-second window was extracted from each 10-second sustained posture; the first three seconds and last second were removed to reduce transition effects. The first measure, *EMG amplitude (Amp)*, was obtained from the EMG signal after full-wave rectification, low-pass filtering (Butterworth, 3Hz cut-off, 4th-order, bidirectional), and correction for resting amplitudes. The second, *EMG mean power frequency (MnPF)*, was determined using a Fast Fourier transform of the EMG signal at each 1-second interval with a 50% overlapping Hamming window. The third, *Dimitrov Spectral Index (DSI)*, was calculated from the raw EMG signal as in Equation 1, where *PS* = power spectrum, $f_7 = 30$ Hz, and $f_2 = 450$ Hz (Gonzalez-Izal et al., 2010). For each experimental session, Amp, MnPF, and DSI were normalized to corresponding mean values determined from the baseline reference contractions. Increases in Amp and decreases in MnPF were interpreted as indicating muscle fatigue (Krogh-Lund & Jørgensen, 1991; Nussbaum, 2001; Potvin & Bent, 1997), and DSI values were expected to increase with fatigue (Dimitrov et al., 2006).

$$DSI = \frac{\int_{f_1}^{f_2} f^{-1} * PS(f) df}{\int_{f_1}^{f_2} f^5 * PS(f) df}$$
(1)

Heart rate was analyzed using percentage of HR reserve (%HRR), which was calculated using Equation 2, where HR_{average} = average HR across the four 15-minute work periods,

 $HR_{max} = 220 - age$ (Fox & Haskell, 1970; Strath, 2000), and HR_{rest} was determined using a 6minute rest period in a supine posture; the last minute of this trial was averaged to determine HR_{rest} (Jouven et al., 2001). Higher %HRR values were considered to represent increased cardiovascular demand (Garet et al., 2005), and to indirectly represent increased physical workload (Kuijer, et al., 1999).

$$\% HRR = \left(\frac{HR_{average} - HR_{rest}}{HR_{max} - HR_{rest}}\right) * 100$$
⁽²⁾

Specific dependent measures were: mean EMG Amp, MnPF, and DSI from each of the muscles tested, mean and peak RPDs from each body part, %HRR, and mean and minimum number of assemblies. EMG was available from the reference contractions, while performance and heart rate were available continuously during the work period. All dependent measures were calculated across the available data from a given condition (i.e., 60 min of repetitive lifting or four reference contractions). Mean values were used to represent the accumulation of fatigue (or the effects of fatigue); since each condition had the same duration, the integral of a measure over the work period is equivalent to the product of the mean of the measure and the duration.

Statistical analysis

One-way, repeated-measures analyses of variance (ANOVAs) were performed separately to assess the effects of condition (six levels) on each of the dependent measures. Gender and presentation order of the six conditions were included in these analyses as blocking variables. When there was a significant main effect of condition, post-hoc contrasts were used for several planned comparisons. In the following, "L" denotes the Lower exertion task, "H" denotes the

Higher exertion task, and each letter represents one 15-minute period. Specific comparisons were made: 1) between no-rotation vs. all rotation conditions (LLLL vs. all rotation conditions and HHHH vs. all rotation conditions); 2) between the two no-rotation conditions (LLLL vs. HHHH); 3) between rotating every 15 vs. 30 minutes (rotation frequency); and 4) between Start L vs. Start H (task order). Significant interactions with gender were explored using simple effects analyses. Summary statistics are presented as means (SD). All statistical analyses were performed using JMP 9.0 (SAS Institute Inc., Cary, NC), and significance was concluded when p < 0.05.

Results

There were significant main effects of condition on many dependent measures, including some EMG measures, all mean and peak RPDs, and both mean and minimum performance measures. From the EMG data, there was a significant main effect of condition on AD MnPF (p = 0.0024); AD MnPF was higher for LLLL (0.99(0.04) compared to the rotation conditions (0.96(0.05); p = 0.046), and lower for HHHH (0.93(0.06)) compared to the rotation conditions (p = 0.021). There was also a significant interaction effect of gender and condition on AD MnPF (p = 0.0095). Simple effects testing showed that for males, LLLL was less fatiguing than the rotation conditions (p = 0.024) and HHHH (p = 0.055), and for females, both LLLL and the rotation conditions were less fatiguing than HHHH (p = 0.0046 and 0.0065, respectively; Figure 18). Further, there were effects of rotation frequency for both genders, however the direction of the effect was inconsistent. For males, MnPF was lower for Rotate 30, though this only approached significance (p = 0.098), while for females, MnPF was higher for Rotate 30 (p = 0.0012) compared to Rotate 15 (Figure 19).



Figure 18. Gender differences in the effects of rotation vs. no-rotation on AD MnPF. Within each gender, values not having the same letter are significantly different. Error bars indicate SDs.



Figure 19. Gender differences in the effects of rotation frequency on AD MnPF. Within each gender, values not having the same letter are significantly different. Error bars indicate SDs.

There was also a significant interactive effect of gender and condition for MD DSI (p = 0.016). Simple effects testing showed that for males, LLLL and the rotation conditions had lower DSI than HHHH (p = 0.050 and 0.12, respectively), while for females, no significant differences were found for the rotation vs. no-rotation conditions (Figure 20). Further, there were effects of task order for both genders. For males, Start L resulted in higher DSI (p = 0.049), while the opposite occurred for females, for which Start L resulted in lower DSI than Start H (p = 0.0056; Figure 21).



Figure 20. Gender differences in the effects of rotation vs. no-rotation on MD DSI. Within each gender, values not having the same letter are significantly different. Error bars indicate SDs.



Figure 21. Gender differences in the effects of task order on MD DSI. Within each gender, values not having the same letter are significantly different. Error bars indicate SDs.

There were main effects of condition on mean and peak RPDs from all body parts, which overall showed that LLLL was less fatiguing than the rotation conditions, HHHH was more fatiguing than the rotation conditions, and LLLL was less fatiguing than HHHH (Table 4), though not all post-hoc comparisons were significant. However, these effects were not seen in the %HRR, for which there was not a significant effect of condition. A figure of the %HRR data is shown in Appendix C. There were also main effects of condition on both mean and minimum performance values, which showed better performance for LLLL compared to both the rotation conditions and HHHH (Table 4). Further, there was an effect for mean performance that approached significance, showing worse performance for HHHH compared to the rotation conditions (p = 0.11). There were no effects of rotation frequency or task order for any of these measures.

Table 4. Summary of the main effects of condition on RPDs and performance. Corresponding mean (SD) values are shown for distinct conditions along with results from post-hoc comparisons. Significant effects are indicated by the symbol *.

					LLLL vs. Rotation		HHHH vs. Rotation		LLLL vs. HHHH
	Measure		Condition	Rotation	LLLL	р	нннн	p	р
		Shoulder	<0.0001*	2.22(1.07)	1.59(1.23)	0.0133*	3.85(1.61)	<0.0001*	<0.0001*
	Mean	Upper Arm	<0.0001*	1.68(0.93)	1.40(1.15)	0.15	2.69(1.90)	<0.0001*	<0.0001*
		Upper Back	0.0038*	1.99(1.10)	1.92(1.12)	0.74	2.86(1.53)	0.0001*	0.0007*
RPDs									
		Shoulder	<0.0001*	4.00(1.60)	2.35(1.62)	<0.0001*	5.53(1.91)	0.0002*	<0.0001*
	Peak	Upper Arm	0.0002*	3.24(1.59)	2.13(1.63)	0.0005*	4.13(2.38)	0.0049*	<0.0001*
		Upper Back	0.018*	3.59(1.71)	3.04(1.68)	0.066	4.30(2.07)	0.020*	0.0014*
Heart Rate		%HRR	0.14	14.7(8.70)	12.3(9.02)	-	14.4(11.0)	-	-
Performance		Mean	0.017*	40.5(6.93)	42.5(5.79)	0.0068*	39.3(5.34)	0.11	0.0009*
		Min	0.016*	36.4(7.55)	39.1(5.99)	0.0025*	35.4(5.76)	0.28	0.0014*

Several main effects of gender were present in this study, suggesting that males were more fatigued than females. From the EMG data, there was an effect of gender that approached significance for AD MnPF (p = 0.066), such that MnPF was lower for males (0.94(0.047)) compared to females (0.98(0.056)). However, simple effects testing of the interaction with gender showed that this effect was only significant for a few of the contrast levels of interest: HHHH (p = 0.024), Rotate 30 (p = 0.0003) and Start H (p = 0.021), and approached significance for Start L (p = 0.11). There were also effects of gender for both mean and peak RPDs from the shoulder (p = 0.056 and 0.061, respectively), which showed higher ratings from males than females; however, these effects only approached significance. Respective values for mean ratings were 2.93(1.21) and 1.85(1.32), and for peak ratings were 4.70(1.54) and 3.26(1.93).

Discussion

In this study we investigated the effects of rotation on localized muscle fatigue and performance, specifically effects of rotation frequency and task order, during repetitive assembly tasks at two

exertion levels. Several measures indicated that rotating between the tasks resulted in less fatigue and improved performance compared to only performing the higher intensity task, and increased fatigue and reduced performance compared to only performing the lower intensity task. This agrees with our expected results, and with prior research on rotation (Kuijer, et al., 2004; Raina & Dickerson, 2009), as well as results from our first two studies (Chapters 2 and 3). Further, these results confirm that the two task conditions were distinct in terms of their physical workload.

Rotation frequency and task order influenced a few of the EMG measures, but the direction of these effects was inconsistent between genders, and these effects were not supported by any other measures. Though it was expected that less frequent rotation (i.e., 30 minutes vs. 15 minutes) would increase overall fatigue, this effect was not present in our results. It is likely that the low intensity loading periods did not allow for recovery from the higher intensity task, which does not follow our expectations that the low intensity loads would serve as active recovery periods and reduce fatigue accumulation (Bogdanis et al., 1996; Bond et al., 1991; Sairyo et al., 2003). This supports results from our first two studies, which also showed no effects of rotation frequency on fatigue (see Chapters 2 and 3). Prior work on repetitive upper extremity tasks, namely the Occupational repetitive action index (OCRA), implicitly assumes an effect of rotation frequency, in that rotation sequences containing longer duration tasks are given higher risk values (Occhipinti et al., 2005).

Regarding task order, we expected that starting with the low intensity load would serve as an active warm-up period and reduce fatigue compared to starting with the high intensity task. However, we did not see this effect in our results. Current research on task order has shown mixed results. Some prior research on rotation has shown an order effect, such that higher exertion ratings are given when starting a sequence with a more (vs. a less) demanding task (Raina & Dickerson, 2009), an effect also seen in our first study results (see Chapter 2). In addition, prior research has shown warm-up exercises can improve performance and increase endurance time (Bishop, 2003). However, other research on rotation shows no effect of task order (Keir, et al., 2011); this is in agreement with results from our second study (see Chapter 3), which showed effects of task order on either fatigue or performance. Further, the OCRA index assumes no effect of task order; Table 5 shows a ranking of the conditions from our results (based on RPD ratings), as well as suggested ranking according to the OCRA index. The ranks shown using the OCRA index are based on the description of the calculation in Occhipinti et al. (2005).

Table 5. Ranked conditions according to our results and the OCRA estimated risk. A lower rank indicates lower risk; ranks of tied conditions are shown as the mean of the tied positions.

	RPDs	OCRA
LLLL	1	1
LHLH	3.5	2.5
HLHL	3.5	2.5
LLHH	3.5	4.5
HHLL	3.5	4.5
HHHH	6	6

Several measures differed between genders, and which indicated males were more fatigued than females, a common finding when performing upper extremity tasks at comparable levels of effort relative to capacity (Avin et al., 2010; Hicks, 2001; Nussbaum et al., 2001); in this study, average effort level (i.e., lifting arms to perform task) for males was ~11% MVC (relative to shoulder flexion MVCs), and was ~13% MVC for females. This effect of gender also agrees

with results seen in our first study (see Chapter 2). Our results did not indicate any effects of condition on heart rate. Heart rate was likely affected by individual performance on the task, since increased work pace can lead to increased metabolic demands (Garg et al., 1978), which in turn leads to an increase in heart rate (Kroemer et al., 1997). Although a lower heart rate was expected for the less demanding task, there was also higher performance for this task, which could have countered the effects of the lower physical demands on heart rate. Further, though some effects of rotation vs. no rotation were seen in the EMG collected from the AD and MD, EMG measures were largely non-significant. A possible reason for this is that EMG data was only available during low-level reference contractions, which were on average ~12% MVC (relative to shoulder flexion MVCs). EMG measures may not be sensitive to fatigue at exertion levels below 30% MVC (Movahed et al., 2011; Oberg, 1994; Sood et al., 2007; Yassierli & Nussbaum, 2008), possibly due to rotation of motor units, changing in firing rates, decruitment of motor units, and additional motor unit recruitment (Kamo, 2002; Westgaard & de Luca, 1999). Further, it is possible that although postures were controlled during each reference contraction, slight changes in posture may have affected muscle activation levels and masked subtle changes occurring due to fatigue (De Luca, 1997).

Several limitations of this study should be noted. The work involved simulated assembly tasks performed in a controlled laboratory setting. Though broadly this type of task occurs in many occupations (i.e., upper extremity tasks requiring fine motor control), the tasks used here may not be representative of actual occupational work. A further limitation is that performance on the tasks in this study can be largely influenced by motivation (Buddenberg & Davis, 2000), and participant motivation here likely was lower than that of actual workers. In addition, several constraints were placed on the study to facilitate implementation in a laboratory setting that may

affect the generalizability of results to actual work environments. A small sample of healthy young adults was used, and it is likely that older workers would respond differently to the fatiguing tasks (Avin & Frey Law, 2011; Deschenes, 2004; Kent-Braun et al., 2002; Merletti et al., 2002; Yassierli et al., 2007). Further, the study may have been underpowered due to the small sample size, and therefore could not detect what may be small effect sizes due to rotation frequency and task order. In addition, a compressed time period of 1 hour was used, therefore fatigue induced may not be representative of that experienced during a longer, more realistic, work shift. As well, this study focused on acute effects of fatigue within a work shift, and did not consider cumulative effects of day-to-day work, which may contribute to WMSD risk.

In summary, the current results indicate that, as expected, rotation reduced/increased fatigue compared to only performing the higher/lower intensity task. However, for this specific task and exertion levels, there did not appear to be any benefits towards increased rotation frequency, nor were there any benefits of starting with a lower exertion task. Further, neither parameter affected performance on the task. Overall, these findings do not provide conclusive information regarding the effects of rotation frequency or task order. It is possible that effects were present but not detected due to their small effect sizes or due to the constrained nature of the task. Therefore further work is needed to assess these effects under more realistic situations, e.g., with longer duration tasks and using a larger, more diverse, sample.

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Chapter 5: Conclusions and recommendations

Rotation, a commonly used administrative control involving the rotation of workers between tasks, is frequently used to reduce the risk of work-related musculoskeletal disorders (WMSDs). However, despite its widespread use, there is limited evidence that rotation is effective in reducing WMSD occurrence. Existing research indicates inconsistent effects of rotation, specifically regarding effects on physical demands and physical exposure variation. There are many parameters of rotation that may contribute to these inconsistences, including which tasks are included in a rotation schedule, how frequently workers rotate between tasks, and the order in which tasks are performed. The focus of this research was to evaluate effects of rotation, and specific effects of these parameters, on fatigue and performance. These effects were evaluated in three separate studies under a variety of simulated occupational work conditions (static and dynamic, whole body, and upper extremity) with varying levels of experimental control. Within each study, rotation occurred between a higher and lower intensity level of the same task; this was performed in order to simulate tasks with limited exposure variation, a common occurrence in occupational work (Aptel et al., 2008; Jonsson, 1988; Keir et al., 2011; Wells et al., 1989). As such, the primary purpose of this research was to determine for rotation schedules that include tasks that load the same muscle(s): 1) if rotation is effective in reducing muscle fatigue; 2) effects of rotation on task performance; and 3) specific effects of rotation frequency and task order on fatigue and performance.

Effects of rotation vs. no rotation

Results indicated that rotation was beneficial in reducing fatigue compared to only performing a higher intensity task, but increased fatigue compared to only performing a lower intensity task; this effect was consistent between all three tasks studied and was expected based on previous 90

studies on rotation (Kuijer et al., 2004; Raina & Dickerson, 2009). Effects of rotation on performance were less consistent between the three studies. In Chapter 2, involving static shoulder abduction, rotation improved performance compared to performing only the higher intensity task, and reduced performance compared to only performing the lower intensity task. Some similar effects were seen in Chapter 3, involving lifting tasks, however other results indicate that rotation in general reduced performance compared to either of the no-rotation conditions. Further, for Chapter 4, involving assembly tasks, there were no effects of rotation on task performance. These results suggest that for Chapter 2, performance on the abduction task was strongly related to fatigue, while the relationship was more complex for the lifting and assembly tasks in Chapters 3 and 4. It is likely that for the tasks involved in Chapters 3 and 4, motivation played a large factor in task performance, which may have masked changes in performance due to fatigue and/or rotation effects.

Effects of rotation frequency and task order

The results from all three studies indicate few substantial, and also somewhat inconsistent, findings regarding rotation frequency and task order. With respect to rotation frequency, we expected that more frequent rotation would reduce fatigue, but may impair task performance. This expectation was based on prior work showing active recovery periods can reduce accumulated fatigue through increased blood flow (Bogdanis et al., 1996; Bond et al., 1991; Sairyo et al., 2003), which increases dispersal of H⁺ ions that accumulate as a result of the breakdown of lactic acid. In these studies, we expected the lower intensity loads to act as active recovery, and that more frequently appearing recovery periods would reduce accumulated fatigue. However, contrary to our expectations, there were no benefits to increased rotation frequency in terms of reducing observed fatigue in any of the studies. Regarding effects on task

performance, we expected increased rotation frequency would impair task performance, as seen in prior research on learning/forgetting effects when rotating between tasks (Allwood & Lee, 2004; Kher et al., 1999). Though this effect was seen in Chapter 2 for one performance measure, it was not consistent between measures for Chapter 2, nor was this effect seen in any performance measure from either Chapter 3 or 4.

With respect to task order, we expected that starting with the lower intensity task would reduce fatigue compared to starting with the higher intensity task. This effect has been seen in prior work on rotation (Raina & Dickerson, 2009), and follows an expectation that low intensity loads would act as a prolonged warm-up period, which can improve performance and increase endurance time (Bishop, 2003). However, only moderate effects of task order were seen, and effects were inconsistent between studies. In Chapter 2, results followed our expectations, in that such that starting with the less demanding task reduced fatigue compared to staring with the more demanding task. This effect was seen through several measures, though none reached statistical significance. The opposite effect was seen for some peak discomfort ratings from Chapter 3, in which peak discomfort was higher when starting with the less demanding task; however, this effect was not seen in mean discomfort ratings. Further, there were no effects of task order on fatigue measures from Chapter 4, which agrees with another prior study on rotation in which there was no effect of task order (Keir, et al., 2011), nor were there any effects of task order on any performance measure in any of the three studies. Though the task order effects seen in Chapter 2 were most consistent, it is likely that these effects were inflated due to the highly constrained nature of the task, and may thus not be practically relevant, as they were not supported by results from the more dynamic, realistic tasks assessed in Chapters 3 and 4.

Research limitations and future directions

There are several limitations of this work that could be addressed in future research. In terms of methodology, the primary limitation involved the use of surface EMG to measure fatigue. Each of the studies involved relatively low-level exertions from which EMG was collected; it has been suggested that EMG may not be sensitive to fatigue at these levels (Movahed et al., 2011; Oberg, 1994; Sood et al., 2007; Yassierli & Nussbaum, 2008). Further, the use of reference contractions during the dynamic tasks to collect EMG may have reduced the reliability of the EMG measurements, as it was difficult to ensure that participants were exactly replicating the postures during each exertion. Overall our results indicate that discomfort ratings were most sensitive to fatigue, in agreement with prior literature (Sood et al., 2007; Nussbaum et al., 2001). Future work should consider other fatigue measurement techniques, such as strength decline assessed through electrically evoked maximal forces, which can improve accuracy of strength measures over traditional voluntary contractions (Enoka et al., 2011).

Further limitations involve the highly controlled nature of the tasks and the constraints set to facilitate implementation in a laboratory setting; these constraints may limit generalizability of our results to actual occupational work. Constraints included the use of a small sample size of only healthy young adults, the use of a compressed time period, as well as the focus on only acute fatigue experienced within a work shift. These studies may have been underpowered due to the small sample size (e.g., many effect sizes from Chapter 2 ranged from 0.09 to 0.14 based on η^2 calculations for the main effect of condition; a larger sample size may have resulted in larger effects). Future research could consider using an older worker population, as outcomes may differ between our participant sample in their responses to the fatiguing tasks (Avin & Frey Law, 2011; Deschenes, 2004; Kent-Braun et al., 2002; Merletti et al., 2002; Yassierli et al.,

2007), as well as in their motivation towards performing the tasks, compared to older, more experienced workers. Further, future work could focus on effects of longer duration tasks and/or cumulative effects of work across multiple days, which may be more representative of actual work shifts. Further, the task performance measures used in these studies were chosen based on the need to precisely measure changes in performance during the compressed time period of the task, therefore the exact performance outcomes may not be generalizable to performance on actual work tasks.

Other possible avenues for future research include the consideration of how different the intensity levels need to be for rotation to be effective in reducing fatigue. Our results were limited by the specific task intensities used for each study; the task levels were chosen based on prior research and on pilot testing, and to ensure that the tasks could be completed for the 60 minute work period for each study. Future research could vary the difference in intensity levels of the included tasks, and assess any changes in rotation outcomes. Another possible consideration for future work is the assessment of effects of rotation on psychosocial factors, for example though collection of ratings using the NASA Task Load Index or the Subjective workload assessment technique. Previous work has shown improved job satisfaction (Dawal et al., 2009), improved worker motivation (Muramatsu et al., 1987), reduced monotony (Aptel, et al., 2008), and increased pride in work (Rissen et al., 2002) with rotation. These outcomes may also be influenced by specific parameters of rotation, which have not yet been analyzed.

Overall conclusions

In summary, the findings from these studies suggest that in workplaces that involve tasks that load the same muscle(s), but vary in intensity level, rotation between them can be beneficial in

reducing fatigue for some workers, but may increase fatigue for other workers. Further, rotation may be beneficial in improving performance, but this effect may depend on the types of tasks involved and for some, rotation may impair performance. The overall findings also indicate that rotation frequency and task order may affect some rotation outcomes, but current results are inconsistent and do not yet show definitive effects, thus the practical relevance of these effects remains unclear.

As such, practical recommendations for implementing rotation can be inferred from these results, though further work is needed to validate these findings. Specific recommendations are as follows:

- Rotation can reduce fatigue when included tasks load the same muscle(s), but vary in intensity level,
- Consideration should be given to the type of task included in rotation schedules, as it is possible for rotation to impair performance, and
- The influence of rotation frequency and task order on these outcomes may not be practically relevant.

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Appendices

Appendix A: Informed Consent Form

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY

Informed Consent for Participants In Research Projects Involving Human Subjects

Title of the Research Study

The Effect of Job Rotation on Fatigue and Performance.

Investigators

Leanna M. Horton 422-2067 - Department of Industrial and Systems Engineering Maury A. Nussbaum, Ph.D. 231-6053 - Department of Industrial and Systems Engineering Mike J. Agnew, Ph.D. 231-0083 - Department of Industrial and Systems Engineering

I. Purpose of this Study

The purpose of this study is to conduct laboratory-based simulations of industrial work tasks under various job rotation schedules. During these simulated tasks, we will be able to use measures to describe the physical demands experienced by workers. The goal of this research is to gain an understanding of the effect of rotating between tasks on muscle fatigue and on performance and provide recommendations for industries in terms of using job rotation to reduce injury risk.

II. Procedures

Approximately 40 adult participants will participate in this study, which will take place in the Industrial Ergonomics and Biomechanics Lab in the Department of Industrial and Systems Engineering. Upon arriving, you will be briefed of the study protocol, asked if you have any questions, and asked to sign this informed consent form. Prior to the experiment, several non-invasive sensors may be placed on your body using double-sided tape to measure the level of activity of certain muscles. At the start of the experiment, you will be given practice performing the simulated industrial tasks until you feel you can do them comfortably. These tasks may include shoulder exertions, box lifting, or peg placement. In the main portion of the experiment, you will perform the tasks you just practiced while measures of physical demands are collected. These measures may include muscle activity, force output, heart rate, postural sway, and your perceptions of the physical demands in different body regions. The experiment is expected to take approximately 2 hours to complete.

III. Risks

The risks involved in this study are minimal. The overall physical exertion required during this experiment is not significantly larger than that required during common work tasks. However, since you are doing moderate physical exertions, there is a small risk of experiencing muscle strain and discomfort. After the experiment, you may feel some residual muscle soreness for up to about 48 hours.

IV. Benefits

You will receive no direct benefit from participating in this study. The scientific community will benefit through the additional information that is expected to result from the completion of this study. This information will contribute to designing safer jobs for industrial workers.

No promise or guarantee of benefits has been made to encourage you to participate.

V. Extent of Anonymity and Confidentiality

The results of this research study may be presented at meetings or in publications. Your identity will not be disclosed in those presentations. All participants in this experiment will be identified based only on their unique identifying number. Only the investigators and students involved in the research will have access to these identifying numbers.

VI. Compensation

You will be paid \$10/hour for your participation in this study and a \$10 bonus after completion of all sessions.

VII. Freedom to Withdraw

Your participation in this research study is voluntary. Refusal to participate will involve no penalty or loss of benefits to which you are otherwise entitled. You are free to withdraw from the study at any time without penalty.

VIII. Approval of Research

This research project has been approved, as required, by the Institutional Review Board for Research Involving Human Subjects at Virginia Polytechnic Institute and State University.

IX. Subject Responsibilities

I voluntarily agree to participate in this study.

X. Subject's Permission

I have read and understand the Informed Consent and conditions of this project. I have had all my questions answered. I hereby acknowledge the above and give my voluntary consent:

Participant's signature

Experimenter's signature

Should I have any pertinent questions about this research or its conduct, and research subjects' rights, and whom to contact in the event of a research related injury to the subject, I may contact:

Principal Investigator: Maury Nussbaum, PhD	231-6053	nussbaum@vt.edu
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Date

Date
Co-Investigator:	Michael Agnew, PhD	231-0083	mjagnew@vt.edu
<u>Chair, IRB</u> :	David M. Moore, DVM	231-4991	moored@vt.edu

Appendix B: MET Calculations

Calculations of metabolic equivalent (MET) were performed to describe the metabolic demands of the lifting tasks, with MET defined as the ratio of work metabolic rate to resting metabolic rate. Equations shown here are in three steps: 1) to calculate the metabolic rate for the tasks, 2) to calculate the resting metabolic rate for each participant (estimated here using basal metabolic rate), and 3) to calculate MET from these data. These calculations were only performed for study 2, as metabolic demands for lifting tasks can be estimated using prediction models.

STEP 1: Calculate work metabolic rate – based on Garg's metabolic prediction models (Garg et al., 1978)

Stoop lift $\Delta E = 0.01 * [0.325 * BW * (0.81 - h_1) + (1.41 * L + 0.76 * S * L) * (h_2 - h_1)] \text{ kcal/lift}$

Stoop lower $\Delta E = 0.01 * [0.268 * BW * (0.81 - h_1) + 0.675 * L * (h_2 - h_1) + 5.22 * S * (0.81 - h_1)] \text{ kcal/lower}$

Standing $\Delta E = 0.024 * BW$ kcal/min

Where:

 ΔE = metabolic rate; kcal/lift (stoop lift), kcal/lower (stoop lower), or kcal/min (standing) BW = body weight (kg) h_1 = vertical height from floor (m) at start of lift (end of lower) = 0.15 for all participants h_2 = vertical height from floor (m) at end of lift (start of lower) = 0.68 to 0.80m S = 1 for males, 0 for females

Total metabolic rate = 6 lifts/minute * kcal/lift + 6 lower/minute * kcal/lower + kcal/min (standing)

<u>Step 1 results:</u> Mean metabolic rate for conditions (averaged over all participants) LLLL: 3.96 kcal/min Rotation: 4.27 kcal/min HHHH: 4.57 kcal/min

STEP 2: Calculate basal metabolism (BM) for all participants - based on ISO 8996 (International Organization for Standardization, 1990)

 $BM \text{ (male)} = \frac{0.04833*(66.473+13.7516*BW+500.33*HT-6.755*A)}{0.00714*BW^{0.425}*(HT*100)^{0.725}} \text{ Watts}$

$$BM \text{ (female)} = \frac{0.04833*(655.0955+9.5634*BW+184.96*HT-4.6756*A)}{0.00714*BW^{0.425}*(HT*100)^{0.725}} \text{ Watts}$$

Where:

BW = body weight (kg) HT = height (m) A = age (years)

1 Watt = 0.85985 kcal/hour Basal metabolic rate (kcal/hour) = BM (in Watts) * 0.85985 kcal/hour

Sample calculation for male: Body weight = 82.6 kg Height = 1.91 m Age = 22 years

 $BM (male) = \frac{0.04833 * (66.473 + 13.7516 * 82.6 + 500.33 * 1.91 - 6.755 * 22)}{0.00714 * 82.6^{0.425} * (1.91 * 100)^{0.725}}$

= 45.97 Watts * 0.85985 = 39.52 kcal/hour

Sample calculation for female: Body weight = 65.8 kg Height = 1.68 m Age = 22 years

 $BM \text{ (female)} = \frac{0.04833 * (655.0955 + 9.5634 * 65.8 + 184.96 * 1.68 - 4.6756 * 22)}{0.00714 * 65.8^{0.425} * (1.68 * 100)^{0.725}}$

= 41.27 Watts * 0.85985 = 35.48 kcal/hour

<u>Step 2 results</u>: Mean basal metabolic rate for males = 39.86(0.23) kcal/hour females = 35.80(0.87) kcal/hour

STEP 3: Conversion to metabolic equivalent (MET)

 $MET = \frac{Work metabolic rate}{Basal metabolic rate}$

<u>Step 3 results:</u> Mean MET for conditions (averaged over all participants) LLLL: 6.23 Rotation: 6.71 HHHH: 7.19

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Appendix C: %HRR Figures

%HRR data is shown below for Chapters 3 and 4. For the figures showing data from all participants, %HRR was averaged across each work period. For the figure showing data from a single participant, %HRR was calculated continuously during each work period, and the plotted lines show the continuous data over the 60 minutes during each session (a 100 point moving average was applied to smooth the data).



Chapter 3 (averaged across all participants):

Chapter 3 (single participant):



Chapter 4 (averaged across all participants):

