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Effects of rotation frequency and task order on localised muscle fatigue and performance during repetitive static shoulder exertions

Leanna M. Horton, Maury A. Nussbaum* and Michael J. Agnew

Industrial and Systems Engineering, Virginia Tech, 250 Durham Hall (0118), Blacksburg, VA, USA

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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 rotating between tasks that load the same muscle group. Twelve participants completed six experimental sessions during which repetitive static shoulder abduction tasks were performed at two exertion levels for one hour either with or without rotation. Compared to only performing a higher or lower exertion task, rotating between the two tasks decreased and increased fatigue, respectively. Increasing rotation frequency adversely affected task performance, and task order had a minor effect on muscle fatigue. These rotation parameters may be important considerations when implementing rotation in the workplace.

Practitioner Summary: Rotation is widely used and assumed to reduce the risk of WMSDs, yet little research supports that it is effective in doing so. Results here show that specific aspects of a rotation scheme may influence muscle fatigue and task performance, though further research is needed under more realistic task conditions.

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

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 (Bureau of Labor Statistics 2011). The costs associated with occupational injuries have been estimated at up to $150 billion in the USA (Anderson and Budnick 2009), and of these costs, overexertion and repetitive motion cases account for around 30% (Liberty Mutual Research Institute for Safety 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 USA 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 non-neutral working postures (Hinnen 1992, Kuijer *et al.* 1999), cardiovascular load (Kuijer *et al.* 1999) and 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, however, 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 (Jonsson 1988, Wells *et al.* 1989) or WMSD rates (Aptel *et al.* 2008).

*Corresponding author. Email: nussbaum@vt.edu

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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 (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). 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 would seem 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, few studies have analysed the effect of different within-day rotation frequencies on physical demands. One such study was performed using a mathematical modelling approach, with the conclusion that workers should rotate every 1–2 hours (Tharmmaphornphilas and Norman 2004). Another recent study compared 1- and 2-hour rotation frequencies, finding reduced discomfort when rotating every hour compared to every two hours (Marshall 2006). Workers on manufacturing assembly lines often rotate every two hours (Wells *et al.* 1989, Jorgensen *et al.* 2005, Aptel *et al.* 2008), 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 1–1.5 hours (Muramatsu *et al.* 1987).

The effect of task order, or the sequence in which tasks are performed, is another potentially important aspect of a rotation scheme. Raina and Dickerson (2009) examined rotating between repetitive shoulder flexion and abduction tasks, finding that perceived 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 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. 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 impair task performance (Kher *et al.* 1999, Allwood and Lee 2004, Azizi *et al.* 2010). 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 on muscle fatigue and task performance. 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 emphasised localised muscle fatigue, due to its potential importance as a risk factor for WMSD development (Winkel and Westgaard 1992, Dugan and Frontera 2000, Allison and Henry 2002, Gorelick *et al.* 2003, Weist *et al.* 2004, Granata and Gottipati 2008), 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 hypothesised that rotating more frequently would reduce fatigue but have adverse effects on performance, and that starting with a lower exertion task would be less fatiguing and have higher performance versus starting with a higher exertion task. Since previous evidence shows that fatigue and performance can differ between genders (e.g. Avin *et al.* 2010, Endo and Kawahara 2011), a secondary purpose was to explore whether these effects of rotation were modified by gender.

2. Methods

2.1. *Participants*

A convenience sample of 12 participants (gender balanced) was recruited from the local community. Mean (SD) age, stature and body mass for males were 22.5 (1.9) years, 1.8 (0.07) m and 79.2 (2.9) kg, respectively, and for females were 23.0 (1.7) years, 1.6 (0.05) m and 54.0 (3.0) 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.

2.2. *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). During these repetitive abductions, participants were asked to match a fixed target moment. Three levels of *rotation frequency* were used, including no rotation, rotating every 30 minutes (Rotate 30), and rotating every 15 minutes (Rotate 15). Shoulder abductions were performed at two exertion levels, which were 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 six experimental sessions, all on separate days, with at least two days between each to minimise 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 × 6 balanced Latin squares (one for each gender).

2.3. *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). Participants were instructed to exert maximally against a padded fixture while keeping the hand relaxed (i.e. in a loose fist), 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

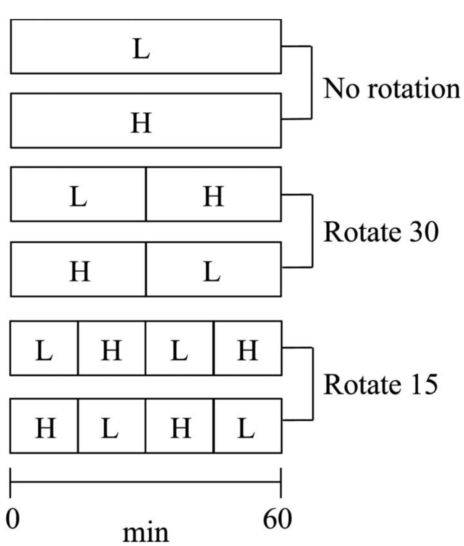

Figure 1. Six experimental conditions (‘L’ denotes the lower exertion task, ‘H’ denotes the higher exertion task), involving all combinations of three levels of rotation frequency (shown on right) and two levels of task order (Start L vs. Start H).

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.

During each experimental session, participants initially performed 20 minutes of warm-up exercises and practice of the experimental tasks. Warm-up exercises included shoulder abduction exercises with and without a hand-held weight (amount of weight depended on participants' strength); all participants completed the same number of warm-up exercises. After a brief rest, they completed three baseline 10-second static reference contractions at 22.5% MVC (mean of 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, which were exerted against the dynamometer (also using the same posture as the MVCs) over a 60-minute work period (see Figure 3 for an overview of activities). The tasks followed a 30 second cycle time with a fixed duty cycle of 0.33 (10 second work, 20 second rest) at either the Lower or Higher exertion levels. Over the 60-minute 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 were provided (Figure 2). The square-wave appeared the same between participants and exertion levels to reduce confounds in visual feedback quality, 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 right arm into a relaxed, hanging posture at their side.

Over the 60-minute work period, reference contractions, as described above, were completed every 15 minutes (Figure 3). Both objective and subjective measures of fatigue were collected during the reference contractions and work period, respectively using electromyographic (EMG) activity and ratings of perceived discomfort (RPDs). Shoulder moments were recorded continuously (as described above), along with EMG activity of the middle deltoid. Electromyographic was obtained using pre-gelled Ag/AgCl electrodes placed 2 cm apart over 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 to 500 Hz, and sampled at 1024 Hz. Ratings of perceived discomfort were collected every five

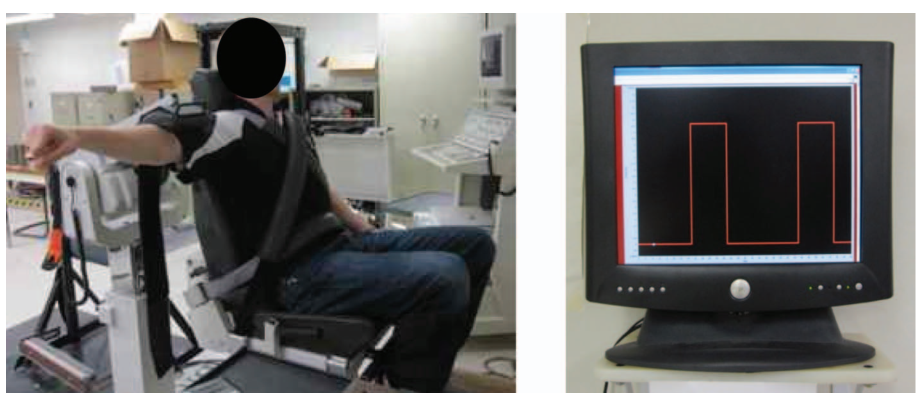

Figure 2. Posture used for shoulder abduction task (left) and visual feedback given during the task (right).

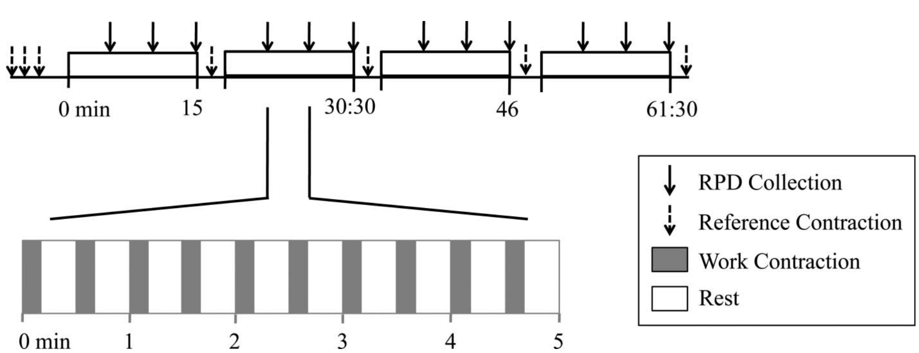

Figure 3. Overview of experimental procedures.

minutes during the work period (see Figure 3) 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), which was continuously visible to participants.

2.4. Data processing and dependent measures

Three EMG-based measures of fatigue were obtained from data collected during each exertion. Specifically, a six-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 from the raw signal after full-wave rectification, low-pass filtering (Butterworth, 3 Hz 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 raw EMG at each one-second interval with a 50% overlapping Hamming window. The third, Dimitrov Spectral Index (DSI), was calculated using 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 Amp, MnPF, and DSI were normalised to the corresponding mean values obtained from the baseline reference contractions, and were averaged over the six-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, Potvin and Bent 1997, Nussbaum 2001), and DSI values were expected to increase with fatigue (Dimitrov *et al.* 2006). Fatigue was also assessed from RPDs, specifically using the mean and peak (i.e. maximum) ratings over each 60-minute trial.

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

Three measures of performance were derived, based on six-second windows (as above) of moments collected during each exertion. First, moment fluctuations (MFs) were determined as the coefficient of variation (SD/mean) of the moment output (Christou and Carlton 2002, Tracy and Enoka 2002). Second, peak error (PE) was calculated as the maximum difference between the generated and target moments. Third, 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, $r = 0.2 \times$ 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). Peak error was used to represent the worst performance during the task (due to the practical relevance of single significant errors), while MF and SampEn represent overall errors during each window. Increases in MF, PE and SampEn 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. Electromyographic and performance measures were available from both the work period (repetitive exertions) and the reference contractions. All of these dependent measures were calculated across the available data from a given condition (i.e. 60 minute of repetitive abductions or four reference contractions). To assess fatigue accumulation, one approach is to take the integral of a measure over the duration of the task (here, 60 minutes). However, since each of the experimental conditions had the same duration, the integral is equivalent to the product of the mean and duration. Therefore, mean values of each dependent measure were used to represent the accumulation of fatigue (or the effects of fatigue).

2.5. Statistical analysis

Initially, a multivariate analysis of variance (MANOVA, using Wilks' Lambda) was conducted, to assess the effects of condition (six levels) on the set of dependent measures. In the MANOVA, gender and presentation order (of the six conditions) were included as blocking variables. Subsequently, one-way, repeated-measures analyses of variance (ANOVAs) were performed separately to assess the effects of the same independent variables on each of the dependent measures. When there was a significant univariate 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; i.e., [LHLH + HLHL] vs. [LLHH + HHLL]) and (4) between Start L vs. Start H (task order; i.e., [LHLH + LLHH] vs. [HLHL + HHLL]). 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 $p < 0.05$.

3. Results

Initial MANOVA revealed significant effects of condition ($p < 0.0001$), gender ($p < 0.0001$) and their interaction ($p = 0.015$). There were also significant univariate main effects of condition on many of the dependent measures (Table 1), and which are explored more specifically below.

3.1. Effects of rotation vs. no rotation

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.

3.2. Effects of rotation frequency and task order

Rotation frequency influenced some dependent measures, namely RPDs from the upper back and PE. 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, 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 and increased mean discomfort ratings for the shoulder and upper arm.

3.3. Effects of gender

Gender had a significant main effect on EMG Amp. Overall, EMG Amp was lower among females in both the work period ($p = 0.021$) and reference contractions ($p = 0.078$), suggesting less fatigue for females. Gender differences for EMG 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 4). The effect of task order also differed between genders (Figure 5). 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.

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 6). Among males, MFs were

Table 1. Summary of the main effects of condition on each dependent measure and results from post-hoc contrasts when the main effect was significant.

			Condition		LLLL vs. rotation		HHHH vs. rotation		LLLL vs. HHHH	Rotation frequency			Task order		
Measure			*p*	Rotation	LLLL	*P*	HHHH	*p*	*p*	Rotate 15	Rotate 30	*p*	Start L	Start H	*p*
EMG	Work	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)	0.39	0.96 (0.16)	0.96 (0.20)	0.88
		MnPF	0.23	0.97 (0.03)	0.98 (0.03)	–	0.95 (0.04)	–	–	0.97 (0.04)	0.97 (0.03)	–	0.98 (0.03)	0.97 (0.04)	–
		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)	0.25	1.14 (0.15)	1.21 (0.18)	0.096
	Reference	Amplitude	0.16	0.90 (0.14)	0.96 (0.12)	–	0.85 (0.13)	–	–	0.90 (0.15)	0.89 (0.13)	–	0.92 (0.13)	0.87 (0.16)	–
		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)	0.99	0.98 (0.03)	0.97 (0.04)	0.27
		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)	0.24	1.15 (0.18)	1.20 (0.21)	0.19
RPDs	Mean	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)	0.82	1.39 (1.15)	1.67 (1.22)	0.091
		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)	0.39	1.15 (1.09)	1.44 (1.21)	0.076
		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 (0.69)	0.036*	0.58 (0.56)	0.59 (0.66)	0.93
	Peak	Shoulder	<0.0001*	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)	0.54	3.04 (2.16)	2.90 (1.90)	0.56
		Upper arm	<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)	0.34	2.34 (1.93)	2.53 (1.92)	0.51
		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)	0.035*	1.60 (1.41)	1.28 (1.30)	0.23
Performance	Work	MF	0.42	0.021 (0.0036)	0.020 (0.0056)	–	0.020 (0.0046)	–	–	0.020 (0.0033)	0.020 (0.0040)	–	0.020 (0.0038)	0.020 (0.0035)	–
		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)	0.91	2.33 (0.18)	2.36 (0.17)	0.29
		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)	0.064	0.44 (0.30)	0.49 (0.38)	0.33
	Reference	MF	0.86	0.018 (0.0036)	0.018 (0.0035)	–	0.018 (0.0040)	–	–	0.018 (0.0032)	0.018 (0.0040)	–	0.018 (0.0040)	0.018 (0.0032)	–
		SampEn	0.58	2.32 (0.23)	2.31 (0.26)	–	2.36 (0.26)	–	–	2.33 (0.25)	2.32 (0.21)	–	2.32 (0.22)	2.33 (0.24)	–
		PE	0.55	0.18 (0.14)	0.16 (0.10)	–	0.18 (0.16)	–	–	0.17 (0.11)	0.19 (0.17)	–	0.17 (0.11)	0.19 (0.16)	–

Note: Significant effects are indicated by the symbol '*', and values are means (SD). Increases in EMG Amp and DSI and decreases in EMG MnPF reflect muscle fatigue, while increases in MF, PE and SampEn represent decreased task performance. 'L' denotes the lower exertion task, 'H' denotes the higher exertion task and each letter represents one 15-minute work period, such that 'LLLL' is the lower exertion task without rotation and 'HHHH' is the higher exertion task without rotation.

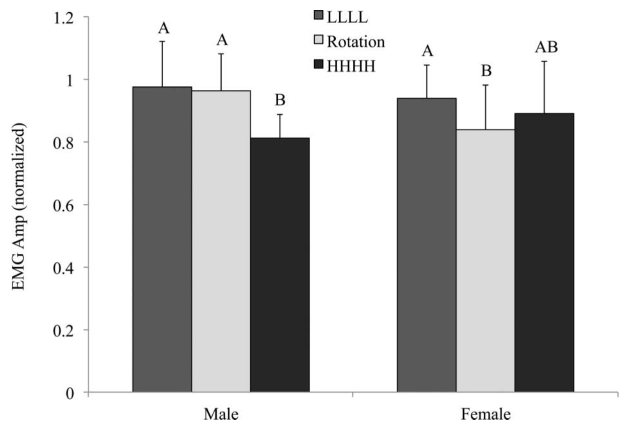

Figure 4. Gender differences in the effects of rotation vs. no-rotation on normalised EMG Amplitude (Amp) during the reference contractions. Within each gender, values not having the same letter are significantly different. Error bars indicate SDs.

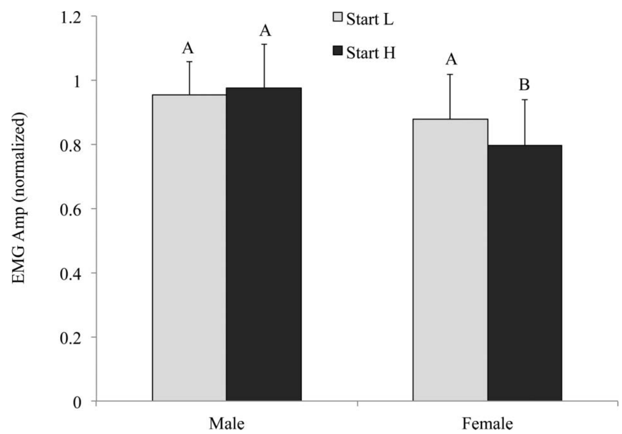

Figure 5. Gender differences in the effect of task order on normalised EMG Amplitude (Amp) during the reference contractions. Within each gender, values not having the same letter are significantly different. Error bars indicate SDs.

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.

4. Discussion

4.1. Effects of rotation vs. no rotation

In this study we investigated the effects of rotation, specifically rotation frequency and task order, on localised 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 exertion task, and increased fatigue and reduced performance compared to only performing the lower exertion task. These effects were evident through both objective and subjective measures of fatigue (Table 2), and similar effects have been reported in prior studies on rotation (Kuijer *et al.* 2004, Raina and Dickerson 2009).

4.2. Effects of rotation frequency and task order

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 and allow for increased dispersal of lactic acid accumulation, thus reducing fatigue (Bond *et al.* 1991, Bogdanis *et al.* 1996, Sairyo *et al.* 2003). 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.

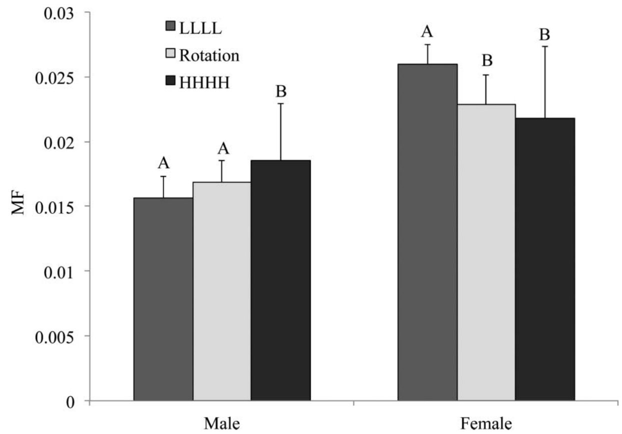

Figure 6. Gender differences in the effects of rotation vs. no-rotation on moment fluctuations (MFs) during the work period. Within each gender, values not having the same letter are significantly different. Error bars indicate SDs.

Table 2. Summary of study outcomes.

	Fatigue				Performance		
	EMG Amp	EMG MnPF	EMG DSI	RPDs	MF	SampEn	PE
Rotation vs. no rotation	Yes	Yes	Yes	Yes	Mixed – G	Yes	Yes
Rotation frequency	No	No	No	Mixed – M	No	No	Moderate
Task order	Mixed – G	No	Moderate	Mixed – M/Moderate	No	No	No

Note: 'Yes' indicates a significant effect (during reference contractions, work periods or both); 'No' indicates no significant effects; 'Moderate' indicates a non-significant trend; 'Mixed – G' indicates mixed effects between genders; 'Mixed – M' indicates mixed results across measures (i.e. between different body parts).

Here, however, this expected effect was only seen in discomfort ratings from the upper back (Table 2). Ratings from the upper back were consistently lower than ratings given for other body parts, suggesting that the upper back was not as affected by task demands, and which may limit the relevance of this result. 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, PEs were higher in the more rapid 15-minute rotation conditions, though similar effects were not seen for the other performance measures (Table 2). 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. This difference, though not significant, was found in both EMG DSI values and subjective ratings of discomfort (Table 2), 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.

4.3. Effects of gender

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, and seen here through reduced PEs and SampEn. 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 MF. 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 MF.

Males and females also responded differently to the experimental conditions in terms of MF 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 (Enoka and Stuart 1992, Hunter *et al.* 2004). 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, Brown *et al.* 2010, Mehta and Agnew 2011). 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 emphasising 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.

4.4. Limitations

Several limitations were present in this study that should be noted. 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 examined. Exertions levels were typically below 30% MVC, for which EMG may not be sufficiently sensitive to fatigue (Oberg 1994, Sood *et al.* 2007, Yassierli, Nussbaum 2008, Movahed *et al.* 2011). 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 since 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).

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 characterised as roughly static (e.g. light assembly), fatigue development during static and dynamic tasks can differ (e.g. Bakke *et al.* 1996, Masuda *et al.* 1999). Further, results from the current study may not generalise beyond the task parameters used (i.e. efforts levels, duty cycle, and cycle time). The specific parameters used were chosen based on pilot testing and prior research, such that the experimental tasks would be fatiguing, within the ability of most participants to perform for a 60-minute work period, and also that the two exertion levels would be distinct in terms of their physical demands.

Another possible limitation is that our measures of performance may have been affected by participant motivation. The task required precise motor control and prolonged attention to exerted moments and, unlike what is likely present in actual work environments, there was no penalty or reward for higher or lower performance; thus it is likely that our participant motivation was less 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 generalised to performance on more complex occupational tasks, since the present task was comparatively quite simple. Hence, generalising 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 (Kent-Braun *et al.* 2002, Merletti *et al.* 2002, Deschenes 2004, Yassierli, Nussbaum *et al.* 2007, 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. Sample sizes within each gender were also relatively small, so interpretations regarding gender-related differences may be limited. To facilitate an efficient experiment, a 'compressed'work period of one 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.

4.5 Conclusions

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 exertion 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 on task performance. Some evidence was found for an effect of task order on fatigue development, supporting the practical recommendation that starting a work shift with a low-exertion 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 can 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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