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Adaptations to isolated shoulder fatigue during simulated repetitive work. Part II: Recovery

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ABSTRACT

The shoulder allows kinematic and muscular changes to facilitate continued task performance during prolonged repetitive work. The purpose of this work was to examine changes during simulated repetitive work in response to a fatigue protocol. Participants performed 20 one-minute work cycles comprised of 4 shoulder centric tasks, a fatigue protocol, followed by 60 additional cycles. The fatigue protocol targeted the anterior deltoid and cycled between static and dynamic actions. EMG was collected from 14 upper extremity and back muscles and three-dimensional motion was captured during each work cycle. Participants completed post-fatigue work despite EMG manifestations of muscle fatigue, reduced flexion strength (by 28%), and increased perceived exertion (~3 times). Throughout the post-fatigue work cycles, participants maintained performance via kinematic and muscular adaptations, such as reduced gleno-humeral flexion and scapular rotation which were task specific and varied throughout the hour of simulated work. By the end of 60 post-fatigue work cycles, signs of fatigue persisted in the anterior deltoid and developed in the middle deltoid, yet perceived exertion and strength returned to pre-fatigue levels. Recovery from fatigue elicits changes in muscle activity and movement patterns that may not be perceived by the worker which has important implications for injury risk.

1. Introduction

Industrial workplaces are often characterized by low load, repetitive and prolonged tasks. Repetitive work, elevated arm postures, constrained workplaces and periods of sustained muscle activity act in combination as risk factors for developing shoulder pain and disorders, stressing the need to understand muscular and kinematic responses to these exposures (Hanvold et al., 2012; Ferguson et al., 2013; Nordander et al., 2009; Svendsen et al., 2004). Much of the evidence for the risk of repetitive injuries in the workplace comes from cross-sectional and longitudinal epidemiological studies, making it difficult to characterize causal relationships. Understanding responses to repetitive work can become even more challenging as workers' functional capacities change with muscle fatigue.

Muscle fatigue can be defined as a combination of increased perceived effort and an eventual decline in force production ability (Enoka and Stuart, 1992). Muscle fatigue can be quantified through changes in muscle activity and maximum force output (Enoka and Duchateau, 2008). Quantifying the development of fatigue and variations in fatigue during workplace tasks is difficult. Workers are typically required to generate submaximal efforts, allowing tasks to be successfully completed even in the presence of fatigue-reduced muscle capacity. With fatigue, the force generating capacity of muscle is reduced, effectively increasing the relative demands of the task. A change in capacity would impact the maximal acceptable effort for a task, which is also dependent on the duty cycle, or the percentage of time a worker is actively engaged in the task, further emphasizing the effect of fatigue on workers (Potvin, 2012).

Repetitive work has been shown to impair recovery when rest opportunities within the day and between work shifts are inadequate (Elliott et al., 2008, 2009). Both muscle fatigue and recovery are time-dependent processes but each proceeds at a different rate (Lucidi and Lehman, 1992; Vollestad and Sejersted, 1988), with recovery statistically modeled to occur 10–15 times slower than the fatiguing process itself (Frey-Law et al., 2012). Long recovery times for fatigued muscles is especially relevant in the shoulder given the frequent demands placed on the postural and stabilizing muscles of the shoulder complex, specifically, the rotator cuff muscles (Karduna et al., 1996; Labriola et al., 2004). In an endurance study of the trapezius muscle, individuals exhibiting greater

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changes in muscle activity had longer endurance times than those with more uniform activity, suggesting that variability in load distribution may allow for recovery during a sustained exertion (Farina et al., 2008). Numerous multi-joint movement strategies are possible with the large range of motion of the shoulder and additional degrees of freedom from the elbow and forearm (Culham and Peat, 1993). In the upper extremity, the presence of muscle fatigue also impacts kinematics, such as scapulohumeral rhythm, scapular motion and glenohumeral range of motion (Endo et al., 2001; McQuade et al., 1998).

In the workplace the specific changes in both scapulothoracic and glenohumeral kinematics would be impacted by task design, as they are sensitive to the angle of humeral elevation during simple movements (Ebaugh et al., 2006a,b; Tsai et al., 2003). In more complex repetitive pointing tasks, participants maintained performance with strategies such as changing their inter-segmental movement timing and compensating for altered shoulder position by varying their elbow and wrist movements (Fuller et al., 2009, 2011). Changes in muscle activity have been assessed by variability and co-dependence between muscles and joints (Fedorowich et al., 2013). Several measures of variability in motion and muscle activity have been related to fatigue, experience, and pain; however, outcomes seem to be dependent on the specific tasks and variables measured (Fedorowich et al., 2013; Fuller et al., 2011; Madeleine et al., 2008a,b; Qin et al., 2014). Although these immediate responses to fatigue protocols have been examined, how these adaptations change over time remains unknown. Understanding the response over time will give insight into the changing demands of repetitive work.

This study is the second part of an investigation examining the immediate and prolonged kinematic and muscular responses to muscle fatigue during repetitive work. In the first paper (Tse et al., submitted), we examined the immediate response in the first eight minutes of "fatigued" work. The purpose of this paper was to focus on how the response of the shoulder complex changed over one hour of simulated repetitive work. We hypothesized that throughout the post-fatigue period, muscular and kinematic adaptations would occur to reduce the load on the fatigued muscles. We also hypothesized that kinematics and muscle activity would return to pre-fatigue values by the end of 60 work cycles after the fatiguing protocol.

2. Methods

2.1. Participants

Twelve right-hand dominant men (20–24 years, 76.5 ± 8.5 kg, 177.9 ± 6.8 cm), free from upper limb or shoulder pathologies within the last year, participated in this study. The Hamilton Integrated Research Ethics Board approved this study and all participants provided informed written consent. Participant information including age, mass, height, umbilicus height, and acromioclavicular height were recorded.

2.2. Protocol

Detailed methods are described in the companion paper (Tse et al., submitted) and are included in the supplementary files. In brief, participants performed 20 simulated, repetitive work cycles before and 60 identical work cycles after a fatiguing protocol. Each work cycle consisted of four tasks performed on a custom apparatus: (1) handle pull (2 kg, 10 repetitions), (2) cap rotation (6 revolutions – 3 clockwise, 3 counter-clockwise), (3) drill press (50% of maximum in the anterior axis, 10 s), (4) handle push (2 kg, 10 repetitions). Each work cycle was repeated every 60 s; participants were instructed to perform the tasks at their own pace within the 60 s. The tasks were chosen to simulate industrial tasks and specific durations were designed to create an 80–90% duty cycle. The fatigue protocol targeted the anterior deltoid and cycled between a static hold (60 s at 45° of glenohumeral flexion) and a dynamic task (20 repetitions of glenohumeral flexion from 0° to 90°) using 25% of their maximum isometric flexion strength. Participants repeated this cycle until one of two stoppage criteria were met: (1) verbal declaration of inability to continue, (2) failure to perform either task with adequate form despite verbal encouragement (Ebaugh et al., 2006a). To quantify fatigue and recovery throughout the protocol, a maximal flexion exertion (digital force gauge, Mark-10, NY, USA) and a static, submaximal 5-s exertion were performed at four time points (baseline, pre-fatigue, post-fatigue, post 60 work cycles). Surface EMG (Trigno, Delsys, Natick, MA, USA) was used to measure muscle activity from 14 muscles (primarily on the right side except where noted): anterior, middle and posterior deltoid, biceps brachii, triceps brachii, bilateral upper and lower trapezius, infraspinatus, latissimus dorsi, sternal and clavicular heads of pectoralis major, serratus anterior. A passive motion capture system using eleven 4-megapixel resolution cameras and 30 reflective markers placed on the upper extremity and trunk was used to track three-dimensional motion during the work cycles (Cortex v4.1.1.1408 and Raptor-4 cameras, Motion Analysis Corp., Santa Rosa, CA). EMG and kinematic data were recorded continuously for each 60 s work cycle. Participants were asked for their rating of perceived exertion (RPE) every second work cycle.

2.3. Data analysis

Work cycles were divided into the four constituent tasks with the handle push and handle pull tasks further divided into load and return phases. Only tasks 1, 3 and 4 were included in the analysis. Task 2 was included to increase the duty cycle and add a complex task above shoulder height; the cap rotation set-up did not include force or position data and was not analyzed. EMG data were linear enveloped (dual pass, 2nd order Butterworth filter, $f_c = 4$ Hz) and were normalized to maximal EMG from maximal voluntary exertions. Mean muscle activity and median absolute deviation (MAD) were calculated for each muscle in each task. Median absolute deviation (MAD) was calculated as a measure of variability in both muscle activity and joint angles (Bosch et al., 2012). Marker data were imported into Visual 3D (C-Motion, Germantown, MD, USA) and the following segments were modeled: pelvis, thorax, clavicle, scapula, humerus, forearm and hand. Local coordinate systems were computed in accordance with ISB recommendations and joint angles were calculated for each task (Wu et al., 2002, 2005). Joint angles were dual-pass filtered with a 2nd order Butterworth filter ($f_c = 10$ Hz). Mean and MAD were also calculated for each joint angle for each task. There were no significant differences between the last 8 pre-fatigue work cycles that were greater than 0.5% MVE or 1°, thus they were averaged to generate one pre-fatigue value for each variable. To evaluate the changes throughout the post-fatigue work-cycles, the mean of every second set of four work cycles was computed (Fig. 1). Using the reduced data set, one-way repeated measures ANOVAs were performed on the mean and MAD for each muscle and joint angle in each task. Preplanned comparisons were made between pre-fatigue and post-fatigue variables using Tukey's HSD tests. Effect sizes were calculated with Eta-squared (η^2) tests and are reported for significant variables. All statistical analyses used an alpha level of 0.05 (SPSS v20.0, IBM, NY, USA).

To assess changes in EMG frequency in the static reference contractions, a power spectral analysis was performed on the middle 3-s window for each muscle using a Fast Fourier Transformation and the median power frequency (MDF) was calculated (0.125 s