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Changes in movement variability and task performance during a fatiguing repetitive pointing task

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ABSTRACT

Changes in neuromuscular strategies employed with fatigue during multi-joint movements are still poorly understood. Studies have shown that motor variability of individual joints increases when performing upper limb tasks to fatigue, while movement parameters related to the task goal remain constant. However, how the inter-limb coordination and its variability change during specific movement phases with fatigue is still unclear. The aim of this study was to assess the effects of neck-shoulder fatigue on shoulder and elbow kinematic variabilities, shoulder-elbow coordination and its variability, and endpoint characteristics during different phases of a forward pointing movement. Nineteen healthy young adults continuously performed a repetitive pointing task until fatigue (Borg rating of 8/10). Changes in elbow-shoulder coordination through the movement were assessed using the continuous relative phase and statistical nonparametric mapping methods. At the end of the task, muscle fatigue was evidenced by significant increases in anterior deltoid (+13%) and biceps brachii (+30%) activity. Shoulder horizontal abduction, elbow flexion variability and shoulder-elbow coordination variability were increased with fatigue at different moments of the movement cycle (shoulder: during the first 17% and most of the second half movement, elbow: from 73% to 91%, coordination: almost the whole movement). However, movement timing errors and endpoint spatial variability were mostly preserved, even with fatigue. We showed that increased variability with fatigue is not only observed in the fatigued joint (shoulder), but also in the elbow and shoulder-elbow coordination, and may have a goal of preserving global task performance.

1. Introduction

Repetitive upper limb movements often cause neck/shoulder muscle fatigue, the manifestations of which may be used as markers for exposures of musculoskeletal disorders (MSDs) (Iridiastadi and Nussbaum, 2006; Winkel and Mathiassen, 1994). Muscle fatigue leads to reduced functional capacity and increased perception of task difficulty (Enoka and Stuart, 1992). In repetitive low-force tasks, fatigue is an ongoing process that develops in time and manifests by increased perceived effort (Jones and Hunter, 1983) and reduced maximal force generating capacity (Vollestad, 1997). The effects of low-force fatigue on a muscle's peripheral characteristics, such as increased activity amplitude (Bigland-Ritchie et al., 1986) and reduced median power frequency are also well documented (Beelen and Sargeant, 1991; Blangsted et al., 2005).

The way that low-force muscle fatigue affects multi-joint movements remains poorly understood. Several studies have reported decreased motion amplitudes at the fatigued joints compensated by changes in joints other than the local site of fatigue (Côté et al., 2002; Forestier and Nougier, 1998; Huffenus et al., 2006). Movement variability, defined as the variability in kinematic properties of movements (Newell and Corcos, 1993), has been linked to both fatigue and performance (Srinivasan and Mathiassen, 2012). Many studies showed that movement variability increased with fatigue even though subjects could still maintain performance (Fuller et al., 2011; Selen et al., 2007). Some aspects of inter-joint coordination change with fatigue even in the absence of change

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in endpoint variability (Fuller, 2011). Cowley and Gates (2017b) documented changes in peak joint angle velocity timing with fatigue. This group used principal component analysis (PCA) to explore how coordination is adjusted to fatigue (Cowley and Gates, 2017a). However, to our knowledge, no group has ever used both spatial and temporal parameters to study how fatigue affects coordination between two adjacent joints responsible for producing an upper limb task.

The way that coordination varies across repeated movements can be measured to assess coordination stability. The continuous relative phase (CRP) method assesses both spatial and temporal aspects of two linked joints' coordination. Using CRP, coordination variability has previously been shown to be related to injury risk (Daunoravičienė et al., 2017; Hamill et al., 2012; Trezise et al., 2011). In addition, in the lower limb, one study found a decrease in coordination variability with fatigue in sprinting (Trezise et al., 2011). However, the effect of fatigue on spatiotemporal characteristics of upper limb coordination variability has not been investigated so far. Moreover, in most studies cited above, movement variability and coordination were quantified either by using single descriptor variables summarizing the entire movement (e.g. range of motion, mean position) or by looking at a specific time point chosen arbitrarily during the movement (e.g. timing of peak velocity, end of the movement). Such data reduction methods lead to significant information loss when compared to time series comparisons (Pataky, 2010). The recent implementation of statistical mapping in biomechanics research allows the comparison of entire spatiotemporal waveforms between conditions (Nichols and Holmes, 2002; Pataky, 2012). Combining CRP and statistical mapping methods to study spatiotemporal coordination and coordination variability during the entire movement may help better understand the motor adaptation in the fatiguing multi-joint upper limb system.

The objectives of this study were to (1) assess the effects of repetitive motion-induced fatigue on shoulder and elbow kinematic variability, spatiotemporal inter-joint coordination and its variability as well as on global task performance during a pointing task, (2) examine the relationship between joint variability changes and coordination variability changes after fatigue. We hypothesized that performing a repetitive pointing task at shoulder height would increase shoulder and elbow joint movement variability, and that the two variabilities would be related. Based on recent findings (Cowley and Gates, 2017a; Trezise et al., 2011), we hypothesized that fatigue would lead to decreased shoulder-elbow coordination variability, and that there would be significant correlations between fatigue-related changes in joint angle variability and CRP variability.

2. Methods

2.1. Participants

Nineteen right-handed healthy young adults (10 men, 9 women; age = 28.6 ± 6.2 years; height = 169.5 ± 7.4 cm; body mass = 65.4 ± 8.7 kg) were recruited in this study. Participants were excluded if they had any self-reported neuro-musculoskeletal or cardiovascular impairments. All participants provided written informed consent prior to participation. The study was approved by the Research Ethics Board of the Centre for Interdisciplinary Research in Rehabilitation (CRIR) of Greater Montreal, and conducted in accordance with The Helsinki Declaration.

2.2. Experimental protocol

Participants performed a repetitive pointing task (RPT) at shoulder height while standing to induce shoulder muscle fatigue (Fig. 1). To guide the RPT, two cylindrical touch-sensitive and audible targets (length: 6 cm, radius: 0.5 cm Quantum Research Group Ltd.) were placed in front of the participant's midline, at shoulder height, at 100% (distal target) and 30% (proximal target) of upper limb length. To ensure that the entire arm moved in the horizontal plane at shoulder height, an elliptically-shaped mesh barrier was placed parallel to the ground under the elbow trajectory covered during the RPT. Participants were instructed not to touch it with any body part during the entire fatiguing protocol. Participants were instructed to maintain a rhythm of one movement per second by matching sounds of a metronome to those emitted when touching the targets. Participants were instructed to "not move their feet and perform the task for as long as possible". Their left arm rested on the side of the body during the whole RPT.

During the last 30 s of every minute that the task was performed, surface electromyography (sEMG) and kinematic data were recorded, at the end of which participants were asked to provide their rating of self-perceived neck/shoulder exertion using a Borg CR-10 scale (Borg, 1982). The stoppage criteria were either that: (1) participants reached or surpassed a score of 8 on the Borg CR-10 scale, or (2) participants felt that they could not continue the RPT, or (3) the arm could not be maintained above the barrier or (4) participants could no longer maintain the rhythm of one movement per second. Participants were unaware of these stoppage criteria. Feedback was provided when the elbow touched the barrier or participants mistimed the rhythm. Three consecutive failures, after feedback provided, were considered enough to stop the task.

2.3. Data acquisition

A six -camera motion capture system (MX3 VICON©, Oxford Metrics Ltd., Oxford, UK) was used to record kinematics (sampling frequency = 120 Hz). A set of 49 passive reflective markers was fixed to the skin using double-sided adhesive tape on different anatomical landmarks, and combined with anthropometric measures to build a modified full-body kinematic model according to the Vicon Plug-in-Gait procedure (Vicon®, 2002). Surface EMG signals were collected to confirm the presence of neck/shoulder fatigue resulting from the RPT (TeleMyo 900, Noraxon USA, Inc.; at 1080 Hz). Electrodes were placed on the right arm's anterior deltoid (AD; below the lateral end of the clavicle) and biceps brachii (BIC; midway on the anterior part of the upper arm, over the muscle belly), according to guidelines by Blumenstein (1980). All data were digitally converted using a 16 bit A/D board over a ±10 V range and stored for further analysis.

2.4. Data analysis

The first 30 s recorded during the RPT were used to extract No-fatigue (NF) data, and the last 30 s as Fatigue-terminal (FT) data. In order to only use the forward pointing movements (proximal to distal target), data were partitioned using the target activation signals or the change in anteroposterior speed of the fingertip, if the participant missed the target ($n < 1\%$).

2.4.1. EMG analysis

All EMG signals were filtered using a zero phase lag fourth-order Butterworth filter, with a band-pass of 20–500 Hz after removing the overall mean value. EMG signals were filtered for removal of heartbeat signals, using the signal cross-correlation approach described in Emery et al. (2010). For the forward movements analyzed, the root-mean-squared (RMS) amplitude and median frequency (MDF) of EMG from the two muscles were calculated for each pointing movement.