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Full Length Article

# Inter-joint coordination changes during and after muscle fatigue

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## ABSTRACT

People produce multi-joint movements by organizing many degrees of freedom into a few major covarying relationships, indicating a high level of inter-joint coordination. These relationships can be identified using data decomposition analyses (e.g. principal components analysis, non-negative matrix factorization). The purpose of this study was to determine how movement coordination changes during muscle fatigue by analyzing the covariance structure of multi-joint movements. Sixteen (16) healthy adults completed a continuous, timed ratcheting task with the right arm for three 1-min intervals before, during, and after an intermittent shoulder fatigue protocol. Joint angles from the right arm and trunk were tracked for subsequent principal components analysis. Principal component waveforms were constructed from the original joint angles, and changes in the waveforms during fatigue were assessed using cross-correlations. The variance explained by the first four principal components reached a maximum of 90.5% in the second minute of the pre-test and decreased to a minimum of 86.0% in the last minute of fatigue ($p = .033$). In the last minute of the post-test, explained variance (87.1%) did not differ from any other pre, fatigue, or post-test time point ($p > .23$). These results suggest that inter-joint coordination decreased during fatigue. Changes in the movement patterns and principal component waveforms suggest that subjects adopted a more rigid movement strategy when fatigued. However, the rigid movement strategy was not observed during the post-test. The results suggest that people adopted a new pattern of inter-joint coordination while using novel kinematics.

## 1. Introduction

Muscle fatigue is defined as a reduction in muscle's capacity to generate force and is accompanied by a sensation of weakness (Enoka & Stuart, 1992). Muscle fatigue leads to altered motor recruitment (Farina, Leclerc, Arendt-Nielsen, Buttelli, & Madeleine, 2008; Wilder et al., 1996) and increased variability of force (Côté, Feldman, Mathieu, & Levin, 2008; Huffenus, Amarantini, & Forestier, 2006) and movement (Enoka & Duchateau, 2008; Gates & Dingwell, 2011). The optimal movement strategy to execute a task in a fatigued state may differ from the non-fatigued state (Monjo, Terrier, & Forestier, 2015). During repetitive tasks, people may compensate for muscle fatigue by reorganizing the movement patterns of individual degrees of freedom (DoF) (McDonald, Calvin, & Keir, 2015) or using different DoF to achieve the task (Côté, Mathieu, Levin, & Feldman, 2002; Côté, Raymond, Mathieu, Feldman, & Levin, 2005). These changes may lead to altered inter-joint (Huffenus et al., 2006) and inter-muscular (Côté et al., 2008) coordination after muscle fatigue. In spite of these changes, people are able to coordinate their joint motions in a way that maintains performance when fatigued (Cowley, Dingwell, & Gates, 2014; Fuller, Fung, & Côté, 2013; Gates & Dingwell, 2008).

It is difficult to analyze inter-joint coordination because the musculoskeletal system is a multidimensional mechanical system with

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many (redundant) DoF. Fatigue studies frequently report only small changes (~3°) or find significant changes in the peak angles or range of motion of only a few joints, leading to the conclusion that movement reorganization may involve a sum of small changes at several DoF (Côté et al., 2002; McDonald et al., 2015; Tse, McDonald, & Keir, 2015). This is further complicated by the fact that the muscle fatigue state changes continuously throughout muscle fatigue and recovery. Moreover, different muscles have different fatigue and recovery rates (Caffier, Rehfeldt, Kramer, & Mucke, 1992), and people continuously learn new movement strategies as they perform tasks (Dingwell, Smallwood, & Cusumano, 2013; Selen, Beek, & van Dieën, 2007). Thus adapting to fatigue requires people to respond to a complex combination of several nonlinear processes via the coordinated action of many DoF.

The way that people modify their inter-joint coordination during widespread movement reorganization is difficult to address with traditional analyses of individual biomechanical variables at discrete time points. Many studies have been limited to analyzing differences only between trials performed before and after fatigue. This approach reduces fatigue to two states (unfatigued or fatigued) and therefore cannot explain how people transition between movement patterns as fatigue progresses (or decreases). Recent studies examined the time course of kinematic changes during and after fatigue (Fuller, Fung, & Cote, 2011; Gates & Dingwell, 2011; McDonald et al., 2015; Qin, Lin, Faber, Buchholz, & Xu, 2014). Joint angles grew increasingly different from baseline levels throughout a fatiguing task (Gates & Dingwell, 2011). During one hour of active recovery, some angles gradually returned to pre-fatigue levels, while others did not (McDonald et al., 2015). Kinematic changes began well before subjects reached voluntary exhaustion and led to changes in the temporal coordination of movement (Fuller et al., 2011). During simulated work, kinematic changes showed cyclic variations associated with rest-work cycles (Qin et al., 2014). It is clear from these studies that people continuously modify their movement patterns throughout the fatigue process. However, most previous analyses focused on average or maximum joint positions during movement. This approach does not quantify how multiple joints are coordinated to produce a movement. Previous findings emphasize the need for methods that can analyze the continuous fatigue response across multiple biomechanical DoF as measured by 3-dimensional kinematic analyses.

Multivariate statistical tools such as factor analysis, non-negative matrix factorization or principal components analysis (PCA) can be used to decompose data from multi-joint movements into smaller sets of highly representative variables. Each representative variable consists of a weighted combination of the original variables that describes a unique feature of the movement and accounts for a significant portion of the variance in the data (Daffertshofer, Lamoth, Meijer, & Beek, 2004). Generally, the combined effects of many variables can be represented well (e.g. > 90% variance explained) using a few linear combinations of covarying DoF (synergies). This indicates that many DoF are organized as a coordinated unit, and greater accuracy in representing the data reflects greater coordination (Chen, Liu, Mayer-Kress, & Newell, 2005).

Inter-muscular (Steele, Rozumalski, & Schwartz, 2015) and inter-joint (Mah, Hulliger, Lee, & O'Callaghan, 1994) control strategies are thought to be simplified by organizing variables into synergies. PCA has been used to quantify differences in multi-joint movements across conditions and thus identify how different conditions affect movement strategies (Bruce, Moull, & Fischer, 2016; Federolf, Roos, & Nigg, 2013; Hodges, Hayes, Horn, & Williams, 2005; Mah, Hulliger, Lee, & O'Callaghan, 1994; Witte, Ganter, Baumgart, & Peham, 2010). Prior work suggests that a variety of multi-joint tasks are executed in a low dimensional space. Just a few synergies account for most of the variance in the multi-joint data, indicating high coordination among DoF (Bockemühl, Troje, & Durr, 2010; Chen et al., 2005; Mah et al., 1994; Sanger, 2000). PCA can be used to measure changes in explained variance and is therefore well-suited to describe how coordination changes during muscle fatigue.

PCA could help to quantify how people modify their coordination during and after muscle fatigue and provide insight into the control strategies that govern the response to fatigue. The purpose of the current study was to quantify how movement coordination changes over time during and after a fatiguing task. We hypothesized that changes in the movement pattern during muscle fatigue would cause inter-joint coordination to decrease. Further, we hypothesized that the inter-joint coordination would increase as subjects recovered after the fatiguing task, but we expected the movement pattern to remain distinct from the pre-fatigue movements.

## 2. Methods

Sixteen (8 female) healthy, right-handed subjects between the ages of 18 and 65 from the local community provided written informed consent and participated in an institutionally approved study. Subjects had a mean age and BMI of 29 ± 14 (range 18–64) years and 24.6 ± 3.3 $\mathrm{kg/m^2}$, respectively. Individuals with a history of serious musculoskeletal, cardiovascular, neurological, respiratory, or visual problems including upper extremity fractures, neuropathy, or tremors were excluded.

### *2.1. Experimental protocol*

Subjects completed one experimental session. First, baseline shoulder flexion strength was recorded using a hand-held dynamometer (Lafayette Instruments, Lafayette, IN). Subjects then performed nine minutes of a repetitive ratcheting task (Fig. 1A). The pre-test consisted of three, 1-min intervals (pre1 – pre3) alternating with 1-min rest periods (Fig. 2A). Subjects then completed a fatigue trial consisting of a repetitive lifting task alternating with three, 1-min intervals of the ratcheting task (fatigue1 – fatigue3). After the fatigue protocol, subjects completed a post-test in which the lifting task was removed and subjects completed three more minutes of ratcheting with alternating rest periods identical to the pre-test (post1 – post3). Muscle strength and ratings of perceived exertion (RPE) were assessed at regular intervals throughout the session to measure the progression of fatigue (Fig. 2A).

The ratcheting task consisted of repeatedly rotating a bolt (1 Hz) using a ratcheting socket wrench (~0.4 kg) with the right hand (Fig. 1A). Subjects were instructed to complete each ratcheting movement in time with a metronome beat but were not given explicit instruction on how far to rotate the bolt. Subjects completed a 1-min practice trial at the start of the session to reduce learning effects.