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Effects of Local and Widespread Muscle Fatigue on Movement Timing

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Abstract

Repetitive movements can cause muscle fatigue, leading to motor reorganization, performance deficits, and/or possible injury. The effects of fatigue may depend on the type of fatigue task employed, however. The purpose of this study was to determine how local fatigue of a specific muscle group versus widespread fatigue of various muscle groups affected the control of movement timing. Twenty healthy subjects performed an upper-extremity low-load work task similar to sawing for 5 continuous minutes both before and after completing a protocol that either fatigued all the muscles used in the task (widespread fatigue) or a protocol that selectively fatigued the primary muscles used to execute the pushing stroke of the sawing task (localized fatigue). Subjects were instructed to time their movements with a metronome. Timing error, movement distance, and speed were calculated for each movement. Data were then analyzed using a goal-equivalent manifold (GEM) approach to quantify changes in goal-relevant and non-goal-relevant variability. We applied detrended fluctuation analysis to each time series to quantify changes in fluctuation dynamics that reflected changes in the control strategies used. After localized fatigue, subjects made shorter, slower movements and exerted greater control over non-goal-relevant variability. After widespread fatigue, subjects exerted less control over non-goal-relevant variability and did not change movement patterns. Thus, localized and widespread muscle fatigue affected movement differently. Local fatigue may reduce the available motor solutions and therefore cause greater movement reorganization than widespread muscle fatigue. Subjects altered their control strategies but continued to achieve the timing goal after both fatigue tasks.

Keywords

Multi-joint movement; Redundancy; Muscle fatigue; Motor Variability; Motor control; Time factors

Introduction

Repetitive tasks performed for extended periods of time often cause muscle fatigue. Muscle fatigue causes a decrease in the force-generating capacity of muscles (Farina et al. 2002) (Bigland-Ritchie and Woods 1984; De Luca 1984; Gandevia 2001). Muscle timing (Wilder

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et al. 1996), coordination (Gorelick et al. 2003), and force variability (Selen et al. 2007) may be affected by muscle fatigue. Fatigue may also decrease proprioception (Myers et al. 1999), alter reflexes (Wojtys et al. 1996), increase response time (Wilder et al. 1996; Lorist et al. 2002), and increase a person's perceived effort level (Gandevia 2001).

Muscle fatigue can negatively impact task performance. Fatigue of the elbow extensors caused subjects to undershoot the final position of a rapid elbow extension task (Jaric et al. 1999), and fatigue of the wrist extensors impeded accuracy in a computer mouse tracking task (Huysmans et al. 2008). However, in more complex, multi-joint movements, individuals may exploit redundant degrees of freedom to counteract the effects of fatigue (Srinivasan and Mathiassen 2012). In fatiguing tasks, people exploit redundancy by altering activation patterns of individual muscles (Madeleine and Farina 2008; Holtermann et al. 2010) or altering inter-joint and inter-muscular coordination (Gorelick et al. 2003; Côté et al. 2008). Identifying and exploiting redundant movement task solutions may be a broadly used motor control strategy (Cusumano and Dingwell 2013; Dingwell et al. 2013). Thus, individuals alter their coordination strategies to maintain the same task outcomes when fatigued (Côté et al. 2002; Selen et al. 2007; Gates and Dingwell 2008; Fuller et al. 2009; Fuller et al. 2011).

Because the available coordination strategies may be different for different individuals and/or different tasks (Bosch et al. 2011), studies of the effects of fatigue do not always agree in their findings. In previous research, fatigue has been induced by different protocols. Typically, fatigue has either been localized specifically in a single muscle group (Corbeil et al. 2003) or has been non-specific and widespread over several muscle groups (Bove et al. 2007). Local fatigue may result in greater muscle imbalances between opposing muscle groups (Alizadehkhayat et al. 2007), and greater changes in neuromuscular coordination (Gorelick et al. 2003). Few studies have examined possible differences between local and widespread fatigue on multi-joint coordination. In one study, local fatigue caused altered neuromuscular coordination in a stoop lift task, while widespread fatigue did not (Gorelick et al. 2003). During a repetitive sawing task, orbital stability of the shoulder joint increased after local fatigue but not after widespread fatigue (Gates and Dingwell 2010). The effects of local and widespread fatigue on movement control have not been examined, however.

Quantifying control in multi-joint tasks is challenging because infinite movement solutions exist to accomplish a given task. One way to quantify control is to study how quickly subjects respond to deviations away from the task goal. The Goal Equivalent Manifold (GEM) approach provides an analysis that maps the observed dynamics of task performance, at the level of the body variables (e.g. position, velocity), onto a goal space that is defined independent of the subject's actual performance (Cusumano and Cesari 2006; Gates and Dingwell 2008; Cusumano and Dingwell 2013; Dingwell et al. 2013). The GEM is the set of all possible body state solutions that exactly meet the task goal.

While conceptually similar to approaches, like the uncontrolled manifold (UCM) analysis (Latash et al. 2007) in that it seeks to differentiate relevant from irrelevant variability in purposeful movements, there are several key advantages to the GEM approach. First, the GEM analysis decomposes variability with respect to an external goal. Critical to this

approach, the GEM is defined *prior* to and *independent* of the observed performance or the person performing the task (Cusumano and Dingwell 2013). In contrast, the UCM analysis decomposes variability about a manifold defined by the average of the observed experimental data, and hence assumes this average recorded trajectory reflects the desired movement goal. This can sometimes be problematic, however, as this average changes between subjects and conditions (Dingwell et al. 2013). Additionally, for a given GEM, we can assess how changes in the body parameters affect the goal error during each movement repetition. By examining changes from one movement to the next, the GEM approach also allows us to analyze not only variability, but also trial-to-trial dynamics. UCM adopts essentially “static” analyses of variance alone, and so, by definition, UCM cannot directly address the issue of “control” because measures of variance averaged over many trials cannot quantify anything related to trial-to-trial error correction, which is critical (van Beers 2009). By analyzing the trial-to-trial dynamics we obtain a measure of control. In previous work on walking (Dingwell et al. 2010) and a virtual shuffleboard task (Cusumano and Dingwell 2013), explicit computational control models of these dynamical behaviors were derived and analyzed to validate these important distinctions. When subjects correct deviations more quickly, this indicates a more controlled process (Gates and Dingwell 2008; Dingwell et al. 2013).

Using a GEM analysis, we found that muscle fatigue led to more rapid correction of timing errors in a sawing task (Gates and Dingwell 2008). Similar work found more rapid corrections in center of pressure trajectories after plantar flexor fatigue (Corbeil et al. 2003). Rapid fluctuations may reflect a more cautious (Dingwell and Cusumano 2010) or stiff movement strategy (Corbeil et al. 2003) in which a greater number of corrective actions are used. Because fatigue can increase force variability (Selen et al. 2007), it is possible that fatigue increases the need for corrective actions.

The purpose of this study was to determine how local fatigue of a specific muscle group versus widespread fatigue of various muscle groups affected the control of movement timing. Subjects performed a continuous sawing task in time with a metronome before and after fatigue. We hypothesized that, similar to our prior work, subjects would correct timing errors faster post-fatigue than pre-fatigue (Gates and Dingwell 2008). We also hypothesized that there would be greater changes in movement distance and speed after local muscle fatigue of the shoulder flexors compared to widespread muscle fatigue of the muscles of the right arm and trunk. Finally, because the shoulder flexors act as a primary agonist in pushing the handle away from the body, we anticipated the effects of local fatigue to be larger during the push movements than the pull movements of the sawing task.

Methods

Subjects

Twenty healthy right-handed adults (9 female, 11 male) participated. Their mean $\pm$ SD age, body mass, and height were 25 ± 2.2 years, 71.2 ± 14.9 kg, and 1.71 ± 0.10 m, respectively. Signed informed consent was obtained from each subject prior to enrollment in this institutionally approved study. All subjects were screened to ensure that they had no history of medications, surgeries, injuries, or illnesses that could affect their upper extremity joint

movements. All subjects scored at least 9/10 on the Edinburgh Inventory, indicating strong right-hand dominance (Oldfield 1971).

Experimental Protocol

Subjects completed two experimental sessions at least one week apart that followed the same general protocol (Fig. 1) previously described in (Gates and Dingwell 2010). Each session consisted of two trials of a repetitive movement task, one before, and one after fatigue. Prior to testing, each subject's maximum isometric pushing/pulling force was obtained using a Baseline® dynamometer (Gates and Dingwell 2008). The average of six peak forces (3 push plus 3 pull) defined the maximum pushing/pulling force.

Maximum isometric strength of the right arm was assessed during maximum voluntary contractions (MVC) to test specific muscle imbalances at baseline and at several points during the session (Fig. 1B). Shoulder flexion/extension, internal/external rotation and elbow flexion/extension strength were measured using a hand-held load cell (Lafayette Instruments, Lafayette, IN) (Gates and Dingwell 2010).

The repetitive task simulated a sawing-type motion (Fig. 1A). Subjects held a handle and pushed a weight equal to 10% of the maximum pushing/pulling force back and forth with their right arm along a low friction track (Gates and Dingwell 2010). Subjects were instructed to maintain time with a metronome so that the end of each push movement and each pull movement coincided with a metronome beat. The frequency of the metronome, f_m , was set to twice the average of each subject's predicted upper arm and forearm resonant frequency (~1 Hz) (Gates and Dingwell 2008). The task was performed continuously for five minutes. To ensure that learning did not affect the results, subjects performed a warm-up trial in which they moved in time with the metronome for at least 30 seconds. Pilot testing confirmed that the warm-up trial was sufficient to learn the task (Gates and Dingwell 2008).

On each visit, subjects performed one of two fatigue protocols, in random order. To verify fatigue, ratings of perceived exertion (RPE) were recorded using the Borg CR-10 scale (Borg 1982). The 'LIFT' fatigue protocol was designed to fatigue the shoulder flexors. Subjects held a weight (10% shoulder flexion MVC) in the right hand, and with the elbow extended, they repeatedly raised the right arm to approximately 90° of sagittal-plane flexion at a frequency of one half f_m (~0.5 Hz). Lifting continued for three minutes or until subjects could no longer continue. Eight of twenty subjects stopped before three minutes. All others were fatigued at the end of three minutes (RPE = 8).

The 'SAW' fatigue protocol was designed to fatigue all muscles involved in the sawing task. Thus, subjects performed the same sawing task described above, but resistance was increased to 25% of the pushing/pulling MVC. Subjects sawed for four minutes or until they could no longer continue. Two subjects could not complete four minutes. Six subjects were not fatigued (RPE < 6) after four minutes and were asked to saw four minutes longer or until fatigue (RPE = 8).

The 3-dimensional position of a marker placed on top of the handle was recorded at 120 Hz using an 8-camera Vicon-612 motion capture system (Oxford Metrics, Oxford, UK). Nine pairs of preamplified EMG surface electrodes (Delsys Inc., Boston, MA) recorded activity in the pectoralis major, upper trapezius, deltoid (anterior, middle and posterior), biceps, triceps, flexor carpi radialis, and extensor carpi radialis longus. Electrode placement followed accepted recommendations (Konrad 2005). Analog data were collected at 1080 Hz using a 64-channel A/D board. Kinematic and EMG data were recorded continuously during all trials.

Data Processing

EMG data were filtered to a bandwidth between 20 and 450 Hz. The instantaneous mean power frequency (IMPF) was calculated according to procedures outlined in (Hostens et al. 2004; Gates and Dingwell 2011). IMPF were calculated using a continuous wavelet transform algorithm (Matlab 7.0, Mathworks, Natick, MA). We used a “daubechies” wavelet (db5) for all analyses. The wavelet had a center frequency of 720 Hz at the lowest scale and was scaled in 1-scale intervals from 1 to 38. So center frequencies ranged from approximately 19–720 Hz (Gates and Dingwell). IMPF values were averaged over each cycle to give a single value per cycle. Localized muscle fatigue causes EMG mean frequencies to decrease (De Luca 1997). Therefore, fatigue was expressed as the rate of decrease of the IMPF (1/scales/cycle).

The handle marker data were resampled to 1080 Hz using a piecewise cubic interpolant in Matlab (Mathworks, Natick, MA) to match the sampling frequency of the metronome. Resampled data were then filtered using a 5th order low-pass Butterworth filter with a cutoff frequency of 6 Hz. The minimum and maximum marker excursions were used to identify the beginning and end of each push and pull movement. Movement distance, average movement speed, and the timing error, E , relative to the nearest metronome signal were computed for all movements (Gates and Dingwell 2008). Time series were then rescaled by subject height and f_m to obtain non-dimensional movement distance, D , and non-dimensional movement speed, S . Non-dimensionalizing D and S by subject height had no effect on the GEM analyses because both variables were non-dimensionalized by the same factor (Gates and Dingwell 2008). Two sets of D , S , and E time series resulted: one for all consecutive pushing motions and one for all consecutive pulling motions.

The primary *goal* of the sawing task was to complete each movement (push or pull) in one metronome beat, thus completing each push or pull movement in *time*, T . The goal can be accomplished with any consistent value of E over repeated trials. Infinite combinations of movement distance, D , and speed, S , achieve this timing goal, $D/S = T$. All $[D, S]$ combinations where D and S have the same magnitude define the *goal equivalent manifold* (GEM) for this task (i.e., all solutions lying on the GEM equally achieve the task goal) (Fig. 2A). Using the defined GEM, variability in the body movement parameters, D and S , can be decomposed into components that directly reflect whether the goal is achieved and those that are not relevant to achieving the task goal. Thus, variability in D and S were decomposed into goal-relevant fluctuations (perpendicular to the GEM) and fluctuations that do not contribute to errors (tangent to the GEM), δ_p and δ_T , respectively. δ_T and δ_p , can be

expressed as the scalar product of $[D, S]$ and the unit vector in the direction of δ_T or δ_P , respectively. Thus, changes in movement distance, D , result in corresponding changes in δ_T when movement time, T , is constant.

To determine how quickly deviations were corrected, we quantified the temporal correlations of variations in each time series using detrended fluctuation analysis (DFA) (Gates and Dingwell 2008). DFA was performed for each time series: D , S , E , δ_P and δ_T . Complete details of the methodology are published elsewhere (Peng et al. 1993; Peng et al. 1994; Peng et al. 1995; Hausdorff et al. 1995). In brief, the data sequence of length N was integrated and divided into equal, non-overlapping bins of length n . Data in each bin, was then detrended by subtracting a least squares linear fit to that data segment. The mean residual ($F[n]$) was calculated as the average of the residuals in each bin. This process was repeated for different bin sizes ranging from 4 to $N/4$. The slope of a line representing the relationship between the log of the mean residual values ($\log[F(n)]$) and the log of the bin lengths ($\log(n)$) defines the scaling exponent, α . Lower values of α indicate that deviations in one direction are more likely to be followed by deviations in the opposite direction (i.e., corrected), while higher values indicate that consecutive deviations are more likely to persist in the same direction (or remain uncorrected). A more controlled process yields a time series that exhibits lower α (Fig. 2B) (Gates and Dingwell 2008; Dingwell and Cusumano 2010).

Statistical Analyses

The primary dependent measures analyzed were the IMPF slopes, MVCs, and the means, standard deviations, and scaling exponents for each time series of S , D , E , δ_T , and δ_P obtained from the consecutive sequences of *pushing* and *pulling* movements separately. To confirm that subjects were fatigued, we determined whether the IMPF slope for each muscle differed from zero using a one-sample t-test. MVCs were compared using a 2-factor (protocol $\times$ MVC number) ANOVA. To determine the effects of fatigue on the control of movement timing, the remaining variables (S , D , E , δ_T , and δ_P) were subjected to a three-factor multivariate, within-subjects ANOVA to test for differences between fatigue (pre vs. post), protocol (LIFT vs. SAW) and movement direction (push vs. pull). We found no significant effects associated with movement direction (i.e., push vs. pull). Therefore, movement direction was removed from the model, and the statistical analyses were re-run using a two-factor multivariate ANOVA. Where interactions were found, estimated marginal means were examined to determine the nature of the interaction. Significance level was set at $p < 0.05$ for all comparisons.

Results

All subjects reached an RPE of 8 or greater before ending the fatiguing tasks. The slope of the IMPF was negative in all muscles measured during both protocols ($p < 0.05$) (Fig. 3). During the SAW fatigue protocol, most muscles fatigued to a similar degree, but the posterior deltoid fatigued less than the anterior deltoid ($p = 0.006$) and wrist extensors ($p = 0.024$) (Fig. 3A). During the LIFT fatigue protocol, the anterior deltoid had a greater fatigue rate than all other muscles ($p < 0.019$) except the lateral ($p = 0.803$) and posterior ($p = 0.101$) deltoids (Fig. 3B). Subjects also exhibited significant decreases in MVC in all post

fatigue measurements ($p < 0.038$). The decrease in shoulder flexion MVC was greater after the LIFT task than the SAW task ($p = 0.035$). See (Gates and Dingwell 2010) for additional details.

Timing errors, E , decreased after fatigue ($p < 0.001$). However, there was a significant protocol by fatigue interaction ($p = 0.003$) (Fig. 4A). Errors decreased after SAW ($p < 0.001$) but did not change after LIFT ($p = 0.649$). Variability of E decreased after fatigue on both days ($p < 0.001$; Fig. 4B). For α of timing errors, there was a significant effect of fatigue ($p = 0.016$) and a protocol by fatigue interaction ($p = 0.014$; Fig. 4C). LIFT caused a significant increase in α ($p = 0.001$), while SAW had no effect ($p = 0.974$).

Average movement distance, D , and speed, S , exhibited similar protocol by fatigue interactions (Fig. 5 and Fig. 6). Subjects reduced D after LIFT ($p < 0.001$) but not after SAW ($p = 0.107$; Fig. 5A and Fig. 6). LIFT also resulted in a significant decrease in S ($p < 0.001$), while SAW did not affect S ($p = 0.273$; Fig. 5D and Fig. 6). Variability of D and S were not affected by fatigue (Fig. 5B and Fig. 5E). There was a significant protocol by fatigue interaction for α of D ($p = 0.016$) and α of S ($p < 0.001$) (Fig. 5C and Fig. 5F). Post hoc tests showed a non-significant increase in α of D after SAW ($p = 0.110$) and a non-significant decrease after LIFT ($p = 0.068$; Fig. 5C). However for S , α significantly increased after SAW ($p = 0.003$) and significantly decreased after LIFT ($p = 0.020$; Fig. 5F).

There was a significant protocol by fatigue interaction for mean deviations along the GEM, δ_T ($p = 0.001$; Fig. 7A). Mean δ_T decreased after LIFT ($p < 0.001$) but did not change after SAW ($p = 0.169$). Variability of δ_T did not change after fatigue (Fig. 7B). There was a significant protocol by fatigue interaction for α of δ_T ($p = 0.001$; Fig. 7C). Post hoc tests show that α of δ_T increased after SAW ($p = 0.018$) and decreased after LIFT ($p = 0.009$). There were no significant main effects or trial by condition interactions for mean ($p > 0.3$; Fig. 7D), standard deviation ($p > 0.5$; Fig. 7E), or α of δ_P ($p > 0.7$; Fig. 7F).

Discussion

This study tested whether localized and widespread muscle fatigue affect the control of movement timing differently. The high rates of perceived exertion, reduced maximal voluntary contractions and decreased mean power frequency of the EMG demonstrate that both fatigue protocols successfully induced muscle fatigue. Additionally, the slopes of the mean power frequencies suggest that the lifting task fatigued the shoulder flexors to a greater extent than other muscles tested, while the sawing task did not fatigue a specific muscle more than the others. MVCs confirmed that subjects experienced a greater decrease in shoulder flexor strength after the lifting task than the sawing task. These findings confirm that the lifting fatigue task induced more specific fatigue of the shoulder flexors compared to the sawing task.

We hypothesized that timing errors would be corrected more quickly after both widespread and localized fatigue compared to pre-fatigue trials. The results did not support this hypothesis or our previous findings in a similar study (Gates and Dingwell 2008). The widespread fatigue protocol used here was similar to the fatiguing task used in (Gates and

Dingwell 2008). In that study, timing errors and deviations in movement speed were corrected more quickly after widespread fatigue. In the current study, no difference in the correction of timing errors was observed after widespread fatigue, and timing errors were corrected slightly less quickly after localized fatigue (Fig. 4C). Furthermore, deviations in movement speed were corrected slightly less quickly after widespread fatigue but slightly more quickly after localized fatigue in the present study (Fig. 5F). Thus, not only were the results of the localized task distinct from two widespread fatigue tasks, different results were found for each widespread fatigue task even though both induced similar widespread fatigue by sawing.

Differences between the two widespread fatigue tasks likely explain the different results observed in these two studies. Subjects in the previous experiment sawed with 15% of their maximum push-pull force to exhaustion (> 20 minutes), and performance measures were taken during the last few minutes of the fatiguing task. In the current experiment, subjects sawed to exhaustion with 25% of their maximum force, and performance measures were taken in a separate trial (10% of max force) following the fatigue task. Thus there are two important differences. First, the fatigue protocol used here was distinctly different from the task used for analysis as the inertia of the object was different. Therefore, subjects may have made adaptations during the fatigue protocol which carried over into their post-test performance. Second, it is possible subjects recovered somewhat prior to the start of the post-test or during the post-trial itself. Rates of fatigue and recovery differed between subjects. While some subjects' MVCs recovered rapidly after the post-fatigue trial, others showed continued decreases (Gates and Dingwell 2008). To test for recovery during the post-test, we calculated the average of each variable during each minute of the five minute trial. Then we analyzed each variable using a single-factor, repeated measures ANOVA to test for differences over time (minutes 1-5). There were no significant changes from minute to minute, which suggests that recovery was not a factor. Rather, the different findings of these studies support the notion that both the type of fatigue and the context in which it occurs may be critical to understanding the onset and effects of fatigue (Gorelick et al. 2003; Fuller et al. 2009; Bosch et al. 2012). For each task, the effects of fatigue were context-specific. Two similar, but distinct, widespread fatigue protocols are unlikely to produce the same effects on movement control.

Our second hypothesis, that there would be greater changes in movement distance and speed after local fatigue of the shoulder flexors compared to widespread muscle fatigue, was supported. After localized fatigue, subjects made shorter and slower movements, thus shifting their 'operating point' on the GEM (Fig. 6B). They also corrected deviations along the GEM more quickly (Fig. 7C) after localized fatigue, unlike deviations in timing errors (Fig. 4C) which were corrected less quickly. This suggests that subjects altered their control strategy to one that focused on more tightly controlling their position along the GEM, rather than deviations from the task goal. In contrast, there were no differences in movement distance and speed post-widespread fatigue. These results agree with a previous study which looked at the effect of localized fatigue of the back extensors and widespread fatigue of the legs and trunk on a repetitive lifting task (Gorelick et al. 2003). While they did not report kinematics, the authors did find greater changes in muscle activation patterns after local fatigue (Gorelick et al. 2003).

Contrary to our third hypothesis, there were no differences between pushing and pulling movements post-fatigue. Unlike widespread fatigue, localized fatigue of the shoulder flexors could affect the push movements while allowing the pull movements to be unaffected. Subjects could have compensated for the fatigued shoulder flexors by generating more force with less fatigued, synergist muscles, e.g. triceps, pectoralis. Instead, they made shorter and slower movements. The distance and speed likely did not change between pushing and pulling because the push and pull movements are coupled. As subjects shortened their push movements in response to fatigue, they would have had to similarly shorten their pull movements to maintain a position near the midpoint of the track. The timing errors at the end of a push and a pull movement could have differed due to the fatigue of only the shoulder flexors where increased force variability of the pushing agonist would result in errors in push while pull would be unaffected. However, we did not see that here. It is possible that the changes in movement distance and speed offset any timing differences between push and pull.

It is possible that the results of this study were affected by motor learning. To combat this, we had subjects practice the sawing movement prior to the experiment. We previously found that subjects were able to learn this relatively simple task within a few movements (Gates and Dingwell 2008). However, we cannot entirely rule out the possible occurrence of further, perhaps more subtle, learning. Continually learning and exploiting motor redundancies may be critical to motor control (Srinivasan and Mathiassen 2012; Dingwell et al. 2013). Selen et al. found that subjects performing a tracking task stayed nearer to the center of the target after fatigue and continued this pattern even after a recovery period, indicating that subjects retained a novel control strategy (Selen et al. 2007). It is possible that subjects learned new control strategies while performing the widespread fatigue task. Furthermore, it is possible that subjects were continually changing strategies even within the five minute post-test. Different subjects, even different muscles, have different fatigue and recovery rates (von Tscharnier 2002; Gates and Dingwell 2008). Each subject may have found different control strategies to account for individual fatigue states. Here, as in numerous previous studies of muscle fatigue, there was high inter-subject variability (Côté et al. 2002; von Tscharnier 2002; Gates and Dingwell 2008; Fuller et al. 2009; Gates and Dingwell 2011). Subjects could change their movement strategies in many ways. In addition to shifting movement distance and speed to various locations along the GEM, subjects may have also shifted control among different body parameters (Dingwell and Cusumano 2010). Clearly, subjects took advantage of task redundancy (Fig. 6), and this probably helped to reduce the load on fatigued muscles. In spite of the differences between subjects, a few consistent movement patterns emerged. Subjects were fatigued after the widespread fatigue task, and they altered their control strategies. The strategy used after widespread fatigue was not used after localized fatigue, either because localized fatigue limited its effectiveness or because subjects did not discover it. In either case, the distinct control strategies observed after each fatigue task allowed subjects to continually achieve the timing goal even in the presence of muscular fatigue.

The findings of this study support that localized and widespread fatigue affect movement differently (Gorelick et al. 2003; Gates and Dingwell 2010). Localized fatigue led to greater movement reorganization, potentially by limiting the movement solutions subjects chose to

use. The nature and degree of movement reorganization may be an important consideration when assessing the risk of injury due to fatigue (Madeleine 2010). After widespread fatigue, subjects exerted less control over task-irrelevant elements of the movement, but after local fatigue, they exerted greater control over these elements. Still, enabled by motor redundancies, subjects in this study discovered new control strategies which allowed them to maintain performance in spite of significant fatigue.

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Fig 1.

Fig 2.

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