INTRODUCTION

Muscle fatigue results in reduced force generating capacity of individual motor units [1] and increased muscle response time [2]. It may also alter muscle coordination [3] and ultimately affect performance. Some have suggested that under muscular fatigue, subjects alter their coordination strategies to achieve the same task goal [1, 4]. However, adaptations in coordination in response to muscle fatigue are not well understood. Studies of the effects of muscular fatigue on performance have utilized different protocols which either localized fatigue to a specific muscle or produced non-specific widespread fatigue across several muscles. It has been proposed that localized fatigue may cause greater changes in muscle activation patterns [3].

Control strategies may be analyzed by assessing how quickly subjects respond to deviations away from a task goal. A goal equivalent manifold (GEM) approach may be used to this end [5]. A GEM analysis allows decomposing movement variability into that which directly affects goal achievement and that which does not. Here, a GEM was defined to analyze changes in control strategies associated with muscular fatigue. We examined changes in performance of a repetitive, timed task under localized and widespread fatigue. We hypothesized that local fatigue would result in greater timing errors and decreased temporal correlations compared to widespread fatigue.

METHODS

20 healthy right-handed subjects (25±2.2 years) performed a bidirectional sawing task (Fig. 1) described previously [6]. Subjects slid a weight along a horizontal track in time with a metronome (∼1 Hz). Data collection sessions included a sawing pre-test followed by a fatigue protocol and a sawing post-test. Maximal voluntary contractions (MVC) and rating of perceived exertion (RPE) were obtained at several points during the session to monitor fatigue (Fig. 1). Subjects pushed 10% of push/pull MVC back and forth along the track. A single marker on top of the handle was recorded at 120 Hz using a Vicon motion analysis system. The first fatigue protocol, ‘SAW’ was designed to induce widespread fatigue of the arm and trunk. Subjects performed the same sawing task with 25% of their push/pull MVC for 4 minutes or until RPE ≥ 8[6]. The second fatigue task, LIFT, was designed to localize fatigue to the shoulder flexors. With the elbows extended, subjects lifted a weight (10% of shoulder flexion MVC) to approximately 90° in the sagittal plane at a frequency of ∼0.5 Hz [6].

Figure 1: The experimental protocol. Subjects completed two sessions on separate days in random order. The only difference between sessions was the fatigue protocol.

Subjects were instructed to maintain movement time so that the end of each stroke (push or pull) coincided with the metronome beat. A non-dimensional movement distance (D) and speed (S) were obtained by dividing distance by subject height and speed by subject height and metronome frequency. The goal equivalent manifold (GEM)
was defined as any combination \([D, S]\) which achieves the correct stroke time. Timing errors, and \(D\), and \(S\) were obtained for all push and pull strokes of each trial. Detrended fluctuation analysis was applied to all data series to obtain temporal correlations, \(\alpha\). The value \(\alpha\) indicates how quickly deviations are corrected in a data series. Lower values indicate that deviations are corrected more rapidly. EMG instantaneous mean power frequencies (IMNF) were calculated to quantify muscle fatigue [6]. Dependent measures were analyzed using three-factor within subjects ANOVAs to test for differences in fatigue state (Pre/Post), fatigue protocol (SAW/LIFT), and stroke (Push/Pull).

**RESULTS AND DISCUSSION**

Significant localized muscle fatigue was confirmed by decreased IMNF during both fatigue tasks \((p < 0.05; \text{Fig. 2})\). LIFT caused shoulder flexion MVCs to decrease 8% more than SAW \((p = 0.035)\).

Timing errors did not change post-fatigue for either fatigue protocol \((\text{pre} = -0.061, \text{post} = -0.051, p = 0.225)\). The standard deviation of timing errors tended to decrease post-fatigue but did not reach significance \((\text{pre} = 0.087, \text{post} = 0.074, p = 0.052)\). The different fatigue protocols affected \(\alpha\) differently \((p = 0.025)\). Errors were more persistent after LIFT \((p = 0.002)\) but not SAW protocol \((p = 0.976)\) (Fig. 3B). This suggests that timing errors were corrected less quickly following localized fatigue.

![Figure 2](image-url)  
**Figure 2.** Slope of IMNF for each muscle

Subjects made shorter \((p = 0.002)\) and slower \((p = 0.002)\) movements after the LIFT task. There were no differences in distance or speed post SAW \((p = 0.158; p = 0.328, \text{respectively})\). No differences were observed between the push and pull strokes \((D: p = 0.100, S: p = 0.744)\).

![Figure 3](image-url)  
**Figure 3:** TOP: Movement distance, \(D\), and speed, \(S\), are shown for each stroke (‘.’) of a representative subject pre and post fatigue. The solid line represents the GEM for the task. Mean pre (black) and post-fatigue (blue) operating points across subjects are highlighted by +. BOTTOM: Mean and 95% CI of \(\alpha\) are shown. ‘*’ signifies significant difference \((p < 0.05)\).

**CONCLUSIONS**

Subjects adapted to non-specific widespread fatigue in a way that did not affect movement speed, distance or timing errors. Specific fatigue of the shoulder flexors resulted in shorter, slower movements and greater temporal persistence in timing errors. Localized fatigue may limit options available by limiting the function of a specific muscle group. Neither fatigue protocol prevented subjects from achieving the desired outcome.

**REFERENCES**