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Cycle time influences the development of muscle fatigue at low to moderate levels of intermittent muscle contraction

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ABSTRACT

Localized muscle fatigue (LMF) during a repetitive task can be influenced by several aspects such as the level and duration of exertions. Among these aspects, though, the influence of cycle time remains unclear. Here, the effect of cycle time on LMF and performance was examined for a simple biomechanical system during repetitive static efforts. Participants performed 1-h trials of intermittent isometric index finger abduction with a duty cycle of 50% in all combinations of two cycle times (30 and 60 s) and two exertion levels (15% and 25% of maximum voluntary capacity). Measures of discomfort, performance (force fluctuations), and muscle capacity (voluntary strength and low-frequency twitch responses) were obtained, all of which demonstrated a beneficial effect of the 30 s cycle time. Specifically, the shorter cycle time led to lower rates of increase in perceived discomfort, lower rates of increase in force fluctuations, lower rates of decrease in voluntary capacity, and smaller changes in twitch responses. These benefits, reflecting less LMF development in the shorter cycle time, were quite consistent between genders and the two levels of effort. Results of this study can be used to modify current models predicting work–rest allowance and/or LMF, helping to enhance performance and reduce the risk of adverse musculoskeletal outcomes.

1. Introduction

Localized muscle fatigue (LMF) has received increasing attention in many disciplines such as occupational biomechanics and rehabilitation, and has been recognized as an important measure in research and interventions aimed at reducing musculoskeletal disorder risks in general, and work-related musculoskeletal disorder (WMSD) risk in the occupational environment specifically. The specific role of LMF in the development of WMSDs is not clear yet, however, and the existence of LMF does not necessarily imply an increased risk of WMSDs (Mathiassen and Winkel, 1992). Within the occupational domain, however, factors such as working posture and sustained muscle contractions that are closely related with muscle fatigue (Lin et al., 2009) have been shown to contribute to soft tissue injuries (Sommerich et al., 1993; Veiersted, 1994). Several theories and conceptual models have also been proposed describing potential links between LMF and WMSD-related mechanisms (Armstrong et al., 1993; Forde et al., 2002; Sejersted and Vøllestad, 1993).

Diverse sources of variability can influence the development of LMF during task execution. Important individual differences include anthropometry, age, gender, fiber type distribution, and fitness status (Dickerson et al., 2011; Yassierli and Nussbaum, 2009). Specific tasks demands can also be highly influential, on both LMF and LMF-induced changes in task performance. Extensive existing evidence has assessed the influence of task parameters such as the intensity and duration of work, as examples of factors affecting physical exposure (Horton et al., 2012; Iridiastadi and Nussbaum, 2006; Nussbaum et al., 2001; Yassierli and Nussbaum, 2009). A majority of previous studies on muscle fatigue have involved prolonged static contractions, with well-described relationships between effort level and endurance times (El ahrache et al., 2006; Frey Law and Avin, 2010). However, this type of loading has relatively low occupational relevance, as most work tasks have intermittent resting periods (Adamo et al., 2009; Iridiastadi and Nussbaum, 2006). Broadly, intermittent contractions can be characterized based on three task parameters: the Exertion Level (EL); duty cycle (DC: the ratio between the exertion period and the CT); and Cycle Time (CT). Consistently, higher ELs and DCs have been found to cause higher rates of LMF development and/or

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decreased endurance times (Björkstén and Jonsson, 1977; Jørgensen et al., 1988), likely a direct result of the increased total effort generated over a given time interval.

In contrast, the influence of CT on LMF development is less clear. However, the extremes of cycle time, specifically very short and long values, are not favorable. Tasks with high levels of repetition can increase pressure around peripheral nerves, initiate chronic nerve compression, and cause subsequent swelling and impairment of the vascular supply (Byl et al., 1997; Forde et al., 2002; Stauber, 2004). In contrast, sustained, low-level, isometric contractions recruit the same low threshold motor units (MUs) according to the size principle (Henneman et al., 1965). Considering contractions that are sustained for a long period, it is expected to have some overloaded muscle fibers that experience a loss of calcium homeostasis, or the "Cinderella" response of MUs (Sjøgaard and Jensen, 1997). This phenomenon can occur with or following fatigue, and has been linked to soft tissue inflammation (Lovlin et al., 1987). As such, while prolonged static exertions can be harmful, high repetitions with very short cycle times may also be unfavorable (Silverstein et al., 1986; Sommerich et al., 1993). For example, Silverstein et al. (1986) observed a higher prevalence of hand/wrist disorders for jobs with CTs of less than 30 s. In between the two noted extremes, a range of CTs can be considered, and is a potential design parameter for occupational tasks. A practical question remains: given a fixed "amount" of workload that has to be generated intermittently for a specific duration (aka the "tension-time product"), how the work and rest should be distributed? In other words, should frequent short rest breaks be given or longer infrequent ones?

Some studies have linked shorter CTs (i.e., more task variation) with a slower development of LMF (Dickerson et al., 2015; Petrofsky et al., 2000; Yassierli and Nussbaum, 2007), while others provided evidence in favor of longer CTs (Byström et al., 1991). Still other studies (Engström et al., 1999; Moore and Wells, 2005) have indicated that the effect of CT was not significant at controlled levels of EL and DC. As such, the specific effects of cycle time on muscular fatigue development remain unclear. Previous work on intermittent exertions has investigated CT effects for several intermittent tasks, but using biomechanically complex systems such as the shoulder joint (Dickerson et al., 2015; Iridiastadi and Nussbaum, 2006; Mathiassen, 1993). This complexity has potential effects on LMF monitoring, which may lead to unclear or inconsistent outcomes. For example, there may be changes in the synergistic or antagonistic contraction of multiple muscles. To our knowledge, the influence of CT during low to moderate level of exertions has not yet been reported for a biomechanically "simple" joint (such as metacarpophalangeal joint of the index finger), for which the specific effects of CT might be more easily identifiable. This study thus investigated the effect of CT for such a simple system, using both subjective and objective measures to assess the development and consequences of LMF. Based on the weight of existing evidence, and the noted adverse physiological effects of sustained contractions, it was hypothesized that under conditions of similar workload a longer CT will negatively influence perceived discomfort, performance, and muscle capacity.

2. Methods

2.1. Participants

Twelve participants (6 males and 6 females) completed the study, who were recruited from the university and local community. Means (SD) of age, stature, and body mass were 25 (3.3) yrs, 175 (9.6) cm, and 72 (10.2) kg, respectively. All participants reported being moderately physically active (i.e., exercising 1–3 times per week), and having no musculoskeletal disorders or injuries currently or in the preceding 12 months. Prior to any data collection, participants gave informed consent using procedures approved by the Virginia Tech Institutional Review Board.

2.2. Experimental design

A repeated measures design was used, in which participants completed five sessions including an initial 1-h practice session, and four subsequent data collection sessions (~3 h each). Each session was separated by at least two days, to minimize carryover effects due to residual fatigue. Participants performed intermittent isometric exertions in four conditions, involving all combinations of two Cycle Times (CT = 30 and 60 s) and two Exertion Levels (EL = 15% and 25% of maximum voluntary contraction = MVC). For each, a single duty cycle (DC = 50%) was used, and the order of exposure to the four conditions was counterbalanced across participants using 4×4 balanced Latin Squares.

These specific task parameters were chosen for two reasons. First, these parameters led to tasks that could all be continued for a reasonable duration (i.e., 60 min). Second, they were intended to represent low to medium levels of occupational exertions for diverse work conditions. A working duration of 1 h was considered as a shortened version of an actual work-shift, to facilitate implementation in a laboratory setting. All tasks involved index finger abduction, due to the simplicity of movement biomechanics and since the first dorsal interosseous (FDI) muscle is solely responsible for this functional effort.

2.3. Experimental procedures

Upon arrival for both the practice and data collection sessions, participants were calibrated to the 10-point Borg CR-10 scale (Borg, 1990) that was used to provide ratings of perceived discomfort (RPDs). Specifically, participants practiced providing ratings using this scale, while leaning against a wall with their knees bent 90°, as in earlier work (Rashedi et al., 2014; Sood et al., 2007); they provided repeated RPDs for the thighs until ratings reached $\geqslant 8$. During data collection, participants were seated comfortably in a chair with the examined forearm (dominant arm) resting on a table. The elbow was flexed to 135°, the shoulder abducted, and the forearm pronated with the palm on the table surface (see Fig. 1a). Both the hand and forearm rested on the table and were constrained with several restraints and with the thumb fully abducted and blocked (Fig. 1b). Adjacent fingers were stabilized using Velcro™ strapping and/or surgical tape (Eichelberger and Bilodeau, 2007; Zijdewind and Kernell, 1994). Several brackets were used to minimize motions of the hand, wrist, and lower arm, and configured so that the lateral surface of the proximal inter-phalangeal joint of the index finger was centered on a load cell.

During experimental sessions, LMF was induced by performing index finger abduction in 6 bouts of 10-min intermittent isometric contractions (see Fig. 2 for an overview). Baseline (pre-fatigue) measures included a minimum of three MVCs (4–5 s duration separated by 1–2 min rest) and low frequency twitches (LFTs). In each MVC trial, participants were asked to maximally activate their FDI muscle in an isometric exertion that involved index finger abduction. The highest value among the completed trials was recorded. Participants were given visual feedback during performance of the intermittent task regarding the level of exertion and the target force (Fig. 1a); this target force was set to 15% or 25% of MVC. Moreover, the level of exerted force was visually monitored through the course of experiment, and participants were verbally encouraged to correct the level of force in case of deviation from the desired level. Single MVC trials were completed between each