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Finger flexor contractile properties and hemodynamics following a sustained submaximal contraction: A study using electrical stimulation and near-infrared spectroscopy

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ABSTRACT

We examined the effect of a low-level sustained contraction on the muscle contractile properties, hemodynamics and oxygenation of the flexor digitorum superficialis muscle (FDS) of the finger. We tested the hypothesis that hemodynamics and oxygenation, reflecting the muscle metabolic characteristics, would recover more quickly than the muscle contractile properties.

Eleven subjects (26 ± 4 years) were equipped with electrodes for electrical stimulation and a near-infrared spectroscopy (NIRS) probe on the forearm over the FDS. The experimental protocol consisted of three baselines measurements (−60, −30 min and pre-exercise), immediately after a sustained 15-min contraction of the FDS at 10% maximal voluntary contraction (post-exercise), and after 30, 60 and 120 min of recovery. For each time point, participants were subjected to a battery of test that included upper arm venous occlusion (at rest), a computer-mouse point and click task (standardized voluntary task), and electrical stimulation. For venous occlusion (50 mmHg, 1 min), slopes were calculated for NIRS-derived total hemoglobin (HbTslope) and deoxyhemoglobin (HHbslope) as estimates of blood flow and oxygen consumption, respectively. The computer-mouse task entailed using the mouse to point and click on targets presented on the screen during which NIRS signals were monitored for determination of change in total hemoglobin (ΔHbT) and oxygen saturation ($\Delta StO_{2\%}$). Electrical stimulation (2 Hz, 5 trains of 15 twitches) provided twitch force (Tw-force), contraction time (CT) and one-half relaxation time (½RT) data.

Statistical analysis revealed significant changes over time for all contractile parameters as well as for HHbslope ($P < 0.05$ for each). Post-hoc testing demonstrated significant decreases for Tw-force post-exercise and at 60 min; for CT at post-exercise, 30 and 60 min; and for ½RT at post-exercise and at 30 min. HHbslope was significantly higher post-exercise as compared to pre-exercise. During the computer-mouse point and click task, no significant differences were detected for ΔHbT, however, $\Delta StO_{2\%}$ showed a tendency to decrease, albeit not significant ($P = 0.11$). Further testing showed $\Delta StO_{2\%}$ was significantly lower post-exercise and at 30 min as compared to pre-exercise.

The present study shows that NIRS provides insight into muscle hemodynamics and oxygenation for low-level sustained activity to fatigue. The overall quick recovery of hemodynamic and oxygenation responses, and a more prolonged recovery of contractile responses confirms our hypothesis, and this may fit well with the classical definition of low-frequency fatigue.

Relevance to industry: Understanding changes in tissue hemodynamics, oxygenation and muscle contractile properties in response to sustained contractions may provide insight into mechanisms behind work-related musculoskeletal disorders. Detecting changes in the underlying physiology of the muscle before the onset and development of an injury, may lead to primary prevention methods to reduce the occurrence of such injuries.

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1. Introduction

Work-related musculoskeletal disorders (MSDs) are of paramount concern due to their obvious burden on the economy as well as on society in general. The disorders are not only associated with heavy work (e.g., moving heavy loads and while working in non-neutral or severe postures), but also with light repetitive work (e.g., light assembly or computer work). While it is not difficult to suggest causal factors for MSDs related to heavy work, the injury mechanism due to light repetitive work is more complex and therefore poorly understood.

Epidemiological reports present a number of physical ergonomic risk factors for MSDs related to low load work. For example, risk factors during computer work include highly repetitive movements, force application and non-neutral working postures (Tittiranonda et al., 1999). Furthermore, several studies have reported a positive relationship between the amount of exposure and the severity of discomfort (cf., Visser and van Dieen, 2006; Ijmker et al., 2007). Despite evidence published in epidemiological reports, research within the areas of primary prevention and rehabilitation has been hampered due to not fully understanding the mechanisms behind these MSDs.

Muscle fatigue is often attributed to the development of MSDs (Baidya and Stevenson, 1988). While a causal relationship between muscle fatigue and MSDs has yet to be established, sustained muscle tension (in relation to fatigue) was identified as a risk factor (Veiersted, 1994). By combining the measurement of muscle fatigue with other recognized risk factors, i.e., high repetitions and long exposures, a better understanding of the link between repetitive work and MSDs may be possible.

Surface electromyography (EMG), which measures the electrical activities of muscles, has been traditionally used as an objective measure of muscle fatigue in moderate to high force work. However, this technique does not have the sensitivity to measure muscle fatigue associated with low-force work. In this regard, electrical stimulation of the muscle has proven to be an effective and sensitive method for detecting muscle fatigue (Ratkevicius et al., 1998; Dennerlein et al., 2003; De Ruiter et al., 2005).

Near-infrared spectroscopy (NIRS) is a non-invasive technique that allows for the continuous monitoring of changes in local muscle oxygenation. NIRS signals represent the dynamic balance between oxygen delivery and consumption and for subsequent determinations of changes in blood volume (Ferrari et al., 2004). NIRS is based on the principle of differential absorption properties of oxygenated (HbO) and deoxygenated (HHb) hemoglobin in the near-infrared range. A probe placed on the skin enables monitoring of NIRS signals from small vessels, i.e., arterioles, capillaries and venules, deep within the muscle for a distinct volume of tissue as determined by the size of the probe. NIRS has been shown to be valid for measuring muscle oxygenation in the forearm (Mancini et al., 1994), and when used in conjunction with venous occlusion, information on blood flow (De Blasi et al., 1994; Van Beekvelt et al., 2001) and oxygen consumption (Homma et al., 1996) can be determined. Thus, NIRS can be used to study the metabolic and hemodynamic function of muscle tissue.

In the present study electrical stimulation and NIRS were combined in order to assess muscle contractile properties, hemodynamics and oxygenation before, immediately after a low-level sustained contraction, and during a recovery period of 2 h. The muscle of interest was the flexor digitorium superficialis (FDS) of the finger because of its association with fatigue related to computer work (Johnson, 1998). The sustained contraction in our experimental design was expected to generate fatigue of the type described in the literature as low-frequency fatigue (LFF, Keeton and Binder-Macleod, 2006). LFF is typified by prolonged recovery of muscle contraction force (especially at low-stimulation frequencies) and usually in the absence of metabolic factors. Therefore, we hypothesized that NIRS-derived parameters, which reflect muscle metabolic characteristics, would recovery more quickly than the muscle contractile properties.

2. Methods

2.1. Subjects

Eleven healthy volunteers consisting of eight males and three females (age 25.5 ± 3.6 years old, height 175.0 ± 7.2 cm, and weight 71.7 ± 12.3 kg) were recruited from the community through an e-mail advertisement. All subjects were right-handed computer-mouse users and were free of upper extremity musculoskeletal disorders and symptoms. Subjects were given verbal and written descriptions of the experimental procedures, and the tests were performed after each subject signed an informed consent. The experimental protocol was approved by the Human Subjects Committee at the University of Washington. Participants were instructed to avoid lifting heavy objects and intensive upper extremity exercises 24 h prior to any of the experimental days.

2.2. Experimental procedure

Subjects attended the experimental laboratory on two occasions, separated by 2–5 days. The first occasion was an orientation day, which consisted of familiarizing the subjects with the testing procedures. The protocol included electrical stimulation of the muscle, identifying the optimal locations for the NIRS probe and stimulation electrodes, and obtaining maximal voluntary contraction (MVC) values.

Muscle location and topology were determined by first identifying the muscle via electrical stimulation using a hand-held electrode probe and visually observing flexion of the flexor digitorum superficialis (FDS) muscle of the middle finger of the right hand. Then, the electrode probe was repeatedly positioned over the muscle in a proximal to distal and a lateral to medial direction until the force response of the finger flexor was no longer present. This allowed us to get a topographical mapping of the muscle so that the stimulation electrode and the NIRS probe could be optimally positioned over the area of the muscle most responsive to the electrical stimulation. In addition, the maximum tolerable stimulation intensity of the subject was determined. This was achieved by slowly increasing the stimulation current until subjects reported a discomfort/pain level of 6 on a 0–10 pain scale (Hanchard et al., 1998). The subjects were then familiarized to venous occlusion associated with the NIRS measurement, the electrical stimulation procedure and a simple point and click task with the computer-mouse. These procedures are described below in detail. All tasks were performed in the manner they were going to be collected on the experimental day.

After familiarization, MVC for finger flexion was done by the subject pressing up with their right fingertip of the middle finger on a force transducer (Greenleaf Medical, Palo Alto, CA, USA) during which the right forearm was fully supinated and the hand placed in a rig (Fig. 1). The rig included restraining straps for the little, ring and index fingers. For MVC, subjects were instructed to press as hard as possible for 5 s. Three exertions were completed with 1 min of rest between exertions. If the third MVC was the highest, subsequent MVCs were collected until MVC force declined. The force signal was recorded at 50 samples per second with the highest 1-s interval representing the MVC for a given trial. The MVC was the highest contraction of all trials. At the end of the orientation day the electrodes were carefully removed as their sites were marked with a Henna tattoo pen in order to facilitate electrode placement in the exact locations for the subsequent experimental day.