Ergonomics

ISSN: 0014-0139 (Print) 1366-5847 (Online) Journal homepage: https://www.tandfonline.com/loi/terg20

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To cite this article: Whitney P. Mantooth, Ranjana K. Mehta, Joohyun Rhee & Lora A. Cavuoto (2018) Task and sex differences in muscle oxygenation during handgrip fatigue development, Ergonomics, 61:12, 1646-1656, DOI: 10.1080/00140139.2018.1504991

To link to this article: https://doi.org/10.1080/00140139.2018.1504991

Published online: 14 Oct 2018.

ERGONOMICS
2018, VOL. 61, NO. 12, 1646–1656
https://doi.org/10.1080/00140139.2018.1504991

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Task and sex differences in muscle oxygenation during handgrip fatigue development

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ABSTRACT
The purpose of this study was to examine task and sex differences in forearm muscle oxygenation, measured using near infrared spectroscopy, during sustained submaximal handgrip exercises. Forty-eight adults (50% males) performed fatiguing handgrip exercises at 20, 40, 60 and 80% of their maximum handgrip strength. While males and females exhibited similar levels of relative fatigability, forearm oxygenation was found to be task (i.e. contraction intensity and phase of fatigue development) and sex dependent. Higher contraction intensities were associated with greater desaturation over time. Compared to females, males exhibited greater desaturation as fatigue progressed and this was augmented at higher contraction intensities. These may be likely affected by sex differences in muscle mass, morphology and strength differences during exercises at relative intensities. Future work that explores sex differences in muscle oxygenation during absolute force intensities are needed, which may have implications for muscle fatigue development and potential fatigue mitigation strategies.

Practitioner Summary: Muscle oxygenation impacts fatigue development that can in turn affect worker health and productivity. Males exhibit greater forearm desaturation than females at higher relative work intensities, despite similar fatigue levels. Females may be predisposed to greater muscle delivery and oxygenation challenges that can increase their fatigability during work at absolute load levels.

Abbreviations: ECR: extensor carpi radialis; FCR: flexor carpi radialis; MSD: musculoskeletal disorders; MVC: maximum voluntary contractions; NIRS: near infrared spectroscopy; TOI: tissue oxygenation index

ARTICLE HISTORY
Received 15 March 2018
Revised 10 June 2018
Accepted 18 July 2018

KEYWORDS
NIRS; upper extremity; gender; intensity; strength

Introduction

Upper extremity musculoskeletal disorders (MSDs) are a major problem across a variety of occupational domains and can significantly burden worker health (Ghosh, Das, and Gangopadhyay 2011; Wu et al. 2014) and increase business costs (Rossettini et al. 2016; Davis and Kotowski 2015). The nature of many industrial jobs has shifted from those requiring high forces to requiring repetitive contractions of the hand/arm and finger muscles, such as power or pinch grips (Sj⊘gaard and S⊘gaard 1998; Bao et al. 2015). These occupational upper extremity tasks can be categorised based on the amount of force required, repetition, duration and type of activity (Bao et al. 2016). The force generating capacity of the muscle can be impacted by these task-related factors over time, leading to fatigue (V⊘llestad 1997) and subsequent decrements in task performance during upper extremity work (Enoka and Duchateau 2008).

Muscle oxygenation is an important factor for maintaining muscle contraction while performing physical activities. The required sustained or repetitive muscle contractions for work increase the need for oxygenation at the target muscles (Perrey, Thedon, and Rupp 2010). While skeletal muscles vary their individual oxygen demand based on the magnitude of their contractions (Pittman 2000), ischemia of active muscle tissue impairs oxygen delivery causing muscle fatigue (Murthy et al. 2001). Muscle oxygenation diminishes due to posture of the body segment, frequency of task, force exerted and type of exertion (Mehta, Nussbaum, and Agnew 2012; Ferguson et al. 2013; Mehta and Agnew 2013). Additionally, tasks involving time pressure can further decrease oxygen saturation

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compared to tasks done at a relaxed pace (Heiden et al. 2005). Working over prolonged periods of time can increase muscle oxygenation demand, which if not met can lead to fatigue and declines in task performance, and gradually can increase likelihood of an accident or injury (Yang et al. 2007). Thus, the ability to monitor oxygenation in muscles during fatiguing exercises can contribute greatly to the understanding of the etiology and prevention of MSDs in workers.

During low-level muscle contractions, muscle oxygenation can be measured by near infrared spectroscopy (NIRS), which is a useful tool for assessing low force repetitive tasks (Murthy et al. 1997). NIRS has shown to be a reliable tool for measuring oxygenation and deoxygenation in contracting muscles (Celie et al. 2012), particularly during isometric activities (Hicks, Mcgill, and Hughson 1999; Crenshaw et al. 2012), and during cuff occlusion (Van Beekvelt et al. 2001). Reliability has been established utilising NIRS to measure oxygenation responses in the forearm and shoulder (Celie et al. 2012; Crenshaw et al. 2012), trunk (Kell, Farag, and Bhambhani 2004) and thigh muscles (Scott et al. 2014). In addition, NIRS has been employed to examine oxygenation changes during fatigue development in the shoulder (Elcadi, Forsman, and Crenshaw 2011; Crenshaw et al. 2012; Ferguson et al. 2013), and forearm muscles (Celie et al. 2015; de Oliveira et al. 2017). Studies have also reported forearm oxygenation changes across a range of submaximal muscle contraction intensities (from 10 to 70% maximum voluntary contractions; MVCs), but findings in these studies are limited to short duration testing (ranging from 20 to 60 s) of relatively small study samples (ranging from 20 to 24 participants) conducted in the same experimental session (Celie et al. 2012; Crenshaw et al. 2012). Forearm muscle oxygenation changes across a range of submaximal fatiguing exercises, conducted in different sessions to minimise fatigue carryover effects, in a larger study sample, have not been investigated.

Inconsistencies in the relationship between muscle oxygenation and electromyography indicators, that is, mean power frequency changes, during muscle fatigue have been reported. While Crenshaw et al. (2010) found no relationship between the hemodynamic and neural responses during isometric knee fatigue at 15 and 30% MVC, Yamada et al. (2008) reported significant relationship between the two indicators during isometric knee fatigue at 50% MVC. It is likely that the changes in muscle oxygenation in the fatiguing muscle is dependent on contraction intensity and can provide a better insight on central versus peripheral aspects of fatigue development (Bhambhani et al. 2014). Additionally, regional differences in oxygenation have been reported between muscles due to differences in intramuscular pressure owing to muscle size and structure (Miura et al. 2000; Quaresima et al. 2001).

Muscle oxygenation differences have been found between males and females (Elcadi, Forsman, and Crenshaw 2011; Kao and Sun 2015) that have been attributed to sex-differences in microcirculation, subcutaneous fat and skeletal muscle distribution (Kao and Sun 2015). Elcadi, Forsman, and Crenshaw (2011) reported that females exhibited wider changes in tissue oxygenation index (TOI) across a range (10–70% MVC) of submaximal forearm contraction exercises resulting in greater changes in oxygen saturation than males. However, it should be noted that the 30–70% MVC exercises in Elcadi, Forsman, and Crenshaw (2011) were performed for a short 20 s duration, and the 10% MVC was performed for a fixed 5-minute duration. Sex differences in muscle oxygenation patterns during the entire fatigue development process, that is, from start of an exercise to voluntary exhaustion, need to be examined. Exploring this during hand grip exercises will be particularly interesting given that prior studies have demonstrated comparable hand grip muscle endurance times between males and females (Nicolay and Walker 2005; Mehta and Cavuoto 2017).

The aims of the present study were (1) to examine changes in muscle oxygenation of the flexor and extensor carpi radialis (ECR) during 20, 40, 60 and 80% MVC submaximal sustained handgrip exercises using near infrared spectroscopy, and (2) to determine whether there are sex differences in oxygenation during these varied submaximal isometric hand/arm contractions. It was hypothesised that changes in muscle oxygenation during fatigue development would differ based on the contraction intensity of the working muscle and that this outcome would be sex dependent.

Methods

Participants

Forty-eight adults (24 males and 24 females) from the local community and university pool in Texas were recruited via email to participate in the study. All participants reported no musculoskeletal limitations or pain/discomfort of the upper extremity. Participants who were involved in aerobic or resistance training exercises (more than 3 sessions of 30 min each per week) or self-identified as hypertensive (>160/90 mm Hg) or diabetic were excluded from the study. All participants were right handed and sedentary or recreationally active to

Table 1. Participant demographics. Values are presented as Mean (SD).

	Males ($n=24$)	Females ($n=24$)
Age (years)	28.2 (3.1)	32.3 (9.1)
Weight (kg)	70.3 (4.9)	60.9 (6.8)
Height (m)	1.75 (0.1)	1.62 (0.1)
Body mass index (kg/m^2)	22.86 (2.0)	23.1 (1.9)
Percent body fat (%)	13.8 (4.1)	29.7 (6.1)
Waist circumference (cm)	87.4 (6.1)	83.7 (9.9)
Hip circumference (cm)	100.7 (6.4)	104.2 (6.9)

minimise confounding effects of physical activity levels. Participant demographics are provided in Table 1. This study was approved by the University Institutional Review Board and all participants provided written informed consent.

Procedures

Participants visited the laboratory on four separate days to perform submaximal fatiguing handgrip exercises at each of the four contraction intensities of 20, 40, 60 and 80% of MVC (one exercise per day). The order of the intensities was counterbalanced and separated by at least 48 h to allow for recovery post fatigue. On each experimental day, participants were seated in an adjustable chair with their right elbow flexed at 90 degrees and a padded guide supported their right forearm weight. The posture of the chair was adjusted to meet the comfort of the individual participant. A standardised grip posture (Nicolay and Walker 2005; Roman-Liu, Tokarski, and Kowalewski 2005) was used throughout testing and the arm was supported to minimise possible effects of fatigue from support of surrounding muscles (Rohmert et al. 1986; Price 1990). Isometric handgrip force was measured using a hand dynamometer and signals were sampled at 1000 Hz by a connected data acquisition system (TSD121C isometric hand dynamometer, BIOPAC Systems Inc, Goleta, CA).

During the first session, informed consent was obtained from participants prior to participation. Measures such as demographics, health history, body mass index (BMI, calculated as weight/height^2 [kg/m^2]), body fat percentage, waist and hip circumference (cm), shoeless height (cm) and shoeless weight (kg) were also recorded. A standard stadiometer and a digital metric scale were used to record height and weight, respectively, and waist and hip circumference were measured at the iliac crest and maximum buttocks region respectively with a flexible, inelastic measuring tape. Bioelectric impedance analysis (Tanita BC 418 MA Segmental Body Composition Analyzer, Japan) was used to obtain body fat percentage from all participants.

The protocol for each session was similar: an initial warm up, MVC strength testing and endurance test at one contraction intensity level until voluntary exhaustion, followed by a post MVC test. On each experimental session, participants first performed 2 min of intermittent gripping warm-up using a stress ball before any testing. On the first day participants preformed a MVC handgrip test protocol that was used to calculate target intensity levels for test days. Three MVCs were performed for 4 s based on standard strength testing procedures (Caldwell et al. 1974) with at least 2 min rest in between each trial, and the highest value was used to determine the contraction intensity level for all experimental sessions. Participants received visual feedback and were verbally encouraged to exert maximum voluntary handgrip strength during the MVC trials. For all subsequent sessions, the same MVC handgrip test protocol was performed to monitor initial MVC for that session. However, the target intensity levels for the four fatiguing exercises for each participant were determined based on MVC level measured at the first session.

After sufficient rest of ~2 min, participants then performed the fatiguing isometric contraction at the assigned level of 20, 40, 60 or 80% of MVC for that session. Participants were instructed to closely track their generated force across a targeted intensity level, which was presented as a red line on a computer screen at eye height. They were verbally encouraged to perform this task for as long as they could. Once the participant could no longer maintain the target force, the endurance task ended and the time was recorded. Participants then completed a post MVC to determine loss in strength from initial MVC for that session.

Measurements

Endurance time was measured to the point of voluntary exhaustion for all participants, which was defined >10% below required target for more than five consecutive seconds for each session. Strength loss for each exercise was calculated from the initial and post MVC values for that session. Handgrip force data was low-pass filtered at 15 Hz and coefficient of variation (i.e. ratio of the standard deviation of the force data to the mean force) was calculated at each consecutive 10 s windows to represent fluctuations in the exerted force.

Muscle oxygenation levels during the handgrip exercises were measured from the ECR and flexor carpi radialis (FCR) muscles of the dominant forearm using NIRS sensors (NIRO 200 NX, Hamamatsu Photonics, Hamamatsu, Japan). The NIRS sensors detected changes in oxygenated hemoglobin concentration by reflecting light onto the skins surface and detecting the diffused-light. TOI was calculated by utilising the spatially resolved spectroscopy methods, based on the manufacturer's guidelines. The light source and detection probe were placed longitudinally to the muscle belly placed approximately 3 cm apart in a black probe case with double-sided medical adhesive tape. The sampling rate for TOI was 5 Hz. TOI reflects local metabolic and hemodynamic changes in the FCR and ECR that were calculated as a ratio of oxygenated hemoglobin to total hemoglobin in the muscle tissue (Felici et al. 2009).

The force fluctuation and the TOI data of the two muscles during the four endurance tests were averaged over 10 s in three phases normalised to each participant's endurance time: early phase (1–10 s), middle phase (5 s around 50% endurance time) and late phase (final 10 s to voluntary exhaustion, defined earlier).

Statistical analysis

Initial handgrip strength difference between males and females was tested by an independent sample *t*-test. A 4 (contraction intensity: 20, 40, 60 and 80% MVC) × 2 (sex: male and female) mixed factor analysis of variance (ANOVA) was conducted on endurance time and strength loss. Separate three-way mixed factor ANOVAs were conducted to test the main and interaction effects of intensity (20, 40, 60 and 80% MVC), phase (early, middle and late) and sex (male and female) on force fluctuations and muscle oxygenation values (i.e. TOI) for the extensor and FCR. The level of significance for all analyses was set at $p < .05$. Where required, post hoc comparisons were performed using simple effects tests with a predetermined alpha of 0.05. All analyses were conducted using SPSS 22 (IBM SPSS Statistics, NY, USA).

Results

Males exhibited greater (∼60%) initial handgrip strength than females ($p = .032$). In general, endurance time decreased significantly with increasing contraction intensities ($p < .0001$) but remained comparable between males and females ($p = .72$). Strength loss was significantly influenced by contraction intensity ($F_{3,138} = 17.23$, $p < .0001$). Post hoc analyses revealed that strength loss decreased as intensity increased. No sex or sex x contraction intensity interaction was observed (all $p > .16$). Means (SD) of endurance times and handgrip strength and strength loss are provided in Table 2.

Table 2. Mean (SD) of initial handgrip strength, endurance time and strength loss during the handgrip fatiguing exercises at different contraction intensities.

	Males ($n = 24$)	Female ($n = 24$)
Initial strength (kg)	25.8 (3.9)	18.4 (18.0)
Endurance time (s)		
20% MVC	255.9 (92.5)	260.3 (113.7)
40% MVC	107.5 (36.2)	120.3 (52.0)
60% MVC	59.4 (23.0)	60.3 (20.6)
80% MVC	36.5 (15.4)	35.7 (14.3)
Strength Loss (%)		
20% MVC	43.7 (11.9)	41.8 (14.8)
40% MVC	34.5 (8.1)	38.6 (15.7)
60% MVC	34.5 (9.8)	27.7 (12.4)
80% MVC	27.0 (13.5)	20.5 (21.0)

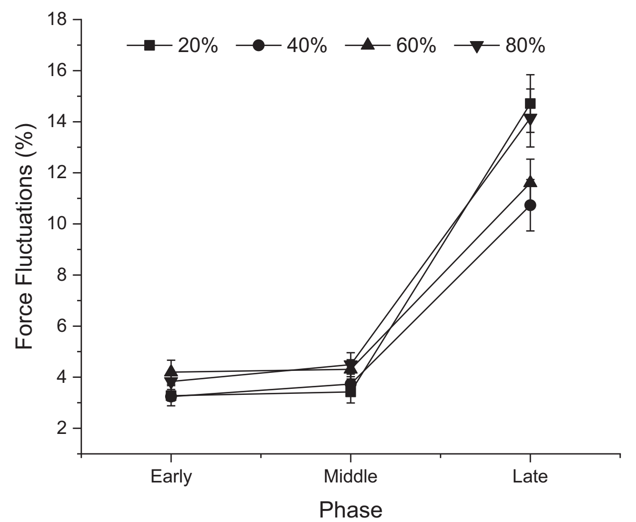

Figure 1. Force fluctuations, measured as coefficient of variation, during early, middle and late phases across each fatiguing task (pooled across males and females). Error bars represent standard error.

Force fluctuation was significantly influenced by contraction intensity ($F_{3,102} = 3.35$, $p = .02$), phase ($F_{2,68} = 178.04$, $p < .0001$) and their interaction ($F_{6,204} = 3.97$, $p = .001$). Overall, participants displayed significantly greater variability of force control at 80% MVC than at 40% MVC intensity, and during the late phases than during the early and middle phases of the fatiguing exercises. Post hoc analyses for the interaction effect revealed that greater fluctuations were observed during the 20 and 80% MVC levels, compared to the 40 and the 60%, but this was significant only in the late phase (Figure 1). No sex differences, either main or interactions with other study factors, were found on force fluctuations (all $p > .282$).

Tissue oxygenation of the ECR was significantly impacted by contraction intensity ($F_{3,96} = 4.73$, $p = .004$), phase ($F_{2,64} = 9.16$, $p < .0001$) and their interaction ($F_{6,192} = 3.15$, $p = .006$). Lower TOI levels were found at 60 and 80% MVC levels than at 20% MVC

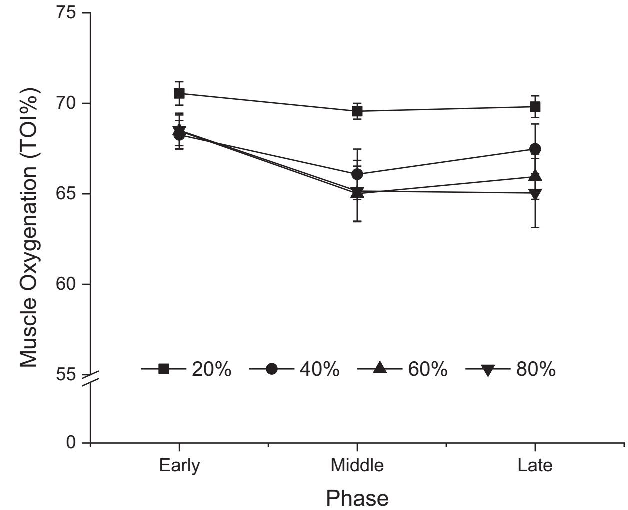

Figure 2. Muscle oxygenation (TOI) of the ECR during early, middle and late phases across each fatiguing task (pooled across males and females). Error bars represent standard error.

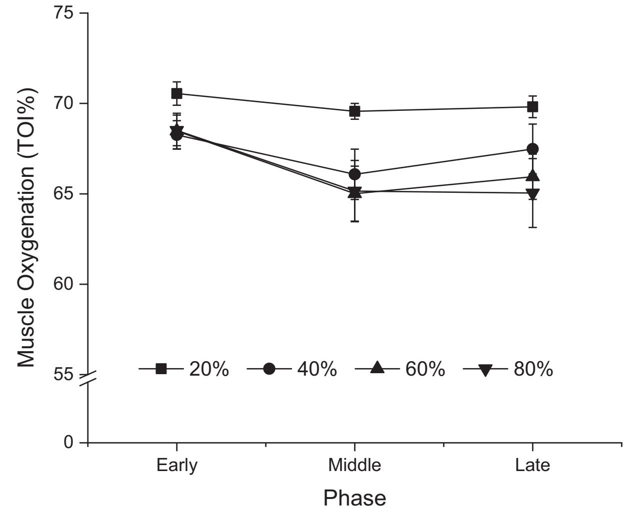

Figure 3. Muscle oxygenation (TOI) of the FCR during early, middle and late phases across each fatiguing task in (A) males and (B) females. Error bars represent standard error.

levels and during the middle than the early phases. Post hoc analyses for the interaction effect revealed that while TOI levels were lower at the middle when compared to the late phases during the 40% MVC levels, at the 60 and 80% MVC levels, TOI levels were lower at the middle and late phases than at the early phases (Figure 2). ECR TOI levels were also higher for females than males ($F_{1,32} = 26.8$, $p < .0001$), however no two or three-way interactions with sex were significant (all $p > .114$).

Tissue oxygenation of the FCR was significantly impacted by contraction intensity ($F_{3,96} = 28.49$, $p < .0001$), phase ($F_{2,64} = 69.51$, $p < .0001$) and their interaction ($F_{6,192} = 17.42$, $p < .0001$). Lower TOI levels were found at 60 and 80% MVC levels than at 40 and 20% MVC levels and during the middle and late than the early phases. Post hoc analyses for the interaction effect revealed that TOI levels during 40% MVC levels were lower at the middle when compared to the early phases. However, at the 60% MVC levels, FCR TOI levels were the lowest at the middle phase, then at the late phase, followed by the early phase. Finally, at 80% MVC levels, the TOI levels were similar between the middle and late phases but these were significantly lower than that at the early phase (Figure 3).

Similar to ECR, TOI levels for the FCR were higher for females than males ($F_{1,32} = 22.89$, $p < .0001$). Additionally, significant sex x contraction intensity ($F_{3,96} = 4.62$, $p = .005$), sex x phase ($F_{2,64} = 16.05$, $p < .0001$) and sex x contraction intensity x phase ($F_{6,192} = 3.7$, $p = .002$) effects were also found. Post hoc analyses revealed that FCR oxygenation showed similar trends during 40, 60 and 80% MVC levels for males; with TOI levels at the middle and late phases being significantly lower than that at the early phase. However, females exhibited significantly different TOI levels between each phase during 60 and 80% MVC levels and between middle and late phases during the 40% MVC levels (Figure 3).

Discussion

The present study compared changes in muscle oxygenation of the flexor and ECR, measured using NIRS, during sustained submaximal handgrip fatiguing exercises at 20, 40, 60 and 80% of MVC in young males and females. It was hypothesised that muscle oxygenation during handgrip fatigue development would be sex- and contraction intensity-dependent. The key findings, which were congruent with the study hypothesis, can be summarised as follows: (1) force fluctuation patterns during the fatiguing exercises were similar between the low (20% MVC) and the high (80% MVC) contraction intensities; (2) exercises at higher intensities (40, 60 and 80% MVC) were associated with greater decrements in both flexor and ECR oxygenation over time, with oxygenation remaining unchanged over time during low intensity (20% MVC) exercise; (3) males and females exhibited different rates of oxygenation changes as fatigue progressed despite demonstrating similar levels of relative fatigability.

Task and sex differences in fatigability

It is widely established that endurance time and strength loss decreases with increasing fatiguing contraction intensity (Rohmert et al. 1986; Garg et al. 2002; Staszkiewicz, Ruchlewicz, and Szopa 2002; Yassierli, Iridiastadi, and Wojcik 2007), and these relationships were also observed in the present study. Additionally, consistent with existing literature, males exhibited ~60% higher handgrip strength than females (Nicolay and Walker 2005; Shih 2007). Sex differences in fatigability have been shown to be task dependent (i.e. influenced by contraction intensity, mode, muscle group; Hunter 2009). The evidence on handgrip fatigability is particularly inconsistent, with reports of greater endurance times observed in females (West et al. 1995), or in males (Shih 2007), or no differences (Nicolay and Walker 2005). In the present study, both endurance time and strength loss were found to be comparable between males and females.

Force fluctuation during the fatiguing exercises was affected by both the contraction intensity and progression of fatigue development (i.e. over time during each exercise). These results are consistent with findings from other studies that reported greater fluctuations at very low and very high muscle contraction intensity and over time during fatiguing exercises (Yoon et al. 2007; Mehta and Agnew 2012; Mehta and Parasuraman 2014; Mehta and Cavuoto 2017). However, unlike Yoon et al. (2007), the present study did not observe any sex differences in force fluctuations, either over time or between different submaximal fatiguing exercises. In their study, Yoon et al. (2007) reported longer endurance times and greater strength loss in females during 20% MVC exercises of elbow flexors, which were largely driven by two female participants' data. Indeed, the two studies found similar results, that is, no sex differences on force fluctuations, at the 80% MVC exercises.

Task differences in muscle oxygenation during fatigue

Muscle tissue oxygenation during static contractions have shown to decrease at the onset of exercise, with greater rates of decline observed during exercises at higher muscle contraction intensities (Blangsted et al. 2005; Felici et al. 2009; Elcadi, Forsman, and Crenshaw 2011). At higher intensities, particularly at or above 50% MVC, intramuscular pressure increases over time that has shown to affect tissue oxygenation, but not blood flow (Van Beekvelt et al. 2002; Wigmore et al. 2004; McNeil et al. 2015). However, muscle oxygenation changes over time across different intensities, particularly up to voluntary exhaustion, have not been adequately investigated. Previous investigations of muscle oxygenation across different contraction intensities have focused on short durations (e.g. 20–60 s; Celie et al. 2012; Crenshaw et al. 2012; Felici et al. 2009; McNeil et al. 2015), which restricts the ability to compare muscle metabolic and hemodynamic changes during prolonged exertions more commonly observed in the workplace. Of the few published studies that investigated multiple submaximal contraction intensities, Felici et al. (2009) tested the relationship between muscle oxygenation and electromyography across 20, 40, 60 and 80% MVC isometric contractions of the biceps brachii for 30 s. They reported two distinct phases of oxygenation decline, an initial fast and a subsequent slow phase, over the course of sustained exertion. The rate of decline of the initial fast phase was intensity dependent, with the greatest oxygenation change seen between 20 and 40% MVC. Similar findings were obtained in the present study (Figures 2 and 3), with greater FCR TOI changes observed in the middle phase when compared to the early phase during exercises at 40, 60 and 80% MVC when compared to 20% MVC. McNeil et al. (2015) reported similar oxygenation patterns over the course of 1-minute isometric dorsiflexion contractions at low, moderate and maximal intensities.

In general, the present study found that muscle oxygenation plateaued over time, that is, similar TOI levels were found between the middle and the late exercise phases, however this relationship was dependent on the exercise contraction intensities. At higher submaximal exercise intensities, that is, at the 60 and 80% MVC levels, ECR and FCR oxygenation levels were comparable between the middle and late phases, but at the 40% MVC levels, oxygenation at voluntary exhaustion was found to be higher than during the middle phase. Prior studies that examined fatigue development at or above 50% MVC levels found comparable muscle oxygenation levels during the middle and late, or end-point, phases (Tachi et al. 2004; McNeil, Murray, and Rice 2006; Booghs et al. 2012; McNeil et al. 2015). The observed oxygenation plateauing may be attributed to increased intramuscular pressure that has shown to impact oxygen delivery and consumption rate in the contracting muscle at higher intensities (Jensen et al. 1999; Elcadi, Forsman, and Crenshaw 2011). Kahn et al. (1998) also attributed the oxygenation plateauing to recruitment of all type I and additional recruitment of type II muscle fibres at higher intensities. Whereas, studies that tested lower intensities, that is, at 40% MVC, found oxygenation at exhaustion to be higher than during the mid-point phase of the endurance testing, which may be attributed in part to potential increase in total haemoglobin levels in the muscle tissue during the sustained contractions (MacLeod et al. 2007; Philippe et al. 2012).

Metabolic state of contracting muscles during intermittent low force exertions associated with ischemia have shown to alter motor unit firing and recruitment patterns, subsequently contributing towards fatigue development (Moritani et al. 1992). The present study did not find any oxygenation differences over time during sustained low contraction intensity at 20% MVC. Studies have shown that at very low- to low-level static contractions (i.e. 5–20% MVCs), blood flow to the contracting muscle can be maintained over time (Sj⊘gaard et al. 1986; Blangsted et al. 2005; Booghs et al. 2012) and as such muscle haemodynamics may not be indicative of fatigue during sustained low level work intensities. However, force fluctuations over time were found to be similar between the 20 and the 80% MVC exercises in the present study. It is likely that the relationship between oxygenation and low-force fatigue development is contraction-mode (sustained versus intermittent) dependent. Alternatively, same few low-threshold motor units remain active during low-force exertions (Olsen, Christensen, and S⊘gaard 2001), thus, it may be possible that the NIRS measurement, which records tissue oxygenation over a larger volume, may not be sensitive enough to detect metabolic changes in specific single muscle fibers that are continuously firing during low-level exertions (Ferrari, Binzoni, and Quaresima 1997; Blangsted et al. 2005).

Sex differences in muscle oxygenation during fatigue

Sex differences in fatigability have been attributed, in parts, to differences in muscle mass, muscle morphology, contracting muscle metabolism and neuromuscular activation (reviewed in Hicks, Kent-Braun, and Ditor 2001). The review emphasised that muscle mass differences between males and females have direct impact on absolute muscle force development during exercises at relative (i.e. %MVC) levels, resulting in greater intramuscular pressure in males owing to higher strengths, which ultimately affects oxygen delivery and consumption in the contracting muscle through greater compression of active tissue vasculature (Barnes 1980; Maughan et al. 1986; Miller et al. 1993). Indeed, strength differences, of ~60%, in males and females in the present study may have played a role in the observed sex differences in the ECR and FCR muscle oxygenation (i.e. greater levels found in females than males). However, initial strength did not result in different levels of fatigability between the groups, as indicated by endurance time, strength loss or changes in force fluctuations; a finding similar to that reported by West et al. (1995).

An important finding of the present study is that sex differences in oxygenation is task-dependent, that is, influenced by contraction intensity and duration or phase of fatigue. While Figure 3 illustrates the main effect of sex on FCR TOI levels, further comparisons reveal that in males, tissue desaturation reaches its lowest point during the middle phase and remains at the same level until exhaustion during 40, 60 and 80% MVC exercises. Whereas in females, oxygenation increases at exhaustion during the higher contraction exercises. Intramuscular occlusion of blood flow has been reported to occur at higher contraction intensities (~50% MVC or above; McNeil et al. 2015; Wigmore et al. 2004; Van Beekvelt et al. 2002), which when compounded with increased intramuscular pressure due to greater absolute force levels in males, may play a role in the increased desaturation found in the contracting FCR muscles in males.

To date, only a few studies have investigated the influence of sex differences in muscle oxygen delivery and metabolism during fatiguing exercises. Greater relative fatigability in males has been shown to be influenced by decrements in oxygen delivery and muscle metabolism in studies that directly measured muscle oxygenation (Kao and Sun 2015) and those that manipulated muscle haemodynamics through experimental postures and protocols (Russ and Kent-Braun 2003; Clark et al. 2005). This is in accordance with the present study. However, some inconsistencies remain in the literature. Elcadi, Forsman, and Crenshaw (2011) reported (1) greater sex differences in muscle oxygenation at lower contraction intensities (i.e. 10–30% MVC; the present study found no sex differences at 20% MVC exercises); and (2) increased ECR and trapezius muscle desaturation in females than males. It should be noted that Elcadi, Forsman, and Crenshaw focused on oxygenation during tasks of 30 s exercise duration across a range of contraction intensities. Additionally, because they measured both electromyography and oxygenation, electrode/probe placements may have altered monitoring of similar muscle regions and depth when compared to the present study (Ferrari, Binzoni, and Quaresima 1997; Blangsted et al. 2005). Another study that examined finger flexor oxygenation during continuous and intermittent finger flexor fatigue exercises reported no sex differences in oxygenation, despite greater fatigue resistance observed in males (Philippe et al. 2012). It is likely that the absolute force levels employed in this study affected the findings. The study also highlighted the importance of training in re-oxygenation of contracting muscles during exercise.

Study limitations

There are a few limitations of the present study that warrant discussion. First, the experimental tasks employed were sustained isometric hand grip contractions that may not be representative of occupational tasks that are intermittent in nature. However, this study is the first to examine forearm muscle oxygenation changes over the course of fatigue development, from onset of exercise to voluntary exhaustion, across a wide range of contraction intensity conducted over multiple sessions in a relatively large sample ($n = 48$). As such, findings reported here may serve as a foundation for future investigations on muscle oxygen kinetics during hand grip fatigability across a variety of occupational task parameters. Second, the study examined relative fatigue development in males and females. However, workers are exposed to absolute loads in their daily jobs and thus, future work should focus on examining sex differences in oxygenation changes during occupational relevant tasks at absolute load levels. Third, individual factors such as age, physical activity and physical work experience and exposure can augment or blunt physiological differences affecting muscle oxygenation between males and females. While the present study minimised variability by recruiting sedentary or recreationally active volunteers within a specific age group and from a university student pool, findings reported here may vary with different worker populations. Additionally, while males and females in the present study had similar BMI levels, the groups differed based on fitness classification for percentage of body fat (American Council on Exercise, n.d.). This could likely contribute to the differences observed in muscle oxygenation, thus warranting further investigation. Fourth, unlike other studies, monitoring electromyography signals and comparing to oxygenation values would have enabled greater inferences on central and peripheral fatigue development process. However, multimodal muscle assessments often result in compromising probe locations, and it would have been particularly challenging to obtain oxygenation from the same muscle fiber bundle without oxygenation contamination from adjacent muscles of the forearm. Finally, NIRS can reliably measure tissue oxygenation up to a depth of 12.5 mm, based on the source-detector distance at the muscle surface. Sex differences in muscle size and depth as well as subcutaneous skin thickness could impact the NIRS measurements (Elcadi, Forsman, and Crenshaw (2011). However, participants in the present study had similar BMI levels across both groups and by only placing the NIRS probes on the muscle belly, measurement inconsistencies were minimised.

Conclusion

The present study examined forearm muscle oxygenation changes during fatiguing exercises, from exercise onset to voluntary exhaustion, at four different relative intensities in 48 young males and females. Handgrip strength of males was two times greater than that of females. While relative fatigability was similar for males and females, forearm oxygenation was found to be task (i.e. contraction intensity and phase of fatigue development) and sex dependent. Forearm oxygenation decreased with increasing intensities, but plateaued over time, particularly at higher intensities. Owing to potential increase in intramuscular pressure during exercise due to sex differences in muscle morphology and mass, males exhibited greater desaturation than females as fatigue progressed and this was augmented at higher contraction intensities. Work tasks performed at absolute loads will likely result in greater challenges in muscle oxygen delivery and utilisation in females that can increase their fatigability during work.

Acknowledgments

The authors would like to thank Ashley E. Shortz from Texas A&M University for her support during data collection.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

Its contents are solely the responsibility of the authors and do not necessarily represent the official views of the Centers for Disease Control and Prevention or the Department of Health and Human Services.

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