

# Neuromuscular responses at acute moderate and severe hypoxic exposure during fatiguing exercise of the biceps brachii

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## ABSTRACT

**Purpose:** The present study examined acute normobaric hypoxic exposure on the number of repetitions to failure, electromyographic (EMG) repetition duration (Time), EMG root mean square (RMS) and EMG mean power frequency (MPF) during biceps brachii (BB) dynamic constant external resistance (DCER) exercise.

**Methods:** Thirteen subjects performed two sets of fatiguing DCER arm curl repetitions to failure at 70% of their one repetition maximum under normoxic (NH), moderate hypoxia  $FiO_2 = 15\%$  (MH) and severe hypoxia  $FiO_2 = 13\%$  (SH). Electromyography of the BB was analyzed for EMG Time, EMG RMS, and EMG MPF. Repetitions were selected as 25%, 50%, 75%, and 100% of total repetitions (%Fail) completed. Pulse oximetry ( $SpO_2$ ) was measured pre-and post-fatigue.

**Results:** There was no significant three-way (Condition x Set x %Fail) or two-way (Condition x Set) interaction for any variable. The number of repetitions to failure significantly decreased from (mean  $\pm$  SEM)  $18.2 \pm 1.4$  to  $9.5 \pm 1.0$  with each Set. In addition, EMG Time increased ( $25\% < 50\% < 75\% < 100\%$ ), EMG RMS decreased ( $50\% > 75\% > 100\%$ ), and EMG MPF decreased ( $75\% > 100\%$ ) as a result of fatiguing exercise.  $SpO_2$  was lower during MH ( $\Delta 5.3\%$ ) and SH ( $\Delta 9.2\%$ ) compared to NH and as a result of fatiguing exercise increased only in MH ( $\Delta 2.1\%$ ) and SH ( $\Delta 5.7\%$ ).

**Conclusion:** The changes in BB EMG variables indicated exercise caused myoelectric manifestations of fatigue, however, acute moderate or severe hypoxia had no additional influence on the rate of fatigue development or neuromuscular parameters.

## 1. Introduction

Acute hypoxic exposure has been shown to induce systemic deoxygenation and increase in sympathetic nerve activity, however, the effects of hypoxia on neuromuscular function under fatiguing conditions remain conflicting (Fulco et al., 1996; Girard et al., 2015; Scott et al., 2017, 2018; Taylor et al., 1997; Torres-Peralta et al., 2014). For example, earlier studies have reported increased muscle activation in the quadriceps muscle during dynamic exercise under severe hypoxic conditions (Fulco et al., 1996; Girard et al., 2015; Scott et al., 2017; Torres-Peralta et al., 2014), while others have indicated that hypoxia had no effect on muscle activation (Scott et al., 2017, 2018; Taylor et al., 1997). Although Scott et al., 2017 reported no change in muscle activation during a deadlift in hypoxia, they did observe a difference in activation of the vastus lateralis and medialis in the same participants

performing a back squat (Scott et al., 2017). These results indicated muscle activation could potentially be dependent on muscle type and the eccentric/concentric muscle action (Scott et al., 2017).

The majority of exercise physiology research on hypoxia has examined muscles of the lower limb such as the vastus lateralis, vastus medialis, biceps femoris, or rectus femoris (Fulco et al., 1996; Girard et al., 2015; Scott et al., 2017, 2018; Taylor et al., 1997; Torres-Peralta et al., 2014). A recent study by Willis et al. (2019) indicated varying vascular responses of the leg and arm under hypoxia, suggesting variable vascular reactivity between large and small muscle masses (Willis et al., 2019). Smaller muscle masses (such as the arm) have a smaller blood vessel diameter and lower oxygen extraction/perfusion abilities; which indicate a greater oxygen sensitivity likely due to an increased oxygen requirement as a result of lower oxygen extraction/perfusion in small muscles (Willis et al., 2019). This variation in vascular reactivity between the arm and legs may potentially elicit differences in

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Abbreviations		Hz	Hertz
%Fail	Percent of Repetitions to Failure	MH	Moderate Normobaric Hypoxia (FiO <sub>2</sub> = 15%)
$\eta_p^2$	Partial eta Squared (Effect Size)	MMG	Mechanomyography
$\mu\text{V}$	Micro-Volt	MPF	Mean Power Frequency
1RM	One Repetition Maximum	MU	Motor Unit
ANOVA	Analysis of Variance	MUAP CV	Motor Unit Action Potential Conduction Velocity
BB	Biceps Brachii	MVIC	Maximal Voluntary Isometric Contraction
DCER	Dynamic Constant External Resistance	NH	Normoxic (FiO <sub>2</sub> = 21%)
Df	Degrees of Freedom	PDS	Power Density Spectrum
EMG	Electromyography	RMS	Root Mean Square
FiO <sub>2</sub>	Fraction of Inspired Oxygen	SH	Severe Normobaric Hypoxia (FiO <sub>2</sub> = 13%)
		SpO <sub>2</sub>	Peripheral Oxygen Saturation

neuromuscular responses under fatigue and hypoxic conditions, however, little research exists examining arm muscle response to fatiguing hypoxic conditions (Peyrard et al., 2019).

Electromyographic (EMG) amplitude provides information regarding the level of neuromuscular excitation and is influenced by the number of active motor units (MU) and their firing rates (De Luca, 1997; Vigotsky et al., 2018). Average MU action potential conduction velocity (MUAP CV) determines the shape of the EMG power density spectrum (PDS) (Lindstrom et al., 1970). As a muscle becomes fatigued a leftward shift towards lower frequencies on the EMG PDS have been observed, which is caused by a decrease in MU discharge rates and changes in MU action potential shape (Beck et al., 2014). The changes in action potential shape have been observed to be caused by decreases in conduction velocity of active fibers, which in turn are greatly affected by intracellular pH causing a left shift of the EMG PDS toward lower frequencies (Beck et al., 2014). Anaerobic exercise causes a greater disruption in intracellular pH compared to aerobic activities, due to an earlier onset of metabolic waste accumulation (Beck et al., 2014; Haff and Triplett, 2015; Kranz et al., 1985; Lindstrom et al., 1970).

Anaerobic exercise (e.g. lifting heavy loads, sprinting, and quick explosive movements) is typically defined as “exercise not requiring oxygen”, however, oxygen is still required for sustained movements and recovery (Hill et al., 2011; Taylor et al., 1997). Anaerobic exercise performance in hypoxic conditions has shown that there is a greater physiological demand as the fraction of inspired oxygen (FiO<sub>2</sub>) is decreased from 21% to 13%, and is accompanied by greater and more rapid fatigue development during exercise beginning at an FiO<sub>2</sub> of 12% compared to sea level (FiO<sub>2</sub> = 21%) (Bowtell et al., 2014). However, aerobic exercise performance in hypoxic conditions also exacerbates the effect of fatigue in working muscles. For example, Taylor et al. (1997) reported a decrease in muscle fiber conduction velocity (measured by EMG mean power frequency or EMG MPF) and an increase in electromechanical delay of the vastus lateralis during cycling exercise in hypoxic conditions (FiO<sub>2</sub> = 11.6%) but no observed change in normoxia (Taylor et al., 1997). In addition, Torres-Peralta et al. (2014) indicated increased EMG amplitude of the rectus femoris and vastus medialis with increased intensity of incremental cycling exercise to exhaustion, with a greater increase in hypoxia (FiO<sub>2</sub> = 10.8%) compared to normoxia (FiO<sub>2</sub> = 21%) (Torres-Peralta et al., 2014). Thus, the effects of hypoxia on the lower body are well investigated utilizing largely aerobic activities, however, there is limited studies examining hypoxia and neuromuscular responses of the upper body (Taylor et al., 1997; Torres-Peralta et al., 2014). Therefore, the primary purpose of this study was to examine the effects of acute normobaric hypoxic exposure on changes in the number of repetitions to failure and the EMG repetition duration (Time), EMG root mean square (RMS) and EMG MPF during dynamic constant external resistance (DCER) exercise of the biceps brachii. We hypothesize reducing FiO<sub>2</sub> will reduce the number repetitions because of the fatiguing effects of hypoxia (Bowtell et al., 2014; Taylor et al., 1997; Torres-Peralta et al., 2014).

## 2. Methods

### 2.1. Participants

Thirteen healthy recreationally active adults (10 men and 3 women, mean  $\pm$  SEM, age = 23.3  $\pm$  1.3 yr; body mass = 80.0  $\pm$  6.5 kg; height = 175.4  $\pm$  1.8 cm) volunteered to participate in this study. All procedures in this study were in accordance with the ethical standards of the University Institutional Review Board for Human Subjects and with the 1964 Declaration of Helsinki and its later amendments or comparable ethical standards (World Medical Association, 2013). All participants completed a health history questionnaire and signed an informed consent document before testing.

### 2.2. Study design

A randomized, repeated measures design was used for this study. Each participant visited the laboratory four times separated by 24–48 h at the same time of day. On visit 1 participants were familiarized with the testing equipment and given instructions on how to perform the exercise correctly. Following the familiarization visit, participants were randomly assigned to perform at normoxic (NH; FiO<sub>2</sub> 21%), moderate hypoxic (MH; FiO<sub>2</sub> 15%), and severe hypoxic (SH; FiO<sub>2</sub> 13%) conditions. During testing visits, participants completed two sets of unilateral arm curls to volitional exhaustion at 70% of one repetition maximum (1RM) separated by 1 min of rest on a Preacher Curl station (Magnum Fitness Systems, Strength Industry Inc., Redlands, CA, USA).

### 2.3. Hypoxic exposure

Participants were hooked up to a Hans Rudolph Oro-Nasal (Full Face) Mask with a Two-way Non-Rebreathing valve and Headgear (7400 Series Silicone Vmask™; Hans Rudolph Inc., Shawnee, KS, USA) for the entire duration of the testing and instructed to sit quietly for a few minutes to relax prior to exercise to become familiarised with the mask. The mask was connected to a hypoxic generator (HYP 123 Generator, Hypoxico Altitude Training Systems, New York, NY, USA) which takes room air and processes it through a filter to the user at a set altitude. In addition, the machine and mask were separated by a double-Douglas bag capable of storing 4 L of air, so the subject may breathe freely and not experience the typical effects of breathing through a restricted tube.

Hypoxic conditions were monitored using an oxygen monitor device (MySign®O; EnviteC by Honeywell, Wismar, Germany). Normoxic condition (NH) was administered by providing ambient room air, and hypoxic conditions were administered using a FiO<sub>2</sub> of 15% (MH) and 13% (SH) (Bowtell et al., 2014; Goodall et al., 2010; Kon et al., 2012; Peyrard et al., 2019; Scott et al., 2015). Participants were exposed to hypoxic conditions for the duration of the exercise and the mask was removed after testing completion. Participants could move freely and recover at normal room air.

#### 2.4. Dynamic constant external resistance exercise (DCER)

Testing was carried out according to the guidelines established by the National Strength and Conditioning Association on the first testing visit at  $\text{FiO}_2 = 21\%$  (Haff and Triplett, 2015). The participants performed a warm-up set of 8–10 repetitions at 50% of estimated 1RM, followed by a heavier warm up set of 3–5 repetitions. Participants began completing trials of a single repetition beginning with 90% of estimated 1RM with increasing loads by 2.3 kg until they were no longer able to complete a single repetition. The highest load (kg) successfully lifted through the entire range of motion was denoted as the 1RM, which was determined in  $\leq 4$  trials for all participants. Two to 4 min of rest was allowed between successive warm-up sets and 1RM trials.

During the 70% of 1RM fatiguing protocol, participants performed unilateral arm curl repetitions to failure. The weight was determined from each participants' first testing visit (at  $\text{FiO}_2 = 21\%$ ) 1RM test. The participant sat on the preacher curl station with seat height adjusted appropriately and starting in the arm flexed (or top position) for all arm curl testing. Failure during the arm curl movement was defined as the inability to complete the full range of motion during the concentric phase of the arm curl movement. A 1-min rest was given between the first and second set to exhaustion. Pulse oxygen saturation ( $\text{SpO}_2$ ) was measured using a finger pulse oximeter (Oxi-Go™ Pulse Oximeter, QuickCheck Pro, Oximeter Plus, Inc. Roslyn Heights, NY) before and after the 70% of 1RM fatiguing protocol at baseline and hypoxic conditions.

#### 2.5. Electromyography

Surface EMG signals were recorded using BioPac MP150 (BioPac MP150 with EMG100C amplifier; Biopac Systems, Inc., Santa Barbara, CA, USA) from the biceps brachii (BB) muscle of the right arm with a bipolar electrode (Kendall 530 series Foam Electrodes; Cardinal Health, Inc., Dublin, OH, USA) arrangement according to the Surface Electromyography for the Non-Invasive Assessment of the Muscles project recommendations (Hermens et al., 2000). The electrodes were placed 66% of the distance between the medial acromion and fossa cubit and oriented in line between the acromion and fossa cubit. The reference electrode was placed over the acromion process. Prior to electrode placement, the skin was dry shaved and cleaned with alcohol.

#### 2.6. Data processing

The EMG signals were sampled at 2000 Hz with an analog to digital converter, recorded on a laboratory computer, and processed off-line with custom written software (LabVIEW v 19, National Instruments, Austin, TX, USA). The EMG signals were bandpass filtered (fourth-order Butterworth) at 10–500 Hz. The repetition duration (EMG Time) to complete a single repetition was taken from the onset to the cessation of each repetition EMG signal. The EMG RMS and EMG MPF were calculated from the middle 33% of the concentric phase of each repetition. The EMG Time, EMG RMS and EMG MPF values from the repetitions corresponding to 25%, 50%, 75%, and 100% of each set were used for analysis. If percent failure was between repetitions, the repetition immediately following was selected.

#### 2.7. Statistical analysis

Three separate, 3 (Condition: NH, MH, and SH)  $\times$  2 (Set: Set 1 and Set 2)  $\times$  4 (percent of repetitions to failure: 25%, 50%, 75%, and 100%) repeated measures ANOVAs were used to examine mean differences for each absolute neuromuscular parameter (EMG Time, EMG RMS, EMG MPF). A 3 (Condition: NH, MH, and SH)  $\times$  2 (Set: Set 1 and Set 2) repeated measures ANOVA was performed to examine mean differences in the number of repetitions to failure. Another 3 (Condition: NH, MH, and SH)  $\times$  2 (Time: Pre-fatigue and Post-fatigue) repeated measures

ANOVA was conducted to investigate changes in  $\text{SpO}_2$  in response to acute hypoxic exposure and fatiguing exercise. We performed follow-up two and one-way ANOVA's when appropriate. Post-hoc Tukey least significant difference were used when appropriate. All statistical analyses were performed using IBM SPSS v 26 (Armonk, NY, USA) and an alpha of  $p \leq 0.05$  was considered statistically significant for all comparisons. If sphericity was not met according to Mauchly's Test of Sphericity, Greenhouse-Geiser Corrections were applied and partial eta-squared effect sizes ( $\eta_p^2$ ) were calculated for each ANOVA.

### 3. Results

#### 3.1. Effect of MH and SH on DCER arm curl repetitions to failure

Overall, hypoxia had no effect on the number of repetitions to failure, EMG MPF, EMG RMS, and EMG Time from DCER arm curl repetitions to failure. The number of repetitions to failure was similar between hypoxic conditions ( $p = 0.501$ ;  $\eta_p^2 = 0.056$ , Fig. 1). Participants completed fewer repetitions to failure in the second set of arm curl repetitions ( $18.2 \pm 1.4$  vs.  $9.5 \pm 1.0$ ,  $p < 0.001$ ;  $\eta_p^2 = 0.891$ , Fig. 1).

#### 3.2. Effect of MH and SH on neuromuscular responses

Repetition duration was similar between hypoxic conditions for both sets ( $p = 0.241$ ;  $\eta_p^2 = 0.112$ ) and percent of repetitions to failure ( $p = 0.377$ ;  $\eta_p^2 = 0.079$ ). Hypoxia had no effect on EMG MPF during repeated arm curl repetitions ( $p = 0.297$ ;  $\eta_p^2 = 0.096$ , Fig. 2). Overall, participants completed repetitions slower in the second set ( $1.25 \pm 0.09$  s vs  $1.12 \pm 0.09$  s,  $p = 0.001$ ;  $\eta_p^2 = 0.628$ , Fig. 2). Repetition duration also increased with the percent of repetitions to failure (25% < 50%,  $p = 0.015$ ; 50% < 75%,  $p < 0.001$ ; 75% < 100%,  $p < 0.001$ ,  $p < 0.001$ ;  $\eta_p^2 = 0.743$ , Fig. 2).

Participants EMG RMS was similar between hypoxic conditions for sets ( $p = 0.201$ ;  $\eta_p^2 = 0.128$ ) and percent of repetitions to failure ( $p = 0.675$ ;  $\eta_p^2 = 0.046$ ). Acute hypoxia had no effect on EMG amplitude ( $p = 0.391$ ;  $\eta_p^2 = 0.070$ ). There was a greater EMG RMS in the first set

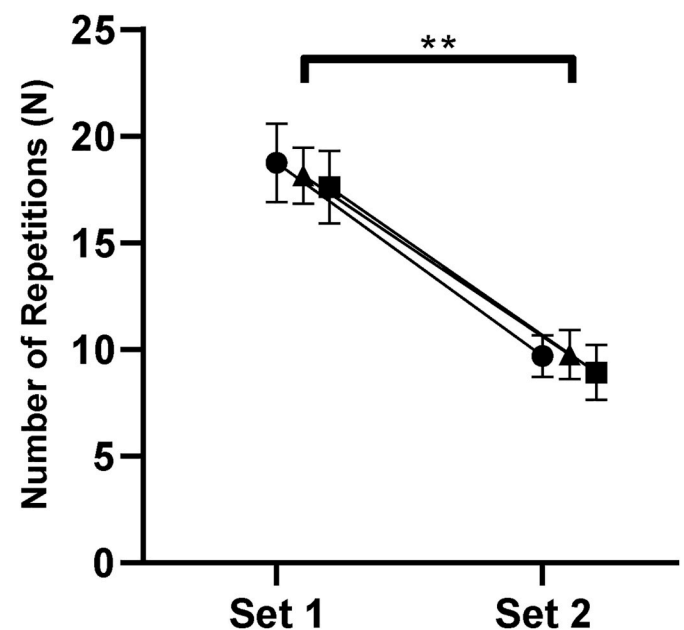


Fig. 1. Number of arm curl repetitions to failure at normoxic (solid circle; ●), moderate (solid square; ■) and severe hypoxia (solid triangle; ▲). Values presented as mean  $\pm$  SEM. \*\*Indicates statistically significant difference ( $p < 0.001$ ).

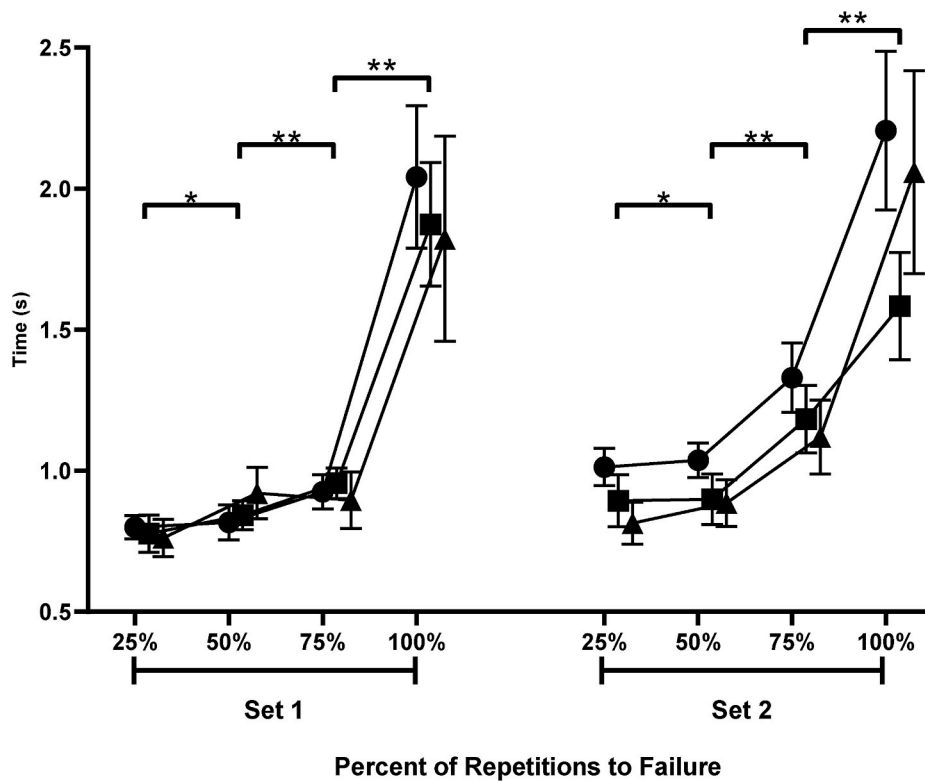


Fig. 2. Biceps brachii repetition duration as measured by electromyography (EMG) Time at normoxic (solid circle; ●), moderate (solid square; ■) and severe hypoxia (solid triangle; ▲). Values presented as mean ± SEM. \*Indicates statistically significant difference ( $p < 0.05$ ). \*\*Indicates statistically significant difference ( $p < 0.001$ ).

compared to the second set of arm curl repetitions ( $339.05 \pm 37.48 \mu\text{V}$  vs.  $318.76 \pm 37.34 \mu\text{V}$ ,  $p = 0.013$ ;  $\eta_p^2 = 0.411$ , Fig. 3), independent of hypoxia. There was also a decline in EMG RMS with each repetition ( $p <$

$0.001$ ;  $\eta_p^2 = 0.704$ ), which indicated that EMG RMS at 50% of repetitions to failure was greater than at 75% ( $p < 0.001$ ) and EMG RMS at 75% was greater than at 100% ( $p < 0.001$ ).

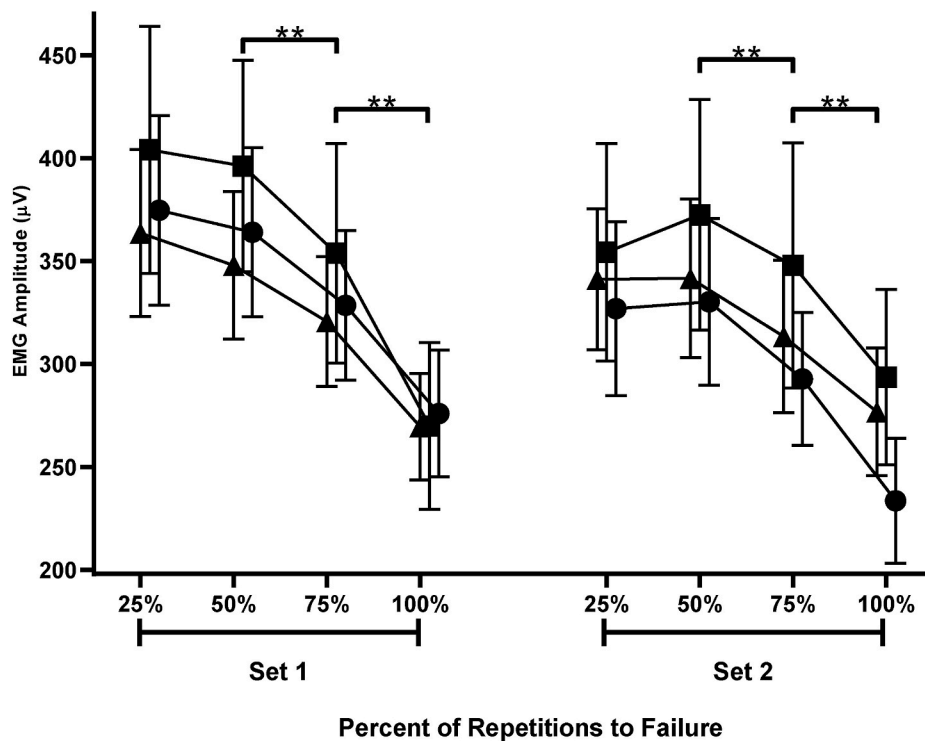


Fig. 3. Biceps brachii electromyography (EMG) amplitude as measured by EMG root mean square (RMS) at normoxic (solid circle; ●), moderate (solid square; ■) and severe hypoxia (solid triangle; ▲). Values presented as mean ± SEM. \*\*Indicates statistically significant difference ( $p < 0.001$ ).

Participants EMG MPF was similar between hypoxic condition for sets ( $p = 0.225$ ;  $\eta_p^2 = 0.117$ ) and percent of repetitions to failure ( $p = 0.736$ ;  $\eta_p^2 = 0.047$ ). The EMG MPF was also similar between NH, MH, and SH ( $p = 0.115$ ;  $\eta_p^2 = 0.165$ ). However, EMG MPF decreased between 75% of repetitions to failure and 100% ( $126.17 \pm 3.41$  Hz to  $116.85 \pm 3.98$  Hz,  $p < 0.001$ ;  $\eta_p^2 = 0.662$ , Fig. 4).

### 3.3. Oxygen saturation at MH and SH exposure

The results indicated a significant interaction effect ( $p < 0.001$ ;  $\eta_p^2 = 0.576$ ) between hypoxic conditions and pre-/post-fatigue for SpO<sub>2</sub>. Follow up one-way ANOVA revealed a difference between SpO<sub>2</sub> before the fatiguing protocol ( $p < 0.001$ ;  $\eta_p^2 = 0.681$ ), where SpO<sub>2</sub> at NH ( $97.08 \pm 0.31\%$ ) was greater compared to MH ( $91.85 \pm 0.59\%$ ,  $p < 0.001$ ) and SH ( $88.15 \pm 1.21\%$ ,  $p < 0.001$ ) exposure. SpO<sub>2</sub> at SH exposure was lower compared to MH ( $p = 0.034$ ) prior to the fatiguing protocol. Furthermore, SpO<sub>2</sub> was also different post-fatiguing protocol ( $p < 0.001$ ;  $\eta_p^2 = 0.574$ ). Post-fatiguing protocol SpO<sub>2</sub> indicated NH ( $97.42 \pm 0.34\%$ ) was greater than MH ( $93.77 \pm 0.85\%$ ,  $p = 0.011$ ) and SH ( $93.17 \pm 0.86\%$ ,  $p < 0.001$ ). Follow-up paired  $t$ -test indicated that at MH ( $p = 0.020$ ) SpO<sub>2</sub> following fatiguing exercise increased from  $91.85 \pm 0.59\%$  to  $93.77 \pm 0.85\%$ . At SH SpO<sub>2</sub> also increased from  $87.33 \pm 0.97\%$  to  $93.17 \pm 0.86\%$  following fatiguing exercise of the BB, however, there was change in SpO<sub>2</sub> following fatiguing exercise at NH.

## 4. Discussion

The purpose of this study was to examine the effects of acute hypoxia exposure on changes in the number of repetitions to failure, EMG Time, EMG RMS, and EMG MPF during DCER exercise of the biceps brachii. The main finding of this study indicated that hypoxia had no effect on rate of fatigue development as measured by number of repetitions to failure, EMG Time, EMG RMS (amplitude), and EMG MPF (frequency). Specifically, the present study showed a decrease in the number of

repetitions to failure performed from Set 1 (18 repetitions) to Set 2 (10 repetitions) (Fig. 1), as well as EMG Time, which increased for each set at 50%, 75%, and 100% of repetitions to failure (Fig. 2). However, there were no differences between hypoxic conditions for number of repetitions to failure and EMG Time. These findings were in agreement with those of Scott et al. (2015) who reported no differences in peak force or power during 5 sets of 5 repetitions of deadlift and back squat at 80% 1RM during normoxia (FiO<sub>2</sub> = 21% [sea level]), moderate hypoxia (FiO<sub>2</sub> = 16%), and severe hypoxia conditions (FiO<sub>2</sub> = 13%) (Scott et al., 2015). These findings were in contrast with Peyrard et al. (2019) who reported a decrease in time to exhaustion during hypoxia (FiO<sub>2</sub> = 13%;  $250 \pm 70$  s) compared to normoxia ( $460 \pm 220$  s) following repeated 10 s arm-cycle ergometer sprints to volitional exhaustion (Peyrard et al., 2019). In addition, Felici et al. (2001) reported decreased endurance time ( $22.4 \pm 4$  s to  $18.3 \pm 4.7$  s) during fatiguing isometric muscle actions of the biceps brachii at 80% of maximal voluntary isometric contractions at hypoxia (FiO<sub>2</sub> = 11%) compared to sea level (Felici et al., 2001). The differing results between the present study and Scott et al. (2015) compared to Peyrard et al. (2019) and Felici et al. (2001) may be due to mode-specific differences in the exercises performed and the magnitude of hypoxia (Felici et al., 2001; Peyrard et al., 2019; Scott et al., 2015).

In the present study SpO<sub>2</sub> was lower during MH and SH exposure, which indicated that hypoxic exposure was able to induce hypoxia and exercise elevated SpO<sub>2</sub> but not recover to Normoxic conditions (Goodall et al., 2010; Kon et al., 2012; Marillier et al., 2017). Similar to present results, Goodall et al. (2010) reported a reduced SpO<sub>2</sub> at mild (FiO<sub>2</sub> = 16%), moderate (FiO<sub>2</sub> = 13%) and severe (FiO<sub>2</sub> = 10%) hypoxia. In addition, the authors also reported an increased SpO<sub>2</sub>, mirroring present result, post fatiguing exercise in hypoxia indicating a potential mechanistic response to increase peripheral oxygenation (Goodall et al., 2010). This was later replicated by Marillier et al. (2017) indicating exercise increased SpO<sub>2</sub> in a hypoxic environment but not at sea level (Marillier et al., 2017). Kon et al. (2012) reported the only reduction in SpO<sub>2</sub> in normoxic conditions occurred 0 min after a bout of resistance exercise

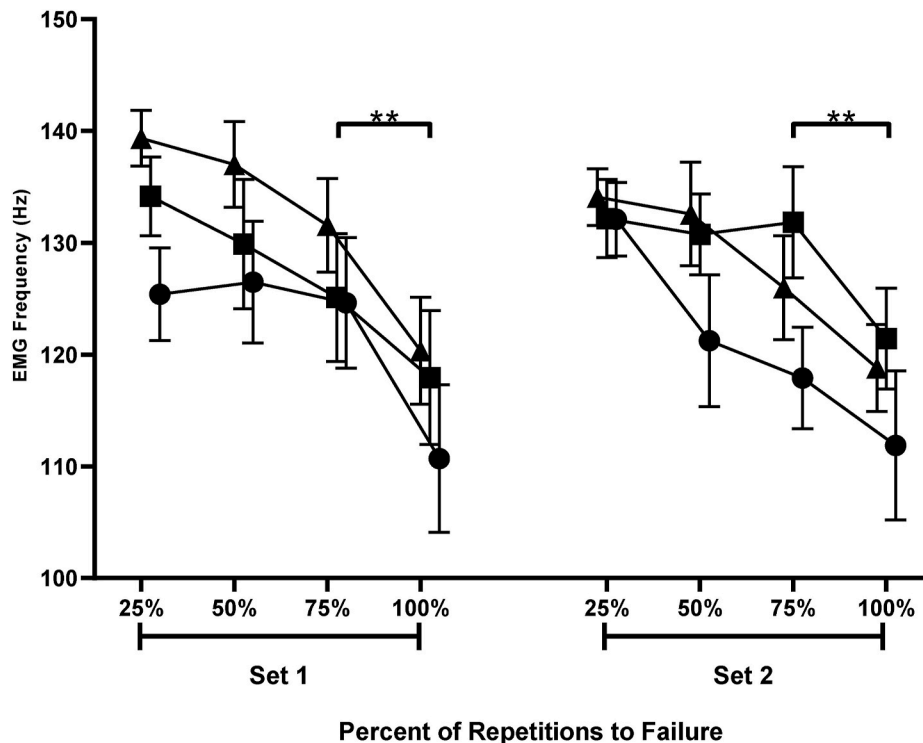


Fig. 4. Biceps brachii electromyography (EMG) frequency as measured by EMG mean power frequency (MPF) at normoxic (solid circle; ●), moderate (solid square; ■) and severe hypoxia (solid triangle; ▲). Values presented as mean  $\pm$  SEM. \*\*Indicates statistically significant difference ( $p < 0.001$ ).

and returned to normal levels after 15 min (Kon et al., 2012). However, despite an overall lower SpO<sub>2</sub> in hypoxia (FiO<sub>2</sub> = 13%) there was no additional change following resistance exercise (Kon et al., 2012). The present data and previous study results indicate a potential resistance exercise induced compensatory mechanism to increase peripheral oxygenation when exposed to hypoxia (Goodall et al., 2010; Kon et al., 2012; Marillier et al., 2017).

Dynamic muscle actions, such as DCER and arm-cycle ergometer exercise, have been known to cause a muscle “milking” action of the blood vessels, increasing venous return and greater arterial inflow into muscle tissue (Peyrard et al., 2019); however, the arm-cycle ergometer likely restricted blood flow to a lesser extent than DCER muscle actions. Furthermore, high intensity, sustained isometric muscle actions, such as those performed in Felici et al. (2001), have been shown to apply mechanical compression of the blood vessels temporarily reducing or eliminating blood flow (Felici et al., 2001). It has been reported that following temporarily blood flow restriction a post-occlusive reactive hyperemia effect occurs which temporarily increases blood flow and oxygenation to the working muscle immediately following high intensity exercise (Alvares et al., 2020; Ichinose et al., 2018). These muscle mechanics and increased blood perfusion to working muscles, could potentially explain an increase in SpO<sub>2</sub> post fatiguing exercise in both previous literature and present results (Alvares et al., 2020; Goodall et al., 2010; Ichinose et al., 2018; Marillier et al., 2017; Peyrard et al., 2019). Therefore, the findings of the present study indicated that acute moderate- and severe-hypoxic exposure does not influence fatigue development, as measured by the number of repetitions to failure and repetition duration during high-intensity upper body DCER exercise.

Although there were no effects of hypoxia on EMG RMS, there was a fatigue-induced decrease in MU activation due to repeated DCER arm curl repetitions to failure at 70% of 1RM (Fig. 3). That is, EMG RMS significantly decreased at 75% and 100% of the repetitions to failure during repeated arm curls at normal, moderate, and severe hypoxia. The findings of the present study were similar to previous investigations which reported fatigue induced decreases in EMG amplitude of the elbow flexors during isometric muscle actions (Kranz et al., 1985; Kumar et al., 2004; Orizio, 1992). For example, Kranz et al. (1985) reported a decrease in EMG amplitude during repeated maximal voluntary isometric contraction (MVIC) of the elbow flexors that was attributed to a fatigue-induced decrease in neural drive (Kranz et al., 1985). In addition, Kumar et al. (2004) found a correlation between the decline in force and decline in EMG amplitude during a sustained maximal isometric arm curl ( $r = 0.39$ ) as well as repeated isometric arm curl muscle actions at 40% MVIC ( $r = 0.11$ ) from the biceps brachii (Kumar et al., 2004). Finally, Orizio (1992) also reported a decrease in EMG amplitude during sustained isometric muscle actions at 80% and 100% MVIC from the biceps brachii (Orizio, 1992). Changes in EMG amplitude are typically attributed to the recruitment and firing rates of active MU and may provide an estimate of neural drive to the activated muscle (Farina et al., 2004). Type II MU have a faster conduction velocity and depolarization/repolarization, as well as shorter action potential duration (Merletti and Parker, 2004). Maximal biceps brachii MU recruitment has been suggested to be achieved at 88% of MVIC (Kukulka and Clamann, 1981), and the present study utilizing 70% of 1RM it can be suggested that there is near maximal MU recruitment during the arm curl repetitions. Therefore, the findings of the present study suggested that repeated arm curls in hypoxic and NH conditions resulted in similar patterns of responses for EMG RMS and that these decreases in EMG RMS were potentially due to decreased MU recruitment.

Furthermore, despite no effect of hypoxia on EMG MPF, the present study indicated a decrease in EMG frequency during DCER arm curl contractions at 70% of 1RM (Fig. 4). Specifically, EMG MPF significantly decreased between 75% and 100% of repetitions to failure. Our results are in agreement with Kranz et al. (1985) where motoneuron firing rate fell 60% during repeated MVICs of the elbow flexors (Kranz et al., 1985). Mottram et al. (2004) also reported a decrease in discharge rate at low

intensity isometric muscle actions from the elbow flexor muscles (Mottram et al., 2005). These studies with similar methods as the present study suggest MUAP CV is influenced by peripheral factors. The hypothesis suggests that muscle energy metabolism and its extracellular environment influences neural activity within a muscle cell (Kranz et al., 1985; Merletti and Parker, 2004; Mottram et al., 2005). Therefore, the findings of the present study indicated that fatiguing arm curl repetitions at normal (FiO<sub>2</sub> = 21%), moderate (FiO<sub>2</sub> = 15%), and severe (FiO<sub>2</sub> = 13%) hypoxia resulted in similar MUAP CV. Further, DCER arm curl repetitions at 70% of 1RM until volitional exhaustion causes a decrease in MUAP CV towards the end of exercise.

The current findings examine neuromuscular changes during DCER arm curls while exposed to hypoxic conditions. A limitation of this study was that participants were exposed to altered inspired oxygen (FiO<sub>2</sub>) and not to natural pressure fluctuations which occur with elevation changes. Previous research has shown that normobaric hypoxia (altering FiO<sub>2</sub> at ambient pressure) to be more difficult compared to hypobaric hypoxia (altering barometric pressure through decompression chamber or ascent to altitude) (Richard and Koehle, 2012). Specifically in normobaric hypoxia there is a greater ventilation rate, breathing frequency, end-tidal O<sub>2</sub> and CO<sub>2</sub>, and respiratory exchange ratio (Loeppky et al., 1997; Savourey et al., 2003). Future studies may want to incorporate metabolic markers of muscle activity, due to decreased O<sub>2</sub> availability (hypoxia) affecting primarily metabolic demand and therefore influencing neuromuscular activity as described above (Hackett and Roach, 2001; Mazzeo, 2008; Naeije, 2010). The addition of mechanomyography (MMG) would provide quantification of both electrochemical and mechanical components of neuromuscular performance. The EMG signals were not synced with force and/or position which could create issues in signal interpretation, future study recommendations is to sync movement with a goniometer, force, or metronome to control for repetition duration. Furthermore, the raw EMG signal has been accepted for use when there are no changes to the EMG set-up (electrode placement, amplification, filtering, etc), under constant temperature/humidity conditions, and a short period of time such as within the present study (Halaki and Ginn, 2012). In addition, the traditional use of maximal voluntary contraction as a normalization method remains highly criticized in relation to dynamic movements with no supported alternative methods as of present (Albertus-Kajee et al., 2011; Fernandez-Pena et al., 2009; Halaki and Ginn, 2012; Rouffet and Hautier, 2008).

In summary, the present study indicated no change in the number of arm curl repetitions to failure, times to complete repetitions, and no change in the muscle contractile process at acute normal (FiO<sub>2</sub> = 21%), moderate (FiO<sub>2</sub> = 15%), and severe (FiO<sub>2</sub> = 13%) hypoxia exposure. There was a decrease in the number of repetitions to failure performed from Set 1 to Set 2 of arm curls. Time to complete repetitions increased at 50%, 75%, and 100% of repetitions to failure. Furthermore, the present study indicated a decrease in EMG amplitude at 75% and 100% repetitions to failure and a decrease in EMG frequency at 100% repetitions to failure. The use of high intensity exercise near maximal MU recruitment, combined with consistent force production and the use of small muscle groups indicate an ability to maintain similar neural activation strategies when acutely exposed to hypoxia. Despite similar performance and EMG time course changes in acute hypoxic exposure, the results of the present study demonstrated DCER repeated arm curl repetitions at 70% of 1RM caused a decrease in both MUAP recruitment (EMG RMS) and MUAP CV (EMG MPF). Acute hypoxic exposure had no influence on rate of fatigue development or neuromuscular parameters of the biceps brachii.

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## CRedit authorship contribution statement

**Jasmin R. Jenkins:** Conceptualization, Methodology, Software, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Owen F. Salmon:** Conceptualization, Methodology, Software, Investigation, Data curation, Writing – review & editing, Visualization. **Ethan C. Hill:** Conceptualization, Methodology, Formal analysis, Writing – review & editing, Supervision. **Jason B. Boyle:** Conceptualization, Methodology, Formal analysis, Writing – review & editing, Supervision. **Cory M. Smith:** Conceptualization, Methodology, Software, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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