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Neuromuscular Responses at Acute Altitude Exposure During Fatiguing Dynamic Exercise of the Biceps Brachii

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NEUROMUSCULAR RESPONSES AT ACUTE ALTITUDE EXPOSURE DURING FATIGUING DYNAMIC EXERCISE OF THE BICEPS BRACHII

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NEUROMUSCULAR RESPONSES AT ACUTE ALTITUDE EXPOSURE DURING

FATIGUING DYNAMIC EXERCISE OF THE BICEPS BRACHII

by

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Abstract

BACKGROUND: The capacity to do work is greatly affected by high altitude exposure. Larger muscle groups of the lower body and exercises primarily aerobic in nature have been well investigated at high altitude. The present study examined acute altitude exposure on the number of repetitions to failure and electromyographic (EMG) repetition duration (Time), EMG root mean square (RMS) and EMG mean power frequency (MPF) during dynamic constant external resistance (DCER) exercise of the biceps brachii.

METHODS: Thirteen subjects performed two sets of fatiguing DCER arm curl repetitions to failure at 70% of their one repetition maximum (1RM) obtained at 1067 m, in simulated normobaric elevations of 1067m, 2438m, and 3810m. Electromyography of the biceps brachii was analyzed for EMG Time, EMG RMS, and EMG MPF. Repetitions were selected as 25%, 50%, 75% and 100% of total repetitions completed.

RESULTS: There was no significant three-way (altitude x set x percent of repetitions to failure) or two-way (altitude x set or percent of repetitions to failure) interaction for any variable. The number of repetitions to failure significantly decreased from (mean ± SEM) 18.2±1.4 to 9.5±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.

DISCUSSION: The changes in biceps brachii EMG variables indicated exercise caused myoelectric manifestations of fatigue, however, acute altitude exposure had no additional influence on rate of fatigue development or neuromuscular parameters.

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Introduction

The United States (U. S.) Army Infantrymen (11b) have one of the most physically demanding jobs in today's military. The infantry is the main land combat force of the U. S. Army, responsible for defending against any threat by land and capturing, destroying, and repelling enemy ground forces. They perform as a member of a fire team during drills and combat, aid in the mobilization of vehicles, troops, and weaponry, assist in reconnaissance missions, process prisoners of war and captured documents, and use, maintain and store combat weapons (e.g. rifles, machine guns, mines, etc.). In Infantry combat battalion soldiers, 54% of total injuries in a 12 month deployment period resulted in 24 hours or more of limited duty designation, with higher rates associated with a lower physical fitness.(48) Therefore, combat battalions, especially infantrymen, are at higher risk of injury under daily occupational tasks, however, when fatigued or exposed to unfavorable environmental conditions, performance and risk of injury may increase.

Altitude influences many physiological functions associated with Military physical task performance, due to the decrease in the amount of available oxygen from lower pressure conditions at high altitude.(23) In many cases, soldiers need to be rapidly inserted from low altitude to high altitude in less than an hour and due to time constraints traditional altitude acclimatization is not feasible. They must be physically capable of deploying at any time, such as to the mountainous regions of Afghanistan where elevation ranges from 1200 m up to 7492 m, making physical fitness important to maintain combat readiness and mission success at high elevations.

Surface EMG is used as an indicator of gross motor unit activity and measures motor unit action potentials that activate skeletal muscle fibers during contraction.(14, 15) The most common application utilizing EMG is investigating muscle activation patterns of torque production during dynamic and isometric muscle actions. Electromyographic amplitude provides information regarding the level of muscle activation and is influenced by the number of active motor units and their firing rates.(14) Average motor unit action potential conduction velocity (MUAC CV) determines the shape of the EMG power density spectrum (PDS).(34) 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 motor unit discharge rates and changes in motor unit action potential shape.(3) Action potential shape changes 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 compression of the EMG PDS toward lower frequencies.(3)

Anaerobic exercise (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.(23, 54) Studies on hypoxic conditions and anaerobic exercise performance have shown that there is a greater physiological demand as the fraction of inspired oxygen (FIO2) is decreased from 0.21 to 0.13, and is accompanied by greater and more rapid fatigue development during exercise beginning at an FIO2 of 0.12 (equivalent altitude at 4438 m) compared to sea level (FIO2 = 0.21).(9) One study done by Bowtell et al., (2014) reported the greatest changes in blood lactate concentration, muscle deoxygenation, and integrated EMG of the vastus lateralis during repeated sprints in hypoxic conditions (FIO2 = 0.13) compared to other altitude conditions (FIO2 = 0.12, 0.14, 0.15, and 0.21).(9) Taylor et al., (1997) found a decrease in muscle fiber conduction velocity (EMG MPF) and an increase in electromechanical delay of the m. vastus lateralis during cycling exercise in hypoxic conditions (FIO2 = 0.116) but no change in normoxia.(54) Another study by Torres-Peralta et al., (2014) saw increased EMG amplitude of the rectus femoris and vastus medialis with increased intensity of incremental cycling exercise to exhaustion, with a greater effect in hypoxia (FIO2 = 0.108) compared to normoxia (FIO2 =

0.21).(56) The effects of hypoxia on the lower body is well investigated in many studies utilizing largely aerobic activities,(9, 54, 56) there is limited evidence, however, on the effects of hypoxia smaller muscle groups of the upper body.

Dynamic muscular endurance capability in acute altitude exposure may be of interest in designing soldier training programs, due to the rapid insertion into high altitude environments where mission requirements demand sustained physical activity which is largely affected by altitude. Neuromuscular fatigue has been defined as "any reduction in the force generating capacity of the total neuromuscular system regardless of the force required in any given situation".(7) This definition can then be broken down into muscle mechanical fatigue "the inability to maintain a desired level of force" and myoelectric fatigue "modifications in the pattern of electrical activity in the muscle occurring in parallel".(37) In the present study, the number of repetitions until volitional exhaustion will be used as a measure of mechanical fatigue and the analysis of surface EMG signals of selected repetitions of arm curls through the complete range of motion to quantify myoelectric fatigue. Therefore, the primary purpose of this study was to examine the effects of acute altitude exposure on changes in the number of repetitions to failure and the EMG repetition duration (Time), EMG root mean square (RMS) and EMG mean power frequency (MPF) during dynamic constant external resistance (DCER) exercise of the biceps brachii.

Literature Review

Muscle Fatigue and Function

Hogan, Richardson, & Haseler, 1999

The purpose of this study (24) was to examine the relationship among muscle phosphocreatine (PCr) hydrolysis, intracellular H+ concentration accumulation, and muscle performance during incremental exercise during the inspiration of different fractions of inspired O2 (FIO2). Six healthy men (n=3) and women (n=3) performed three maximal exercise bouts of 2 min unloaded plantar flexion (at a work rate of 1 contraction/s), followed by 1 W work rate increases every 2 min until exhaustion. The three different exercise bouts were performed at 1.00, 0.21, or 0.10 oxygen concentration. Magnetic resonance spectroscopy (MRS) was continuously acquired during pre-exercise to recovery. Levels of PCr, phosphate ions (Pi), and ATP determined from the areas under their respective spectral peaks were normalized (percentage of rest) to the average values obtained from the last 32s of rest for each subject. The results showed a significant difference among time to exhaustion among all three conditions 17.7 ± 1.3 min (FIO2 = 0.10), 21.0 ± 0.9 min (FIO2 = 0.21), and 24.0 ± 1.8 min (FIO2 = 1.00) ($p<0.01$). Skeletal muscle ATP did not change in response to workload or FIO2 conditions. Resting heart rates were significantly different ($p<0.01$) among each FIO2 condition. Resting muscle PCr was not different among conditions, and fell from resting values as workload increased. Work rates of 6 W and higher, showed a greater depletion of PCr ($p<0.01$) in the FIO2 of 0.1 compared to the other conditions. PCr at exhaustion did not differ among conditions. Relative values of Pi were greater at work rates above 5 W ($p<0.01$) in the FIO2 of 0.1 compared to the other two conditions, and was greater in 0.21 vs. 1.00 FIO2 at 9 W. Relative Pi at exhaustion was not different among the three conditions. Furthermore, at work rates of 5 W and higher, pH was less in the hypoxic (FIO2 = 0.1; $p<0.01$)

compared with the other two, and no difference at the time of exhaustion. Muscle ADP rose in a linear manner, but there were no differences at any workload. The authors concluded that muscle performance was improved during increased FIO2, and skeletal muscle PCr and pH were decreased at identical submaximal workloads in hypoxic conditions compared to others. The authors suggest that exhaustion in all FIO2 occurred when a particular intracellular environment was achieved.

Nagamachi, Ikata, Katoh, & Morita, 2000

The purpose of this study (41) was to examine the relationship of spectral changes of surface electromyography (sEMG) and exercise intensity determined from respiratory gas analysis during maximal treadmill running. Thirteen male athletes between 19-24 yrs (mean ± SD, 170.2 ± 4.3 cm, 67.5 ± 8.2 kg) performed two consecutive ramp exercise tests on the treadmill. Intensity was gradually increased (speed and percent grade) until subjects were no longer able to maintain running on the treadmill. Electrodes were placed over the erector spinae, and myoelectric signals were amplified through a low-pass filtered with 0.5 kHz cutoff frequency, and sampled in 0.5 s sequences at a rate of 1kHz into computer, then a 1,024-point fast Fourier transformation for mean power frequency (MPF) to be calculated every ten seconds. Gas exchange measurements were collected continuously using a breath-by-breath system. Prior to loading, MPF and gas exchange ratio (R) were 74.2 ± 7.2 Hz, 0.81 ± 0.07 in the first test and 74.7 ± 8.3 Hz, 0.80 ±0.06 in the second test, respectively. During loading, MPF decreased steadily and then exponentially fell to a base level in both tests. Within the first 30 s of quitting loading, MPF recovered to before loading in all subjects. The first test MPF, R, and percent oxygen uptake (%VO_2) were 59.4 ± 12.4 Hz, 0.99 ± 0.06, 74.3 ± 7.4% in the first test and 55.0 ± 11.2 Hz, 0.96 ± 0.06, 74.6 ± 7.3% in the second test. During the exponential decrease in MPF, which happened after the anaerobic threshold, MPF, R, and %VO_2 57.3 ± 12.9 Hz, 0.89 ±0.10, 65.8 ±9.2% in the first test and 59.2 ± 11.0 Hz, 0.86 ± 0.06, 61.2 ± 9.9% in the second test. The beginning of the base level, MPF, R, and %・VO2 were 41.4 ±9 .8 Hz, 1.00 ± 0.04, 78.0 ± 7.7% in the first test and 43.7 ± 6.9 Hz, 1.00 ± 0.10, 78.7 ± 6.7% in the second test, respectively. The authors concluded that a sudden fall and a base level of MPF is characteristic of local muscle fatigue, which occurs after anerobic threshold and before exhaustion.

Tenan, McMurray, Blackburn, McGrath, & Leppert, 2011

The purpose of this study (55) was to examine the relationship between mean power frequency (MPF) of surface electromyography (sEMG) during a maximal voluntary isometric contractions (MVIC) and lactate/potassium accumulation in the blood stream during a progressive cycling exercise test and recovery. Eight subjects (mean ± SD, 28.0 ± 6.4 yrs, 172.8 ± 10.0 cm, 68.4 ± 8.1 kg), four males and four females, came in on four separate occasions: (1) a screening trial to perform a submaximal exercise test to estimate maximal aerobic capacity; (2) a glycogen normal progressive cycling trial; (3) a 2 h timed exercise session designed to reduce glycogen stores; and (4) a glycogen reduced progressive cycling trial performed the morning after session three. Oxygen uptake was measured using a ParvoMedics TrueMax 2400 metabolic system. Whole blood lactate was measured using a calibrated Accutrend Lactate analyzer. Blood potassium (K^+) was measured using a blood chemistry analyzer system. Vastus lateralis sEMG data was sampled at 4096 Hz, amplified 10,000 (20-450 Hz), first bandpass filtered (20-350 Hz), and notch (59.5-60.5 Hz) filtered (fourth order Butterworth). Median power frequency was calculated for each contraction using fast Fourier transform. Changes in blood lactate (%LAC) increased as intensity increased ($p<0.001$). The reduced glycogen trial had lower values at 40%, 60%, 80%, and 100% of peak oxygen consumption (VO_{2peak}) ($p<0.028$). The change in K^+ increased with exercise intensity ($p<0.001$) but was not different between glycogen conditions ($p=0.169$). There was no change in MPF with increase in exercise intensity during either glycogen conditions ($p=0.399$). There was no difference between glycogen conditions for MPF ($p=0.363$). During both glycemic conditions the %LAC decreased with progression of time during recovery ($p<0.001$). The glycogen reduced condition had lower %LAC at 3- and 6-min post-exercise ($p<0.005$). Furthermore, during recovery %K increased with time ($p<0.001$) but was not different between glycogen conditions ($p=0.224$). During either condition change in MPF did not change over time and there was no difference between conditions ($p>0.05$). The authors concluded that lactate and potassium changes during/after progressive exercise did not relate to changes in MPF.

Febbraio & Dancey, 1999

The primary aim of this study (16) was to examine muscle energy metabolism throughout prolonged, fatiguing submaximal exercise. Six healthy untrained subject (mean ± SD, 20.7 ± 2.4 yrs, 62.7 ± 8.0 kg, 2.49 ± 0.5 l/min peak oxygen uptake) exercised on a cycle ergometer to voluntary exhaustion at an intensity equivalent to 93 ± 3% of lactate threshold (LT) or approximately 65% peak oxygen uptake (VO_{2peak}). Muscle biopsies were obtained at rest, 10 min of exercise, approximately 40 min before fatigue (F-40 = 143 ± 13 min) and at fatigue (F = 186 ±31 min). The authors found that both muscle and plasma lactate accumulation increased ($p<0.05$) at the onset of exercise but returned to resting levels thereafter. Heart rate also initially increased ($p<0.05$) and reached steady state after 80 min. Respiratory exchange ration progressively fell the first 80 min ($p<0.05$) and was maintained thereafter. There was no change in plasma glucose concentration throughout the exercise. Plasma free fatty acid concentrations increased significantly after 60 min of exercise ($p<0.05$). Muscle glycogen concentration decreased progressively ($p<0.05$) throughout exercise, and concentrations were very low (<50 mmol glucosyl U/kg dw) at fatigue. Muscle phosphocreatine (PCr) was higher when rest was compared with 10 min, F-40, and fatigue ($P<0.05$). Intramuscular creatine (Cr) increased throughout exercise ($p<0.05$) and was different from rest at 10 min, F-40, and fatigue. There was no change in muscle adenosine triphosphate, adenosine diphosphate, or adenosine monophosphate. Finally, there was a correlation ($r=0.95$, $p<0.05$) between time to exhaustion and glycogen use. The authors concluded that fatigue during prolonged exercise may be related to carbohydrate availability, therefore insufficient availability may influence muscle contractile function.

Pitcher & Miles, 1997

The purpose of this study (47) was to compare time course changes of fatigue and recovery under normal conditions and during blood flow occlusion. Nine males (18-28 yrs) performed two experimental sessions separated by 1 week. Subjects performed a maximal voluntary contraction force (MVC) followed by fatiguing hand-grip exercise at 80% of their pre-exercise MVC on a 6 s contraction/5 s relaxation cycle. During the last 100 ms of each contraction a digital timer triggered the delivery of a transcortical magnetic stimuli to assess the level of voluntary effort in each contraction. Exercise was terminated at volitional exhaustion. Subjects performed the same protocol, when force loss reached a plateau a cuff was inflated to 200 mmHg and maintained throughout exercise until volitional exhaustion. To assess recovery Pitcher & Miles (1997) had subjects perform brief MVC at 30 s intervals for 3 min, then at 1 min intervals for 5min, and then at 2 min intervals for a further 12 min. Finally, MVC's were performed every 5 min for 40 min or until pre-exercise MVC was replicated. The authors found no difference in pre-exercise MVC in cuff and no cuff conditions ($p>0.05$; t-test, d.f. = 7). No subjects reached exhaustion in the no-cuff condition and were only able to perform 14 ± 2 contractions (mean ± SD) with inflated cuff before exhaustion. Mean total force loss with the inflated cuff was $82 \pm 5\%$ MVC compared with 51 ±

11% MVC without the cuff. After 116 s of exercise, mean peak force was reduced in the cuff condition when compared to no cuff ($p<0.05$; t-test; d.f. = 7) and persisted until exhaustion. The most rapid recovery occurred in the first 30 s post-exercise. Peak force recovered from 19 ± 6 to 65 ± 14% MVC in the cuff condition. This recovery was greater than in the no cuff condition (49 ± 11 to 58 ± 14% MVC; $p<0.05$; t-test, d.f. = 7). Force continued to recover more rapidly after the cuff exercise so that after 2, 2.5, 3, and 4 min of recovery, the forces produced were greater than that of the cuff exercise ($p<0.05$; t-test, d.f. = 7). The authors concluded that muscle blood flow occlusion during intermittent exercise reduced muscular endurance without prolonging recovery.

Signorile, Digel, Moccia, Applegate, & Perry, 1991

The purposes of this study (50) were to 1) examine whether amplitude and frequency changes of fatiguing isometric exercise be produced by isotonic exercise and 2) investigate if the frequency shifts produced during fatiguing exercise is the result of increased metabolite concentration. Ten subjects (five men and five women, aged 22-43 yrs) performed two sets of 25 isotonic biceps curls in partially occluded (PO) and nonoccluded (NO) condition. Partial occlusion was performed using a standard blood pressure cuff at the proximal end of the muscle and inflated to midway between systolic blood pressure and diastolic blood pressure. Electromyography (EMG) electrodes were placed immediately distal to the midpoint of the muscle and medial to the longitudinal axis, and reference electrode over the radial condyle. Data was collected at 1,024 samples per second, bandpass at 10 and 1,000 Hz, and processed using Hamming window function and 512-point fast Fourier transform to obtain a power frequency spectrum. The authors found no difference in PO and NO amplitude (rmsEMG) of the first repetition. In the NO condition there was an increase in rmsEMG values (532 ± 112 and 737 ± 161 µV, $p<0.0312$). The first and last repetitions of the PO conditions also increased (596 ± 153 and 1,110 ± 244 µV, $p<0.0020$).

Furthermore, the last repetition of the PO condition had a higher rmsEMG than NO ($p<0.0063$). The frequency spectrum for the first repetitions across conditions was not different ($p=0.1488$). The frequency shifts from the first to last repetitions for both conditions was significantly different (NO, $p=0.0216$; PO, $p=0.0002$). The frequency shift between first and last repetition for the PO condition was greater than that of the NO condition (PO > 29.4 Hz, NO = 7.93 Hz, $p<0.0001$). The authors conclude that changes in amplitude and frequency characteristics of fatigue during isometric exercise can be produced to a lesser degree during dynamic exercise and amplified by the addition of occlusion.

<u>Komi & Tesh, 1979</u>

The purpose of this study (28) was to investigate electromyography (EMG) spectral changes under maximal dynamic fatigue conditions. Eleven male physical education students were divided into Group I with <50% fast twitch fibers (27.8 ± 2.8 yrs, 74.0 ± 3.4 kg, 180.4 ± 1.8 cm) and Group II with >50% fast twitch fibers (23.1 ± 1.1 yrs, 69.6 ± 2.0 kg, 178.0 ± 1.3 cm) of the vastus lateralis muscle. Subjects performed 100 maximal voluntary knee extension on an isokinetic device through a motion range from 100° (0.55 π) flexion to a fully extended knee joint and angular velocity of 180° x s^{-1} (π rad x s^{-1}). Passive recovery time between contractions was 0.7s. Electromyographic activity was taken from the vastus lateralis at a frequency range of 10 to 10,000 Hz and processed using custom processing system. The authors found a greater decline in torque in group II (absolute, $p<0.01$; relative, $p<0.05$). Tension outputs at the end of exercise had decreased to 51 and 38 % of initial value in groups I and II, respectively. There was also a positive correlation between decline in torque and % fast twitch area ($r=0.73$, $p<0.01$). Integrated EMG (IEMG) declined in group II by 15 ± 3% ($p<0.01$). There was an increase in IEMG/torque ration with fatigue ($p<0.01$) and a relationship between relative increase in IEMG/torque ration and torque decline ($r=0.88$, $p<0.001$). Mean power frequency (MPF) declined 26 ± 3 Hz or 25 ± 3% ($p<0.001$) in group II, but non-significantly in group I. Changes in the power spectral density function (PSDF) in both groups occurred after only 25-30 contractions ($p<0.01$). Individual torque decline after 25 contractions was positively related to shift in PSDF expressed as a relative change in MPF ($r=0.73$, $p<0.01$) and individual decrease in MPF was greater in subjects with greater relative area of fast twitch fibers ($r=-0.60$, $p<0.05$). Group II had higher ($p<0.01$) relative content of lower bandwidth and lower content ($p<0.05$) of the higher bandwidth compared to group I after 25-30 contractions. The authors concluded that muscle contraction failure is related to qualitative changes in motor unit recruitment patterns.

Hypoxia

Bowtell, Cooke, Turner, Mileva, & Sumners 2014

The purpose of this study (10) was to determine a dose response to different inspired oxygen fractions on acute physiological and performance on sprints. Nine healthy, male athletes (mean ± SD, 23.6 ± 3.7 yrs) performed ten consecutive 6s sprints separated by 30s rest, in normoxia at 21% fraction of inspired oxygen (FIO2) and four levels of hypoxia at an FIO2 12%, 13%, 14%, and 15%. Bowtell et al. 2014 found a lower peak speed in all hypoxic conditions compared to the normoxic conditions (12%: 31.4 ± 1.5; 13%: 31.2 ± 1.8; 14% 31.8 ± 1.8; 15%: 32.1 ± 1.5; 21% 32.0 ± 1.5 km h-1; $p=0.019$). The results also indicated a greater fatigue index during the 12% (-17.6 ± 4.2%) compared to 21% FIO2 (-10.0 ± 3.4%; $p<0.001$). There was also a greater percent decrement score (Sdec) at 12% FIO2 (-9.9 ± 2.2%) compared to in all other conditions (13%: -6.2 ± 2.2; 15%: -6.9 ± 1.0; 21%: -4.9 ± 1.2%; $p<0.05$), but the 14% FIO2 (14%: -7.4 ± 2.1) sprint. Peripheral capillary oxygen saturation (SpO2) was lower in hypoxic conditions during sprints and recovery between sprints ($p<0.001$). Heart rate increased and to different extents across trials and conditions (12%: 2.4 ± 11.3; 13%: 10.9 ± 8.4; 14%: 8.2 ± 8.0; 15%: 7.0 ± 9.8; 21% 12.0 ± 15.8%, interaction effect p=0.035). Minute ventilation increased across sprints and was higher with sharper increases in hypoxic conditions. Total oxygen consumed during sprint trials and recovery intervals was lower in hypoxia. Blood lactate concentrations were found to be higher post exercise in hypoxic conditions (12%: 11.2 ± 1.4; 13%: 11.9 ± 1.6; 14% 11.3 ± 1.1; 15%: 11.7 ± 0.8; 21% 10.6 ± 1.7 mM; p=0.012). Maximum deoxyhemoglobin concentration (maxHHb) and post maxHHb increased across sprints (p<0.001), where maxHHb was lower in normoxic compared to hypoxic sprints (p<0.05). Total deoxyhemoglobin concentration (HHb) area under the curve was lower in normoxic compared to hypoxic at 12% and 13% (p<0.05). Finally, normalized integrated electromyography (iEMG) decreased across sprinting trials (p<0.001). Muscle activation decreased across sprints (p<0.001) and was shorter in hypoxic conditions (12%: 22.5 ± 3.4; 13%: 25.3 ± 6.5; 14%: 27.1 ± 5.9; 15%: 30.4 ± 5.2; 21%: 29.4 ± 6.6 s; p=0.047). Normalized median EMG power spectrum frequency (MDF) showed no change across sprints, but was higher in all hypoxic conditions (12%: 0.96 ± 0.13; 13: 0.93 ± 0.24; 14%: 0.89 ± 0.27; 15%: 0.73 ± 0.26; 21%: 0.78 ± 0.30; p=0.046). The authors concluded a greater physiological demand as FIO2 decreased to 13% and fatigue development was only affected at FIO2 12%.

Ogura, Katamoto, Uchimaru, Takahashi, & Naito 2006

The purpose of this study (43) was to compare two different levels of hypoxia on anaerobic energy release during supramaximal cycling exercise. Seven male soccer players (mean ± SD, 20 ± 1 yrs, height 171 ± 7 cm, body mass 66 ± 7 kg) performed a series of 6 testing sessions. Subjects performed a maximal cycling test at 60rpm and a workload of 90W with workload increases of 15W every minute until volitional exhaustion. On two separate testing days subjects also performed constant cycling exercise for 6 minutes at workload intensities of 40%, 60%, and 80%

maximal oxygen uptake (VO2max) at pedaling frequencies of 46, 66, 86, and 106 rpm. Finally, the Wingate Anaerobic test (WT) was performed under three different inspiratory oxygen fraction (FiO2) conditions of normoxia, low-moderate hypoxia (LMH: 16.4%), and high-moderate hypoxia (HMH: 12.7%) on separate days. The results indicated no difference in absolute or relative peak power output, absolute or relative mean power output, peak pedal frequency or mean pedal frequency among all three conditions. There was also no difference in oxygen demand. Absolute and relative oxygen uptake (VO2) were lower in HMH compared to normoxia. The percentage of anaerobic energy release (%AnAER) was higher for HMH compared to normoxia. Finally, there were no differences in oxygen deficit or blood lactate concentrations between conditions. Ogura et al. 2006, concluded that an FiO2 of 16.4% was not sufficient stimulus to increase the contribution of the anaerobic energy pathways to overall energy production during the WT. However, at HMH mean VO2 was reduced and anaerobic energy release during the last seconds of the WT increased without significant effects on performance.

Friedman, Frese, Menold, & Bärtsch 2007

The primary aim of this study (19) was to analyze the effects of acute moderate normobaric hypoxia on anaerobic capacity. The study utilized eighteen male endurance-trained athletes (mean ± SD, 23.9 ± 3.9 yrs, 182 ± 6 cm, 70.8 ± 6.7 kg) to perform two supra maximal oxygen consumption (VO2max) treadmill tests in hypoxic (FiO2 0.15) and normoxic conditions for measurement of maximal accumulated oxygen deficit (MAOD), blood lactate concentration, and ammonia concentrations. Participants first performed an incremental treadmill test at 5% grade beginning at 6 km h-1 which then increased by 2 km h-1 every 3 min until volitional exhaustion. The supra VO2max was conducted 15 min after the incremental treadmill test, at an incline of 8% and speed of 14.8 ± 0.6 km h-1 until exhaustion. The results indicated a significant decrease of

15.1 ± 4.7 ml kg-1 min in VO2max in hypoxia compared to normoxia (22.3 ± 7.2%). There was no difference in peak capillary lactate concentration and MAOD between conditions. However, hypoxia had a significantly reduced time to exhaustion (28.3 ± 7.4%) and accumulated oxygen uptake (45.0 ± 9.4%) compared to normoxia. Peak capillary ammonia was decreased in hypoxia (97 ± 52 μmol l-1) compared to normoxia (121 ± 44 μmol l-1). The authors concluded that exposure to moderate hypoxia does not affect anaerobic capacity. Anaerobic energy capacity may possibly increase in exercises ranging from 40s to 120s in duration when exposed to moderate hypoxia, but had no effect on exhaustive exercise beyond a duration of 2 min.

Calbet, De Paz, Garatachea, Cabeza De Vaca, & Chavarren 2003

The purposes of this study (11) were to investigate whether severe acute hypoxia can be counteracted by enhancing anaerobic energy production during a 30s Wingate test. Furthermore, whether endurance-trained elite cyclists would experience a greater decline in performance compared to sprint-trained elite cyclists. Five endurance-trained cyclists (mean ± SD, 18.8 ± 0.4 yrs, 179 ± 0.7 cm, 65.8 ± 1.0 kg) and five sprint-trained cyclists (19.0 ± 0.7 yrs, 176 ± 2 cm, 74.7 ± 3.1 kg) performed a Wingate anaerobic cycling test in normoxic and hypoxic (FIO2 0.104) conditions. Whole blood lactate and oxygen consumption (VO2) were monitored during both tests. Calbet et al. 2003 found a 6-7% reduction in mean power output (Pmean) and pedaling rate in sprint cyclists in hypoxia compared to normoxia, but no differences between conditions among endurance cyclists. Oxygen demand was lower in the sprint cyclists exercising in hypoxia, however, both sprint and endurance cyclists exhibited a 16% decrease in mean VO2. The hypoxia condition resulted in a 5% decrease in the oxygen deficit for the sprint cyclists, but a 7% increase in endurance trained cyclists. Endurance cyclists exhibited an 11% overall increase in blood lactate concentration, but no change in sprint cyclists. The rate of blood lactate accumulation was similar between groups in both conditions. The fatigue index was greater in sprint cyclists but did not change in the hypoxic condition for either group. Finally, Calbet et al. 2003 reported a greater anaerobic energy contribution to energy expenditure in hypoxic conditions compared to normoxia in endurance trained cyclists. In conclusion, the authors found no detriment in performance during a 30s Wingate test in severe hypoxia, which suggested an increase in anaerobic energy production.

Filopoulos, Cormack, & Whyte, 2017

The aim of this study (18) was to determine if the addition of normobaric hypoxic stress to a single high-intensity, low-volume resistance exercise session augmented the growth hormone response. Sixteen, resistance trained males (mean ± SD; age 24 ± 5 yrs; height 160 ± 6 cm; body mass 81.6 ± 7.6 kg) performed three sessions of one repetition maximum (1RM) leg press (LP), bench press (BP), and isometric maximal voluntary contractions (IMVC). Two sessions were completed in normobaric hypoxia (HYP; FiO_2 0.12) or normoxia (NOR; FiO_2 0.21) with a five-minute acclimatization period prior to exercise. Measures of 1RM, heart rate (HR), arterial oxygen saturation (SpO_2), ratings of perceived exertion, muscle activity, time under tension, lactate and serum growth hormone (GH) levels were determine each session. Maximum strength was assessed for LP and BP using a standardized warmup of one set of five repetitions at 50% and one set of three repetitions at 75% of their 1RM. Subjects then completed five sets of three repetitions at 85% of 1RM, with three minutes of rest between all sets. After warm-up subjects performed single repetitions with increasing weight until 1RM was determined. Neuromuscular activation of the right vastus lateralis was measured using surface EMG only during the LP, and data was passed through a 500Hz low pass anti-alias filter and full wave rectified using root-mean-square method. Contraction time was determined through a mechanical goniometer between the tibiofemoral articulations of the right knee and aligned with the greater trochanter and lateral malleolus. A second goniometer was placed on the lateral epicondyle of the right elbow and aligned with the humeral and ulna shafts. Venous blood samples (5mL) were obtained before altitude exposures, and 5, 15, 30, and 60 min post-exercise for analysis of serum GH and lactate concentrations. Differences between conditions were assessed using effect size (ES). The authors found a decrease in SpO2 at all time points following hypoxia (post-exposure ES -1.81 ± 0.14, LP ES -2.45 ± 0.15, BP ES -2.25 ± 0.15). As well as an increase in HR following hypoxia exposure and during LP and BP compared to baseline (post-exposure ES 1.17 ± 0.41, LP ES 1.33 ± 0.37, BP ES 1.37 ± 0.31) with no differences between recovery of each trial. Area under the curve analysis showed greater lactate levels in HYP (138.7 ± 33.1 min.mmol.L-1) compared to NOR (105.8 ± 20.8 min.mmol.L-1; ES 1.27 ± 0.24). There was also an increase in AUC of HYP GH (117.7 ± 86.8 min.ng.mL-1) compared to NOR (72.9 ± 85.3 min.ng.mL-1, ES 0.56 ± 0.46). The authors also found an increase in total contraction time during HYP (ES 0.37 ± 0.39), with no difference in total LP contraction time (ES 0.14 ± 0.37) but an increase in BP (ES 0.52 ± 0.39). The findings of the vastus lateralis were unclear for the vastus lateralis activation in either conditions, therefore the authors were unable to draw conclusions regarding muscle activation. The authors concluded that the addition of normobaric hypoxia during maximal strength exercise induced a higher metabolic stress and greater GH elevation compared to normoxia.

Inness, et al., 2016

The purpose of this study (25) was to investigate if heavy intermittent hypoxic resistance training (IHRT) is more effective at improving strength, power, and increasing lean mass than the same training in normoxia. Twenty strength-trained male participants (18-34 yrs) were pair matched into the hypoxic (IHRT) or placebo groups. The placebo group was exposed to an FiO2 of 0.20 for the entire seven weeks and the hypoxic group to an FiO2 of 0.145 for the first four weeks and increased to an FiO2 of 0.141 for the last three weeks of heavy resistance training. Subjects completed seven weeks of heavy resistance training three times per week, with each session on nonconsecutive days. Each training session consisted of 2-4 sets of 3-6 repetitions of squats deadlifts, and lunges separated by 3 minutes of rest. Outcome measures were body composition by dual energy x-ray absorptiometry, 1RM squat strength, countermovement jump, and a 20-m sprint time with 5 and 10-m splits. SpO2 and heart rate were taken via pulse-oximetry. There were no differences between groups at baseline. The authors reported improvements by mid-training testing in both groups in absolute (IHRT 12.7 ± 3.9% and placebo 8.7 ± 4.7%) and relative (IHRT 12.9 ± 5.1% and placebo 8.2 ± 5.3%) 1RM squat. The IHRT group had possibly greater change in absolute 4.4%) and relative 1RM (5.1%). There were no differences in lean mass or countermovement jump between or within groups. At post-testing both groups improved absolute (IHRT 22.2 ± 7.6% vs placebo 14.2 ± 6.0%) and relative (IHRT 20.5 ± 8.5% vs placebo 13.6 ± 6.4%). The IHRT group had greater change from pre to post in both absolute (7.0%) and relative (8.0%) compared to placebo 1RM. Only IHRT improved countermovement jump peak power post-training, however, there was no clear comparison between groups. Furthermore, there were no differences between or within groups compared to pre in the 20-m sprint of body composition. The authors concluded that heavy resistance training in hypoxia is more effective than placebo for improving absolute and relative strength.

Amann, et al., 2006

The purpose of this study (1) was to determine the change in arterial oxygen concentration (CaO2), as affected by inspired O2 fraction (FIO2), arterial oxygen saturation (SaO2), and arterial partial pressure of oxygen (PaO2) on peripheral quadriceps fatigue by high intensity cycling exercise. Eight healthy male cyclists (mean ± SE; 22.5 ± 1.7 yrs, 69.8 ± 2.8 kg, 173.9 ± 3.0 cm, 63.3 ± 1.3 ml·kg-1·min-1) performed a maximal incremental exercise test on an electrically braked cycle ergometer at a workload of 20 W + 25 W/min. Followed by three constant-workload trials (313.8 ± 12.9 W, 82.5 ± 1.7% of peak power output in normoxia) on different days in hypoxia (FIO2 = 0.15), room air (FIO2 = 0.21), or hyperoxia (FIO2 = 1.00) until exhaustion. Quadriceps electromyography (EMG) was recorded from the right vastus lateralis (VL), vastus medialis (VM), and rectus femoris (RF). Signal was amplified and filtered using Butterworth band-pass filter with a low-pass cutoff of 10 Hz and high-pass cutoff frequency of 1 kHz. Onset of activity was classified as >2 SD above baseline for more than 99ms. Magnetic nerve stimulation was done with the knee resting at 90° of flexion, and two magnetic stimulators stimulated the femoral nerve and the evoked quadriceps twitch force (Qtw) was obtained from a load cell. A single (1 Hz) and paired stimulus (10 Hz, 20 Hz, 100 Hz) was used to discriminate between low- and high-frequency fatigue. To determine supramaximal nerve stimulation, three single twitches were obtained every 30s at 50, 60, 70, 80, 85, 90, 95, and 100% of maximal stimulator power output at the beginning of each experiment. Integrated EMG (iEMG; the integral of each EMG burst) of the VL rose from the onset of exercise to the termination of exercise at all CaO2 (p<0.01). The exercise-induced increase in iEMG was 13.0 ± 2.7% greater in hypoxia than in normoxia (p<0.01) and 4.1 ± 1.4% greater in normoxia than hyperoxia (p<0.05). The continuous increase in iEMG was associated with a significant decrease in mean power frequency (MPF) for the duration of exercise at all conditions. At the end of exercise, MPF had a greater decrease in hypoxia than normoxia and hyperoxia. Quadriceps twitch force significantly decreased from baseline across various stimulation frequencies. Force output decreased by 34.6 ± 9.6 N in normoxia, 54.4 ± 13.8 N in hypoxia, and 27.5 ± 7.8 N in hyperoxia 2.5 minutes after exercise. Reduction in Qtw were greater in hypoxia than in normoxia and greater in normoxia than in hyper for 1 Hz potentiated, 1 Hz, 10 Hz, and 50

Hz. One half of relaxation time was increased more after hypoxia than normoxia, and more after normoxia than hyperoxia ($p<0.05$). Maximal relaxation time declined more after hypoxia than normoxia, and more after normoxia and hyperoxia ($p<0.05$). Finally, peak force, during pre- and post-exercise 5-s maximal voluntary contraction was decreased from baseline in hypoxia (11 ± 2%, $p<0.01$), whereas no change in normoxia and hyperoxia. In conclusion, Amann, et al. 2006 found that strenuous systemic exercise at equal workload and duration affects the rate of locomotor muscle fatigue development during exercise and immediately after exercise.

Kryskow, Beidleman, Fulco, & Muza, 2013

The purposes of this study (30) were to determine the following: 1) the altitude threshold (between 2500-4300m) of degraded simple and complex military task performance; 2) the degree of decline in performance is related to altitude illness, fatigue or sleepiness; 3) the level of hypoxemia, independent of altitude, affects simple and complex military task performance. Fifty-seven (mean ± SD; age 22 ± 3 yrs, height 177 ± 8 cm, weight 79 ± 12 kg) Active duty healthy men (N=53) and women (N=4) participated in this study. Subjects were assigned to four independent groups exposed to either 2500m (N=17), 3000m (N=12), 3500m (N=11), or 4300m (N=17) and tested at sea level (SL), and after 8 (HA8) and 30 h (HA30) of altitude exposure. Subjects performed mission-related performance measures relevant to special operations forces such as weapon disassembly and reassembly (DsAs) and rifle marksmanship (RM). In addition, they received a questionnaire from the Environmental Symptoms Questionnaire (ESQ) to measure acute mountain sickness (AMS) severity/prevalence and a fatigue factor score (ESQ-F), as well as a sleepiness score (SS) from the Stanford Sleepiness scale. Immediately prior to the questionnaires a resting SaO_2 was obtained. The authors found no differences at SL in DsAs, RM speed, AMS severity or prevalence, ESQ-F, SS, or SaO_2 (%) between groups. There was no change in DsAs performance from SL, HA8 or HA30 at any altitudes. RM speed decreased (P= 0.05) from SL (20 ± 6) to HA8 (17 ± 5) and HA30 (17 ± 5) at 4300m but not at other altitudes. Altitude had no effect on accuracy (targets hit per shots fired). There was no change in AMS severity or prevalence at 2500m. However, there was an increase in severity and prevalence (%) from SL to HA8 or HA30 at 3000, 3500, and 4300m (P = 0.004). Individual changes in DsAs or RM speed or accuracy at different exposure durations were not correlated to individual changes in AMS severity or prevalence at any altitude. All altitudes increased ESQ-F (P =0.0001) from SL to HA8 and remained elevated at HA30 at 3000 and 4300m. Sleepiness Score increased from SL to HA8 at 2500, 3000, and 4300m (P = 0.002), but only remained elevated at HA30 at 4300m. Individual changes in RM speed were negatively correlated with individual changes in SS from SL to HA30 (P = 0.004). Resting SaO2 (%) was decreased (P = 0.0001) at HA8 at 2500m (93 ± 3), 3000m (91 ± 2), 3500m (90 ± 3), and 4300m (78 ± 8); as well as at HA30 for 2500m (94 ± 3), 3000m (92 ± 2), 3500m (91 ± 2), and 4300m (79 ± 6). The level of hypoxemia, independent of altitude, was correlated with RM speed (r = 0.27; P = 0.04) at HA30 but not HA8. However, SaO2 was not correlated to DsAs performance at either exposure time. The authors concluded simple psychomotor performance (DsAs) is not affected by altitudes between 2500-4300m but complex psychomotor performance (RM) is degraded at 4300m. Increased symptoms of AMS, fatigue, and sleepiness did not affect simple or complex psychomotor performances at lower altitudes but increased sleepiness may have had an affect on RM speed at 4300m.

<u>Pilmanis, Balldin, & Fischer, 2016</u>

The purpose of this study (46) was to determine the effects of short-term low-grade hypoxia on cognitive function. Ninety- three active military personnel (passed physical examinations for U.S. Air Force class III flight physical) were exposed in series to four altitude conditions of ground level (GL, 1500ft), 5000ft, 8000ft, and 12,000ft. Subjects were allowed 20min to equilibrate at each altitude and half were exposed to all altitudes in ascending order and the other half in descending order. The subjects were then required to complete a test battery (duration of approximately 30min) measuring accuracy (%) and mean response time (ms) of the following tests: Choice Reaction Time, Tower, Continuous Performance, Grammatical Reasoning, Mathematical Processing, Match to Sample, Spatial Processing, and Manikin Test. Blood oxygen saturation and heart rate were measured periodically using finger oximetry and averages. During the final 15min at altitude, subjects completed a survey covering 65 general symptoms, only 33 were utilized pertinent to common symptoms of hypoxia. Oxygen saturation decreased from 97.5% (± 0.8%) at GL to 86.6% (± 2.9) at 12,000ft, with there being a difference from GL at all altitudes. Heart rate increased from 66.5 bpm (± 9.2) GL to 74.4 bpm (± 9.7) at 12,000ft, and was higher than GL at 8000ft and 12,000ft. The continuous performance task had a significant altitude main effect both for accuracy ($p<0.001$) and mean response time ($p=0.048$). Accuracy was decreased at 8000 and 12,000ft compared to GL. Mean response time (MRT) increased at 5000, 8000, and 12,000ft relative to GL, however differences were relatively small. Grammatical Reasoning task had a significant altitude main effect only for accuracy measure ($p=0.036$). Accuracy was decreased at 12,000ft relative to GL, however, again the change was relatively small. The Math Processing, Spatial Processing, Tower Task, and Two Choice Response Time task had no differences in each altitude condition. The Manikin Task compared learning rates under the four conditions and showed an increase in accuracy from trial 1 to 4 and a decrease in MRT from trial 1 to 4 as the authors expected. However, the trial by altitude interaction had no difference for accuracy or MRT. The authors did note that learning may have been reduced at the two higher altitudes but could not be confirmed with the present sample size. There was an increase between GL and 12,000ft in frequency of symptoms reported. Therefore, the authors concluded that there were none to very small decreases in cognitive performance at 5000 and 8000ft, and some differences between GL and 12,000ft. Subjects were able to perform assigned tasks despite experiencing hypoxia symptoms.

Legg, et al., 2014

The purpose of this study (33) was to examine the effects of mild hypoxia (approximately 8000ft) on complex logical reasoning, multiple memory, and self-perceived risk judgment. Twenty-five healthy nonsmoking men (mean ± SD; age 23.8 ± 3.9yrs) were exposed to normobaric normoxia or normobaric mild hypoxia for 2h each. Subjects were given 30min blocks of: 1) a complex logical reasoning task that assessed accuracy, response time, and reasoning quality index for easy (nonconflic valid or NV), difficult (nonconflict invalid), difficult (conflict valid), and very difficult (conflict valid) syllogisms; 2) multiple memory test assessing sentence judgement error, working memory span, and prospective memory; and 3) simple vigilance psychomotor task to assess frequency and mean time a disk was outside the target area and braking reaction time. Self-perceived risk judgment was assessed immediately before the end of each altitude condition. The mean change in working memory span was lower in mild hypoxia (0.9 ± 4.6) than normoxia (4.4 ± 7.2). Reasoning quality index for conflict invalid syllogisms was marginally less in mild hypoxia (0.22 ± 0.29) than normoxia (0.39 ± 0.35). The authors concluded that a two-hour exposure to normobaric mild hypoxia significantly impaired working memory and only marginally impaired complex logical reasoning with more difficult conflicts. There was no effect on psychomotor vigilance or self-perceived risk judgment.

Bouak, Vartanian, & Hofer, 2019

The primary goal of this study (8) was to evaluate the effect of extended hypoxic hypoxia (HH) on physiological measures, cognitive and simulated flight performance, hypoxic hypoxia symptoms, fatigue and mood states of helicopter pilots. Seventeen military helicopter pilots (mean ± SD; age 34 ± 9yrs; weight 81.9 ± 14.2kg; height 1.77 ± 0.09m; flying experience 1,815 ± 1670 h) were exposed for 6 hours uninterrupted to 8000ft and 9900ft altitude conditions. A series of assessments included self-reported questionnaires on HH signs and symptoms (S&S), mood, and fatigue. Performance data was obtained from a flight simulation task (Sim) and a cognitive test battery (CTB). The CTB consisted of assessments of short-term memory (STM), working memory (WM), executive function (EF), and multi-tasking (MT). Short term memory was assed using the delayed matching to sample test (dMTS). Working memory was assessed by the n-back task (n-back), consisting of presenting subjects with a series of stimuli (i.e. letters) and prompted to report stimuli that were previously presented. Executive function was assessed by the Stroop task (Stroop) and MT using the Multi-Attribute Task Battery (MATB-II). Oxyhemoglobin saturation was monitored using fingertip pulse oximetry (SpO_2) and forehead regional oxygen saturation (rSO_2). The authors found fingertip and forehead oxygen saturation to be significantly decreased from baseline ($p<0.001$) to altitude in both conditions but remained constant throughout. There was an increase in number of subjects presented with S&S at altitude and ground level post-exposure than baseline. However, there were no differences between conditions. There was no difference between altitude conditions neither the change from assessment periods had any effect on Sim or MATB. The increase in altitude nor the elapsed time had any effect on accuracy on the dMTS, n-back, or Stroop. Based on their findings, the authors concluded that helicopter pilots flying between 8000 and 9900ft for up to 6 hours showed expected decreases in blood oxygen saturation without any adverse or negative effects on performance.

Legg, et al., 2016

The purpose of this study (33) was to examine the effects of exposure of Air Force personnel to hypobaric hypoxia equivalent to altitudes of ground level, 8000ft and 12000ft. Thirty-six of the Royal New Zealand Air Force (between 18 and 40 years old) underwent three hypobaric chamber exposures at ground level (0ft), 8000ft, and 12000ft, and also with 100% supplementary oxygen at 12000ft while performing seven mood and six cognition tests. Peripheral oxygen saturation (SpO2%) was measured by finger pulse oximetry and monitored throughout the study. The mood and cognitive tests were selected from the Automated Neurophysiological Assessment Metrics (ANAM) test battery, and presented in the following order: mood (anger, anxiety, depression, fatigue, happiness, restlessness and vigour), complex cognition, logical relations, 3-dimensional spatial rotation (Manikin test), mathematical processing, memory search, selective attention/inhibition (Stroop test), problem solving (decision-making/mental flexibility) and Tower Puzzle test. Baseline SpO2 values were similar between altitudes and decreased from baseline upon reaching altitude. Then SpO2 recovered and increased beyond baseline after supplemental O2. SpO2 values also differed between altitude conditions. The tests for mood showed an increased level of fatigue ($p=0.001$) and a decreased level of vigour ($P=0.035$) at 12000ft. This was then restored with supplemental oxygen to baseline levels. The only significant results for the test of cognition was logical relations ($p=0.023$), however the authors speculated this was due to a single outlying mean score. The authors concluded that these study results conflicted prior findings that mild hypoxia (8000 to 12000ft) impairs complex cognition, but found that some aspects of mood may be affected at 12000ft and can be restored with 100% supplemental oxygen.

Electromyographic Patterns of Responses

Bigland-Ritchie, Donovan, & Roussos 1981

The purposes of this study (6) were to identify changes in electromyographic (EMG) power spectrum and muscle fiber conduction velocity in the adductor policis muscle during both fatiguing and nonfatiguing isometric contractions. Three healthy volunteers performed a series of brief nonfatiguing contractions at 10, 25, 50, 75, and 100% maximal voluntary contraction (MVC). A 10s rest period was given and then four 40% maximal voluntary isometric (MVI) and two 100% MVI contractions were performed separated by rest. Then a 60s fatiguing maximal mode muscle action was performed. Force and EMG were measured during all muscle actions. These results indicated that during brief nonfatiguing isometric contractions there was no change in the spectral frequency distribution of the EMG signal. There was, however, a decrease in conduction velocity from 4.7 to 8.0ms, with proportional increases in action potential rise time but no corresponding decline in peak amplitude. The authors concluded that small changes in conduction velocity during sustained maximal isometric contraction were insufficient to account for large changes in the power spectrum. Furthermore, to generate equivalent power spectral changes during nonfatiguing submaximal isometric contraction a larger change in conduction velocity is required.

Masuda, Masuda, Sadoyama, Inaki, & Katsuta, 1999

The purpose of this study (36) was to compare changes in muscle fiber conduction velocity (MFCV), median frequency (MDF), and mean amplitude (AMP) during isometric and isotonic fatiguing muscle action from the vastus lateralis. Nineteen healthy males (age: 19-73 yrs) performed a fatigue test consisting of an isometric muscle action sustained at a 90° knee joint angle with a load of 50% maximum voluntary contraction until exhaustion. After a 30-min rest, subjects performed repetitive isotonic knee extension to exhaustion at 50% maximum voluntary contraction (MVC). Electromyography (EMG) was collected from the right vastus lateralis using a 10-channel linear surface electrode array. The results indicated a significant 7.4% decrease in MFCV from the beginning of the isometric muscle action, but no change in the isotonic muscle action. However, isotonic muscle action showed significantly higher MFCV compared to isometric muscle action at the end of exercise. Median frequency in the isometric and isotonic muscle action significantly decreased 22.4% and 15.2% respectively from the initial value. Similarly, the isotonic muscle action showed significantly higher values of MDF compared to the isometric muscle action at the last stage of exercise. Further results indicated an increase in AMP from the beginning to end of exercise in both isometric (34.4%) and isotonic (48.0%) muscle actions. Isotonic muscle action showed significantly higher AMP than isometric muscle action, throughout the protocol. The authors concluded the significant decrease in MFCV in the isometric muscle action but not during the isotonic muscle action, could have been caused by reduced blood flow during the isometric muscle action compared to the isotonic contractions limiting the removal of metabolic byproducts.

Hedayatpour, Arendt-Nielsen, & Farina, 2008

The purpose of this study (21) was to examine the electromyography (EMG) signal during fatigue and recovery after two submaximal voluntary isometric contractions from the vastus medialis and lateralis. Ten healthy males (mean ± SD, age: 25.6 ± 3.6 yrs) performed three maximal voluntary contractions (MVC) separated by 2 min rest, prior to two contractions at 40% and 80% MVC until task failure separated by a rest period of 40 min. Hedayatpour et al. 2006, found a greater time to task failure at 40% MVC (70.7 ± 25.8 s) compared to 80% MVC (27.4 ± 16.8 s). Furthermore, mean frequency and conduction velocity of both muscles were greater at the onset compared to the end of the fatiguing task. Initial EMG amplitude values and patterns of responses for mean frequency during recovery were influenced by electrode placement on the muscle, indicating non-uniform recovery of membrane potentials.

Yoshitake, Ue, Miyazaki, & Moritani, 2001

The purpose of the present study (59) was to investigate the etiology of lower-back fatigue using electromyography (EMG), mechanomyography (MMG), and near infrared spectroscopy (NIRS). Eight healthy male college students (Mean ± SD; 24.8 ± 0.8 yrs, 179 ± 1.9 cm, 65.3 ± 1.4 kg) performed isometric back extensions in a prone position for a period of 60s at an angle of 15° with reference to the horizontal plane. Electromyography electrodes were placed over the erector spinae at the level of L3, with the MMG specially designed microphone sensor (frequency response between 5-2000 Hz) on the center of the belly of the erector spinae. Signals from the EMG and MMG were band-pass filtered (5-1000 Hz) and differentially amplified (Nihon-Koden Meg 6100; gain: x100, input impedance: >100 MΩ, common mode rejection ration: >80 dB). Then were digitized at a sampling rate of 1 kHz via an analog to digital converted with anti-aliasing low-pass filtering at 520 Hz. The NIRS probe was attached to the muscle belly of the erector spinae paravertebrally to the EMG and MMG side. The authors found the mean power frequency of the EMG signal (MPFe) and the root mean square of the MMG signal (RMSs) decreased as a function of time. Root mean square of the EMG (RMSe) increased significantly from 231 ± 25 µV to 258 ± 24 µV ($p<0.01$), and then fell to 243 ± 21 µV ($p<0.05$). Mean power frequency of the EMG decreased progressively as a function of time from 126 ± 5.9 Hz to 89.9 ± 6.4 Hz ($p<0.01$), RMSs increased from 236 ± 75 mV to 289 ± 70 mV ($p<0.05$), and MPFs remained unchanged (11.9 ± 0.73 Hz to 10.5 ± 0.68 Hz, $p>0.05$). Oxygenated hemoglobin and blood volume decreased throughout the exercise at 15° back extensions compared to 0°. The authors concluded the restriction of blood flow due to high intramuscular mechanical pressure is an important factor in muscle fatigue in the lower back muscles.

<u>Snyder, Cauthen, & Senger, 2017</u>

The primary purpose of this study (51) was to examine differences in lower back muscle activity and body posture between a "walk-in" deadlift (WID) and conventional deadlift (CDL). The secondary purpose was to determine differences between highly-skilled deadlifters (HS) and lower-skilled deadlifters (LS). Fifteen weightlifters (2 females and 13 males) were divided into HS (mean ± SD; height: 1.78 ± 0.097 m, weight: 78.9 ± 4.4 kg) and LS (height: 1.79 ± 0.035 m, weight: 84.2 ± 12.3 kg). Subjects came in on three separate days. On the first day, subjects performed a three repetition maximum (3RM) conventional deadlift. The second visits subjects performed a 3RM on a Nautilus XPLoad Deadlift and Shrug machine with handles set to the lowest setting. On the third visit, electrical activity of the erector spinae (ES), gluteus maximus (GM), biceps femoris (BF), and vastus lateralis (VL) were monitored using electromyography (EMG) during the conventional straight-bar deadlift (CDL), WID with handles aligned with the toes and held with a pronated grip (ToePro), and WID aligned with the ball of the foot and held with a pronated grip (BallPro). Biomechanical markers were placed on the acromion process, greater trochanter, lateral side of the knee between the distal femur and proximal tibia, and the lateral malleolus to examine trunk and knee angles during three different lift phases (start, midconcentric, and mideccentric). Electromyography signals were filtered using bandwidth of 20-450 Hz, 1,000 gain, and collected at 1,024 Hz. Electrical activity was expressed as a percentage of maximal root mean square from a maximal isometric contraction. The mean CDL 3RM (129.2 ± 23.6 kg) was higher than the mean WID 3RM (195.3 ± 46.8kg, $p \leq 0.001$) in the combined groups. The mean CDRL 3RM per kg of body weight for combined skill groups (3.46 ± 0.64) was lower than WID 3RM per kg of body weight (5.15 ± 1.15, $p \leq 0.001$). Trunk angle at the start of the lift for the CDL (23.7 ± 11.3°) was smaller ($p \leq 0.05$) for both the BallPro (29.9 ± 12.0°) and ToePro (32.4 ± 10.4, d=0.75). The trunk angles of the of the ToePro were different from the CDL and BallPro at the midconcentric and mideccentric (*d*=0.65 and *d*=0.61 respectively, $p \leq 0.05$). Relative knee angle during the start was lower during the ToePro (101.6 ± 10.6°, *d*=0.93) compared to the CDL (110.8 ± 11.5°) and BallPro (104.7 ± 13.1°, $p \leq 0.05$). Midconcentric and mideccentric of relative knee angle of both ToePro and BallPro were less than the CDL ($p \leq 0.05$). Trunk lengths in the starting and finishing positions for the combined groups were also greater in the ToePro and BallPro ($p \leq 0.05$) compared to the CDL. There were no differences between skill levels in any phase or joint angle. Electrical activity of the ES during the BallPro (53.1 ± 8.5%, *d*=0.69) was lower than the CDL (73.19 ±6.9%, $p \leq 0.05$). There was greater activity of the VL and lower activity of the GM compared to the CDL in both the ToePro and BallPro ($p \leq 0.05$). Activity of the BF remained the same for each activity. There were no differences between skill levels. The authors concluded that the walk-in deadlift machine has the potential to place less stress on the low back during the deadlift, with a generally more upright posture and ES activity depending on foot position. However, the authors also noted a general shift away from the GM and towards the knee extensors, limiting its long-term usefulness as a deadlift replacement.

<u>Bezerra, et al., 2013</u>

The purpose of this study (5) was to analyze electromyography (EMG) signal of the biceps femoris (BF), vastus lateralis (VL), lumbar multifidus (LM), anterior tibialis (AT), and medial gastrocnemius (MG) during the deadlift (DL) and stiff-legged deadlift (SLDL). Fourteen men (mean ± SD; 26.71 ± 4.99 yrs, 88.42 ± 12.39 kg, 177.71 ± 8.86 cm) with two years of recreational resistance training experience performed exercises on three nonconsecutive days. On the first test day, they performed a one repetition maximum (1RM) for both the DL and SLDL and was re-tested on the second day. On the third testing day, both exercises were performed with 70% of the 1RM and EMG data was recorded of the BF, VL, LM, AT, and MG during three repetitions of

70% of their 1RM. Electromyography signals were recorded at a frequency of 1000 Hz and smoothed using a second order Butterworth low pass filter with a frequency of 500 Hz. EMG normalization was done using peak average for each muscle in three repetitions of the DL and SLDL. Temporal activation patters were obtained using a linear wrap trace after normalization. Muscle activation level was obtained using the root mean square (RMS) and relative time of activation was expressed a percentage of how long EMG signal was above at least 50% of peak temporal activation patterns. RMS of the VL was greater during the DL (128.3 ± 33.9) compared to SLDL (101.1 ± 14.6, p=0.027). MG was greater during the SLDL (108.3 ± 16.3) compared to DL (103.8 ± 12, p=0.012). Relative time activation was greater for the VL during the DL (43.42 ± 18.85) and SLDL (21.11 ± 14.71, p=0.026). In conclusion, the authors found the DL is more effective for targeting VL than the SLDL, however, the MG showed higher muscle activation during the SLDL than the DL.

Nijem, Coburn, Brown, Lynn, & Ciccone, 2016

The purpose of this study (42) was to compare muscle activation (by surface electromyography or EMG), ground reaction force (GRF), and rate of force development (RFD) of a barbell deadlift with free weights and a barbell deadlift loaded with free weights and chains. Thirteen (mean ± SD; 24.0 ± 2.1 yrs, 179.3 ± 4.8 cm, 87.0 ± 10.6 kg) recreationally resistance-trained men performed two days of testing with a minimum of 48 hrs in between visits. Day one consisted of a standardized dynamic warm-up of two repetitions of 20m (A-skips, high knees, butt kicks, lunges, cariocas, and backward running). They then followed standard testing protocol to test one repetition maximum (1RM) for the deadlift exercise. The second visit consisted of three deadlift repetitions at 85% 1RM with chains (CH) and one set of 3 repetitions without chains (NC), with the order of conditions (CH and NC) was randomized. For the CH repetitions, the chains accounted for 19.9 ± 0.6% of their 85% 1RM. Subjects stood upright on a force plate with an unloaded barbell and safety clips. The force plate was zeroed, and chains were added to each side until a desired load of 20% of the subjects 1RM was reached. The chains plus the remaining load from free weights were added to the barbel to reach the total weight of the subjects 85% 1RM. Surface EMG was used to measure activation of the gluteus maximus, erector spinae, and vastus lateralis muscles of each of the third repetitions for the concentric phases, eccentric phases, top and bottom range of motion (ROM) of the 1RM test. Signals of the EMG were preamplified (gain 1,000X) using differential amplifier (EMG 100C, bandwidth: 1-500 Hz), and band-pass fourth-order Butterworth filtered at 10-500 Hz. Amplitudes of the signals were expressed as root mean square (rms) values. Force plates were used to measure GRF and RFD of the experimental trials and sampled at 1,000 Hz. The authors found significant main effects for condition and phase of movement ($p \leq 0.05$). There was greater EMG activity during the NC compared to the CH condition ($p \leq 0.05$). Furthermore, the concentric phase resulted in significantly greater EMG activity ($p \leq 0.05$) than the eccentric phase. For the erector spinae, there were significant main effects for ROM and phase ($p \leq 0.05$). The bottom ROM had greater EMG activity than top ROM ($p \leq 0.05$). The concentric phase of the deadlift demonstrated greater EMG signal than the eccentric phase. Finally, EMG of the vastus lateralis showed greater EMG activity for the concentric compared to eccentric phase ($p \leq 0.05$). Ground reaction forces were reduced, with no change in RFD ($p > 0.05$), while deadlifting with accommodating chain resistance ($p \leq 0.05$). The authors concluded that the use of chain resistance during deadlifting alters muscle activation and force characteristics of the lift.

Anderson, et al., 2018

The purpose of this study (2) was to compare muscle activation level of the gluteus maximus, biceps, femoris, and erector spinae in the hip thrust, barbell deadlift, and hex bar deadlift. Thirteen healthy men (mean ± SD, 21.9 ± 1.6 yrs, 81.4 ± 7.2 kg, 180 ± 5.0 cm) with 4.5 ± 1.9 yrs of strength training experience participated in three testing sessions. The first familiarization session was used to optimize and standardize technique. The second session was used to identify one repetition maximum (1RM) for all three exercises. The third session subjects performed their 1RM for each exercise and when necessary load was increased or decreased until 1RM was achieved. Electromyography (EMG) sensors were placed on the gluteus maximus, biceps, femoris, and erector spinae on the dominant leg for all exercises. Electromyography signal was preamplified at a frequency of 8-600Hz, and converted to root mean square (RMS) at 0-600Hz. Converted signal was sampled at 100Hz using 16-bit A/D converter. Mean EMG was used from the ascending movement of the lift and divided into upper and lower phases. A linear encoder identified the beginning and end of the lift, lift phases, and lifting time. Finally, subjects performed two maximal voluntary isometric contractions (MVCs) for at least three seconds for all three muscles. The MVC with the greatest average EMG amplitude was used to normalize dynamic EMG data. The authors results indicated a 16% greater activation in the gluteus maximus during the complete ascending movement of the hip thrust compared to the hex bar deadlift ($p=0.025$). The biceps femoris activation was 28% higher during the barbell deadlift compared with the hex bar deadlift ($p<0.001$) and 20% higher than the hip thrust ($p=0.005$). the gluteus maximus activation was 26% higher in the upper movement phase during the hip thrust compared to the hex bar deadlift ($p=0.015$). Biceps femoris activation was 48% higher during the lowering part of the movement phase of the barbell deadlift compared with the hip thrust ($p<0.001$) and 26% higher for the hex bar deadlift compared to the hip thrust ($p=0.049$). The upper part of the movement phase was 39% higher for the biceps femoris compared to the hex bar deadlift ($p=0.001$) and 34% higher for the hip thrust compared with the hex bar deadlift ($p=0.002$). There were no differences in erector spinae activation. Finally, the authors reported a greater 1RM in the hip thrust (176.6 ± 32.4 kg) than both barbell (150.6 ± 24.2 kg, $p=0.001$) and hex bar deadlift (153. 5 ± 22.4 kg, $p<0.001$). Lifting times were similar among all three exercises. The authors concluded that the barbell deadlift had greater biceps femoris activation compared to hex bar deadlift and hip thrust, whereas the hip thrust provided the greatest gluteus maximus activation of the three. There were no differences between exercises in erector spinae activation.

Camara, et al., 2016

The purpose of this study (12) was to examine electromyography (EMG), force, velocity, and power characteristics of a hexagonal barbell and straight barbell deadlift. Twenty men (mean ± SD, 23.3 ± 2.1 yrs, 176.8 ± 7.6 cm, 89.9 ± 18.3 kg) with at least one year of resistance training experience participated in three testing sessions. Sessions one and two included one repetition maximum (1RM) with each barbell in randomized order. The third session, participants performed 3 repetitions with submaximal loads associated with power (65% 1RM) and strength development (85% 1RM) with each barbell in randomized order. Electromyography of the biceps femoris, vastus lateralis, and erector spinae (longissimus) were preamplified (gain 1,000X) using a differential amplified (EMG 100C, bandwidth = 1-500 Hz) and band-pass filtered (fourth-order Butterworth) at 10-500Hz. Amplitudes were expressed as root mean square values. Signals for the experimental visits were normalized to the EMG values of the concentric phase of the straight barbell 1RM tests. The three repetitions of each load (65 and 85% 1RM) were averaged. A velocity transducer attached to the end of the barbell and a force plate were used to collect force data and were averaged for the three repetitions of each load. There were no differences in 1RM values between straight and hexagonal barbells. Normalized EMG amplitude of the vastus lateralis was greater during the entire hexagonal barbell deadlift than with the straight barbell ($p \leq 0.05$). There was greater activation for the biceps femoris only in the concentric phase (Straight: 0.835 ± 0.19, Hexagonal 0.723 ± 0.20) and erector spinae only in the eccentric phase (Straight: 0.753 ± 0.28, Hexagonal: 0.614 ± 0.21) with the straight bar than the hexagonal bar ($p \leq 0.05$). For all three muscles and both barbells, concentric phase of the lift had greater EMG activation than the eccentric phase ($p \leq 0.05$). Peak ground reaction force (PGRF), peak power (PP), and peak velocity (PV) were greater ($p \leq 0.05$) with the hexagonal barbel (PGRF: 2,553.20 ± 371.52 N, PP: 1,871.15 ± 451.61 W, PV: 0.0805 ± 0.165 m/s) than the straight barbell (PGRF: 2,509.90 ± 364.95 N, PP: 1,639.70 ± 361.94 W, PV: 0.725 ± 0.138 m/s). Furthermore, the authors reported a greater PGRF during 85% 1RM load and greater PP and PV for the 65% 1RM load. The authors concluded that each barbell led to different muscle activation patterns and that the hexagonal barbell may be more effective at developing maximal force, power, and velocity.

Near Infrared Spectroscopy

Van Beekvelt, Colier, Wevers, &, Van Engelen 2001

The purpose of this study (57) was to investigate local muscle O2 consumption (muscVo_2) and forearm blood flow (FBF) in resting and exercising muscle by near-infrared spectroscopy (NIRS) and to compare results with global muscVo_2 and FBF from the Fick method and plethysmography. Twenty-six participants (16 men and 10 women; mean ± SD, 28.8 ± 7.7 yrs, 178.9 ± 10.9 cm, 70.0 ± 11.1 kg) performed a maximum voluntary contraction (MVC) of the flexor digitorum superficialis (FDS) and brachioradialis (BR). The continuous-wave near-infrared spectrophotometer was placed over the top of both muscles, and data sampled at 10Hz and a DPF of 4.0. The difference (Hb_{diff}) between oxy- and deoxyhemoglobin/myoglobin (O_2Hb/O_2Mb and HHb/HMb) was used for the calculation of O_2 consumption during arterial occlusion. Strain-gauge plethysmography was also used to measure forearm blood flow (FBF). A pneumatic arm cuff around the upper arm was inflated to 50 mmHg for venous occlusion and wrist cuff inflated to 260 mmHg to exclude blood flow from the hand. The strain gauge was stretched halfway around the forearm on top of the FDS muscle and between NIRS optodes to measure plethysmographic flow in the same region as the NIRS measurement. A catheter was inserted into the antecubital vein for blood samples. After performing the MVC, participants underwent a series of venous and arterial occlusions. Following a five-minute recovery period, participants performed sustained isometric handgrip exercise at 10% MVC, then a brief venous occlusion. The authors found no differences between the three consecutive venous occlusions during rest in calculated blood flow by NIRS (FBF_{NIRS}). There were also no differences in the venous occlusions during rest in the plethysmographic flow measurements (FBF_{pleth}). There were no differences in muscVo_2 derived from NIRS using venous occlusion [musc$Vo_{2(NIRSvo)}$] and muscVo_2 from NIRS using arterial occlusion [musc$Vo_{2(NIRSAO)}$]. During exercise muscVo_2 increased for all measurements compared to rest ($p \leq 0.01$). Despite marked differences between the different muscles in musc$Vo_{2(NIRSAO)}$, the increase in musc$Vo_{2(NIRSvo)}$ was the same independent of the measured muscle and depth of measurement. Therefore, musc$Vo_{2(NIRSvo)}$ in FDS at superficial depth (IO_{35}) was lower compared with musc$Vo_{2(NIRSAO)}$, but no difference in BR. The musc$Vo_{2(NIRSAO)}$ at rest was lower in the deeper region of the FDS (IO_{50}) compared with the IO_{35} ($p \leq 0.01$). From rest to low-intensity exercise at 10% MVC musc$Vo_{2(NIRSAO)}$ increased more than five times independent of the measuring depth ($p \leq 0.01$). Higher musc$Vo_{2(NIRSAO)}$ at IO_{35} compared IO_{50} was accompanied by higher FBF_{NIRS} at IO_{35} compared to IO_{50}. Rest to exercise FBF_{NIRS} increased ($p \leq 0.01$) at both depths but did not match the fivefold increase in muscVo_2. The difference in FBF_{NIRS} between depths at rest was still present during exercise ($p \leq 0.01$). Muscle O_2 consumption was higher during rest for the Fick method compared with NIRS at FDS IO_{35}. During exercise muscVo_2 of both methods increased, but the increase in musc$Vo_{2(NIRSAO)}$ was larger than the increase in muscle O_2 consumption by the Fick Method [musc$Vo_{2(Fick)}$]. Blood flow measured with plethysmography was more than double the flow measured by NIRS ($p \leq 0.01$). From rest to exercise both methods increased, therefore the difference between each method remained during exercise ($p \leq 0.01$). The authors concluded that NIRS is an appropriate tool to measure local muscVo_2 and local FBF, and that the placement and depth of NIRS optodes reveal local differences not detectable by the established Fick method.

Van Beekvelt, Van Engelen, Wevers, & Colier, 2002

The purpose of this study (58) was to test the precision of the near infrared spectrometry (NIRs) by day-to-day reproducibility of muscle oxygen consumption (mVO_2) at rest and various workloads of isometric handgrip exercise on three separate measurement days and to compare mVO_2 from arterial occlusion, calculated from the rate of decrease in O_2Hb and that from the rate of decrease in oxy- and deoxyhemoglobin difference (Hb_{diff}). Seven volunteers (one female and six males; mean ± SE, 36 ± 4 yrs, 175.3 ± 3.4 cm, 68.7 ± 2.7 kg) came on three separate days to perform a maximum voluntary contraction (MVC), undergo arterial occlusion , and rhythmic isometric handgrip exercise at incremental work intensities. Muscle oxygen consumption of the flexor digitorum superficialis was measured using a near infrared spectrophotometer with a differential path-length factor (DPF) of 4.0 and sampled at 20 Hz. Oxygen consumption was 0.14 ± 0.01 mlO_2 min^{-1} $100g^{-1}$ at rest and increased to 2.68 ± 0.58 mlO_2 min^{-1} at 72% MVC. There was no difference between each visit in MVC and mVO_2. The authors concluded local muscle oxygen consumption at rest and exercise can be measured reliably by NIRs and is robust enough to measure over several days and various workloads.

Kawaguchi, Tabusadani Sekikawa, Hayashi, & Onari, 2001

The purpose of this study (26) was to examine whether the kinetics of local muscle oxygenation reflect systemic oxygen intake (VO_2). Sixteen men aged 19-27 yrs (mean ± SD; 173.7 ± 7.6 cm, 66.6 ± 9.2 kg) performed a ramp exercise test on an electromagnetically braked bicycle, where load intensity increased 30 W every minute. Pedal rotation was set at 50 rev/min and expiratory gas analysis was monitored breath-by-breath throughout the test. Peripheral muscle oxygenation of the vastus lateralis was monitored using a laser tissue blood oxygen monitor with a sampling frequency of 10 Hz. Kawaguchi et al., 2001 found deoxygenated hemoglobin (DeoxyHb) gradually increased with exercise intensity. However, oxygenated hemoglobin (OxyHb) and tissue blood oxygen saturation (S_tO_2) gradually decreased. The authors reported no changes in total hemoglobin (TotalHb) in some subjects, and either decreased or increased with exercise intensity with others. There was a positive correlation between DeoxyHb and VO_2 ($r=0.893 - 0.986$, $p<0.0001$) and a negative correlation between S_tO_2 and VO_2 ($r=0.859 – 0.99$, $p<0.001$). There was also a negative correlation between OxyHb and VO_2 ($r=0.726 – 0.978$), with a lower correlation coefficient than for DeoxyHb and S_tO_2. There was no trend with TotalHb, where some subjects had a marked correlation ($r=0.132 – 0.874$), in other subjects there was no correlation. The authors concluded that the kinetics of peripheral muscle oxygen saturation adequately reflect systemic VO_2.

Tamaki, Uchiyama, Tamura, & Nakano, 1994

The purpose of this study (53) was to examine blood volume and muscle oxygenation of contracting muscle during weight-lifting exercise. Nine healthy adult men (mean ± SD, 24.3 ± 5.0

yrs) performed unilateral bicep curls in the seated position while changes in oxygenated hemoglobin (oxy-Hb), deoxygenated hemoglobin (deoxy-Hb) and blood volume (total-Hb) were monitored. Three of these men were well trained in weightlifting, three were not well trained in weightlifting but regular performed resistance training, and three untrained men participated in this study. Participants performed ten repetitions of non-weighted curls, a ten-repetition maximum (10-RM), and only the well-trained subjects performed three sets of five repetitions with 1 minute rest periods. Participants also underwent arm blood flow restriction using a tourniquet. Tamaki et al. 1994 found deoxy-Hb and total-Hb increased during blood flow restriction, but returned to resting levels at the end of restriction. There were no significant changes in muscle oxygenation during non-weight exercise. There was a rapid decrease in oxy-Hb and total-Hb in the beginning of the 10-RM, but total-Hb gradually increased toward the end of exercise. A similar response was seen during the blood flow restriction condition During the three sets of exercise performed by the well-trained participants, changes in oxy- and deoxy-Hb were found to be the same as in the 10-RM. Blood volume increased with each set during exercise and the recovery level of total-Hb volume also increased and remained elevated for more than 90 s after the last set. The authors concluded that weight-lifting exercise causes a lack of oxygen supply to working muscles, similar to venous restricted blood flow.

<u>Belardinelli, Barstow, Poszasz, & Wasserman, 1995</u>

The purpose of this study (4) was to examine hemoglobin (Hb) and myoglobin (Mb) oxygen saturation during incremental cycling exercise near lactic acidosis threshold (LAT) and approaching maximal oxygen consumption (VO2max). Eleven healthy men (n=8) and women (n=3) (mean ± SD, 33.8 ± 5.4 yrs, 72.5 ± 11.7 kg, 1.73 ± 0.1 m) performed an incremental ramp bike protocol until volitional exhaustion. Inspiratory and expiratory volumes were monitored throughout the test for the determination of oxygen consumption (VO2) and estimation of LAT. Near infrared spectroscopy (NIRs) was used to monitor tissue O2 saturation of the vastus lateralis muscle. Belardinelli et al. 1995, found a peak VO2 of 44 ± 10 ml · kg-1 · min-1, an LAT of 1.7 ± 0.6 l · min-1 occurring at 53.9 ± 7.7 % of VO2max. Exercise time was 618 ± 34 s and the peak work rate reached 262 ± 83 W. Tissue O2 saturation decreased from 70% of saturation at rest to 65% at LAT. Tissue O2 saturation fell steeply at a VO2 of 1.2 l·min-1, then fell to 10% of functional rage at a VO2 of 1.7 l · min-1; with a final decrease between a VO2 of 1.7 and 2.8 l · min-1. The decrease in O2 saturation started off gradual between LAT and 80% of VO2max and became more asymptotic above 80% VO2max. The rapid decline in O2 saturation occurred at 1.6 ± 0.5 l · min-1 or a work rate of 116 ± 43 W, and the LAT occurred at 1.7 ± 0.6 l · min-1 or a work rate of 124 ± 47 W. Belardinelli et al. 1995, found a consistent decrease in muscle oxygenation, with a slower rate during low work load, a more rapid decrease nearing LAT, which then reaches minimum saturation at approximately 80% of VO2max.

Subudhi, Dimmen & Roach, 2007

The purpose of this study (52) was to monitor changes in central and peripheral oxygenation during incremental exercise to volitional exhaustion. Thirteen competitive amateur cyclists (mean ± SD, 30 ± 7 yrs, 182 ± 6 cm, 78 ± 9 kg) performed a familiarization incremental exercise test to exhaustion under ambient conditions. On two additional days, participants performed an incremental exercise test under normoxic (FIO2=21%) and hypoxic (FIO2=12%) conditions. Participants warmed up on a cycle ergometer for 20 min at a work rate (watts) of 1.5 of their body weight (kg). Initial work rate was set at 25 W and increased 25 W per minute until volitional exhaustion or failure to maintain a pedal cadence of >50 rpm. Near infrared spectroscopy (NIRs) probes were placed across the left frontal cortex region of the forehead and over the belly of the left vastus lateralis muscle. Data was filtered with a Savitzky-Golay smoothing algorithm prior to analysis. Peak oxygen uptake (VO2peak, ml ·kg-1 · min-1) and peak power output (Powerpeak, watts) were lowered by 37% and 29%, respectively, in hypoxic conditions compared to normoxic. Oxygen uptake and power at ventilatory threshold (VT) were 33% lower in hypoxia, but when controlled for body weight there were no differences. Cerebral oxyhemoglobin (ΔO2Hb), deoxyhemoglobin (ΔHHb), and total hemoglobin (ΔTHb) increased during moderate intensities of 25% to 75% Powerpeak. Moreover, there was a decrease in cerebral oxygenation, but no change in total blood volume at higher workloads of 75 to 100% Powerpeak. During hypoxic conditions cerebral oxygenation decreased until volitional exhaustion. There was no change in ΔTHb as a result of absolute work rate between normal and hypoxic conditions, but there was a smaller increase in cerebral ΔTHb at work rates of >75% Powerpeak in hypoxic conditions. Oxygenation of the vastus lateralis decreased until 75% Powerpeak with an increased blood volume in normoxic conditions. At work rates of 75% to 100% Powerpeak, ΔO2Hb plateaued, but ΔHHb and ΔTHb slightly increased in normoxic conditions which suggested a decrease in muscle deoxygenation. Muscle oxygenation was similar in hypoxia compared to normoxia, however, ΔHHb and ΔTHb continued to increase near maximal intensity and muscle deoxygenation was greater than normoxia at all work rates. Subudhu et al. 2007 concluded that incremental exercise performance is not limited by cerebral oxygenation. Muscle oxygenation was similar in hypoxia and normoxia at work rates of 75% Powerpeak, but differed at work rates above 75% Powerpeak. Tissue deoxygenation during hypoxia was greater at all relative and absolute work rates compared to normoxia.

<u>Miura, Araki, Matoba, & Kitagawa, 2000</u>

The purpose of this study (39) was to determine the relationship between muscle oxygenation and muscle activity, as well as muscle oxygenation and blood lactate concentration.

Seven healthy subjects (mean ± SD, age 23.0 ± 4.5 yrs, weight 63.8 ± 7.0 kg, height 1.73 ± 0.05 m) participated in this study. Subjects underwent a preliminary incremental exercise test on an electromagnetically braked cycle ergometer to determine VO2max and VO2 at ventilatory threshold. On five separate days, subjects underwent five 6-minute cycling exercise at 60rpm at work rates of 50, 100, 150, 200, and 250 watts. The near infrared spectroscopy (NIRs) probe was placed over the right vastus lateralis for determination of muscle oxygenated hemoglobin/myoglobin (oxy-Hb/Mb) content, and myoelectric activity (EMG) was measured using surface electrodes over the distal half of the vastus lateralis muscle belly. The percentage of oxy-Hb/Mb remained constant at low work rates corresponding to 25.0 ± 5.0 and 36.6 ± 6.2% VO2max. At a work rate of 150 watts (50.6 ± 7.7 % VO2max) oxy-Hb/Mb decreased slightly, which then further decreased at 200 watts (67.8 ± 6.9 % VO2max) and 250 watts (82.9 ± 7.5 % VO2max). Myoelectric activity increased slowly at 25.0 ± 5.0 to 50.6 ± 7.7 % VO2max and a rapid increase in integrated EMG occurred at 67.8 ± 6.9 and 82.9 ± 7.5 % VO2max. Blood lactate concentration remained steady between 50 and 150 watts and increased linearly at 200 and 250 watts. Miura et al. 2000 reported a negative correlation for oxy-Hb/Mb and EMG (r = -0.947 to -0.993), oxy-Hb/Mb and BL (r = 0.890 to -0.982), as well as oxy-Hb/Mb and VO2 (r = -0.929 to -0.994). The authors concluded that the change in muscle oxygenation during exercise at a constant work rate is reflected in muscle activity and blood lactate concentration.

Methods

Overview of study Design

Thirteen healthy adults (10 men and 3 women, mean ± SEM, age = 23.3 ± 1.3 yr; body mass = 80.0 ± 6.5 kg; height = 175.4 ± 1.8 cm) volunteered to participate in this study. The study was approved by the University Institutional Review Board for Human Subjects at the University of Texas at El Paso (El Paso, Texas), and all participants completed a health history questionnaire and signed an informed consent document before testing.

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 the 1067 m, 2438 m, or 3810 m testing conditions. During testing visits, participants completed two sets of unilateral arm curls to volitional exhaustion at 70% of one repetition maximum (1RM) separated by one minutes of rest on a Preacher Curl station (Magnum Fitness Systems, Strength Industry Inc., Redlands, CA, USA).

Altitude simulation

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 VmaskTM; Hans Rudolph Inc., Shawnee, KS, USA). The mask was connected to an altitude generator (HYP 123 Generator, Hypoxico Altitude Training Systems, New York, NY, USA) which takes ambient room air and processes it through a filter to the user at a set simulated altitude. In addition, the machine and mask were separated by a double-Douglas bags capable of storing 4 liters of simulated altitude, so the subject may breathe freely and not experience the typical effects of breathing through a restricted tube. Altitude conditions were monitored using an oxygen monitor device (MySign®O; EnviteC by Honeywell, Wismar, Germany). An altitude of 1067 m was set by opening the valves to allow normal ambient air (~18.3% oxygen) of the current elevation of El Paso, Texas. An altitude of 2438 m and 3810 m were simulated by setting the generator to deliver an oxygen percentage of 15.4% and 13.0%, respectively.

One repetition maximum testing and repetitions to failure

Testing was carried out according to the guidelines established by the National Strength and Conditioning Association.(20) 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 one 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 ≤4 trials for all participants. A 2 to 4 minutes of rest was allowed between successive warm-up sets and 1RM trials.

During the 70% of 1RM fatiguing protocol, the participants performed unilateral arm curl repetitions to failure. The weight was determined from each participants' first testing visits (at 1067 m) 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.

Electromyography Procedures

Surface EMG signals were recorded using BioPac MP150 (BioPac MP150 with EMG100C amplifier; Biopac Systems, Inc., Santa Barbara, CA, USA) from the biceps brachii muscle of the right arm with a bipolar electrode (Kendall 530 series Foam Electrodes; Cardinal Health, Inc., Dublin, OH, USA) arrangements according to the Surface Electromyography for the Non-Invasive Assessment of the Muscles project (SENIAM) recommendations.(22) 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.

Signal 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 repetitions EMG signal. The EMG amplitude (root mean square: RMS) and EMG frequency (mean power frequency: MPF) were calculated from the middle 33% of the concentric phase of each repetition. The 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.

Statistical analysis

Three, 3 (Altitude: 1067 m, 2438 m, and 3810 m) × 2 (Set: Set 1 and Set 2) × 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 (Altitude: 1067 m, 2438 m, and 3810 m) × 2 (Set: Set 1 and Set 2) repeated measures ANVOA was performed to examine mean differences in the number of repetitions to failure. We performed follow-up two and one-way ANOVA's when appropriate. Post-hoc Tukey least significant difference (LSD) 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.

Results

There was no significant altitude × set two-way interaction ($p = 0.926$; $\eta_p{}^2 = 0.006$) for number of repetitions to failure. There was no significant main effect for altitude ($p = 0.501$; $\eta_p{}^2 = 0.056$). However, there was a significant main effect of set for number of repetitions to failure ($p < 0.001$; $\eta_p{}^2 = 0.891$), where the number of repetitions to failure decreased with each set (Set 1: 18.2 ± 1.4 > Set 2: 9.5 ± 1.0).

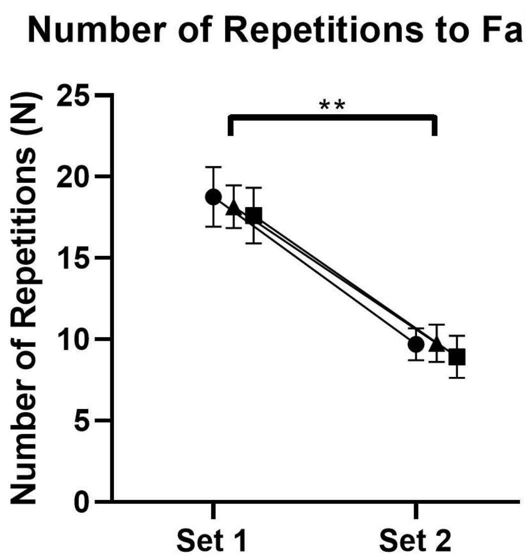

FIG 1. NUMBER OF ARM CURL REPETITIONS TO FAILURE

Number of arm curl repetitions to failure at 1067 m (solid circle; ●), 2438 m (solid square; ■), and 3810 m (solid triangle; ▲) of simulated altitudes. Values presented as mean ± SEM. *Indicates statistically significant difference ($p < 0.05$). **Indicates statistically significant difference ($p < 0.001$).

There was no significant three-way interaction for altitude × set × percent of repetitions to failure for EMG Time ($p = 0.391$; $\eta_p{}^2 = 0.076$). There was no significant altitude × set two-way interaction ($p = 0.241$; $\eta_p{}^2 = 0.112$) and no significant altitude × percent of repetitions to failure two-way interaction (p = 0.377; $\eta_p{}^2$ = 0.079) for EMG Time. There was no significant main effect for altitude (p = 0.297; $\eta_p{}^2$ = 0.096). However, there was a significant main effect for set of EMG Time (p = 0.001; $\eta_p{}^2$ = 0.628), where repetition duration were slower in set 2 (1.25 ± 0.09 s) compared to set 1 (1.12 ± 0.09 s). There was also a significant main effect of EMG Time of percent of repetitions to failure (p < 0.001; $\eta_p{}^2$ = 0.743), where repetition duration increased with percent of repetitions to failure (25% < 50%, p = 0.015; 50% < 75%, p <0.001; 75% < 100%, p <0.001).

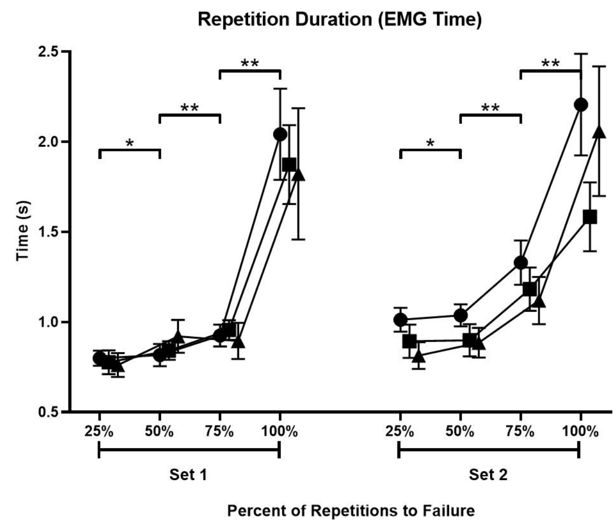

Fig 2. Repetition Duration (EMG Time)

Biceps brachii repetition duration as measured by electromyography (EMG) Time at 1067 m (solid circle; ●), 2438 m (solid square; ■), and 3810 m (solid triangle; ▲) of simulated altitudes. Mean values are presented. *Indicates statistically significant difference (p < 0.05). **Indicates statistically significant difference (p < 0.001).

There was no significant three-way interaction for altitude × set × percent of repetitions to failure for EMG RMS (p = 0.432; $\eta_p{}^2$ = 0.072). There was no significant altitude × set two-way interaction (p = 0.201; $\eta_p{}^2$ = 0.128) and no significant altitude × percent of repetitions to failure two-way interaction (p = 0.675; $\eta_p{}^2$ = 0.046). There was no significant main effect for altitude (p

= 0.391; η_p^2 = 0.070). There was, however, a significant main effect for set (p = 0.013; η_p^2 = 0.411), where EMG RMS was greater in set 1 (339.05 ± 37.48 μV) than in set 2 (318.76 ± 37.34 μV). There was also a significant main effect for percent of repetitions to failure for EMG RMS (p < 0.001; η_p^2 = 0.704), which indicated that 50% was greater than 75% (p < 0.001) and 75% was greater than 100% (p < 0.001).

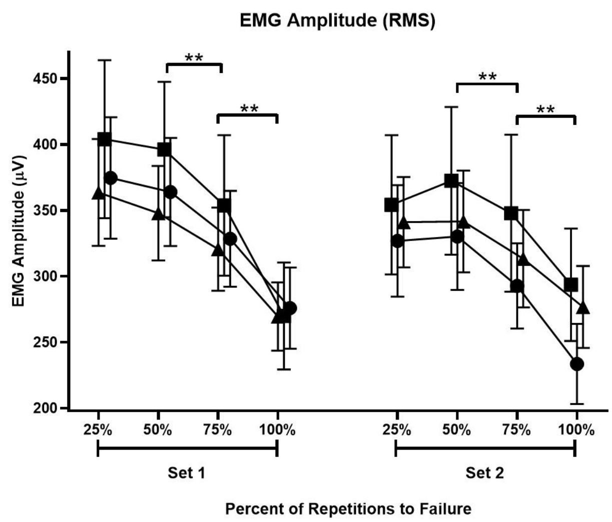

FIG 3. EMG AMPLITUDE (RMS)

Biceps brachii electromyography (EMG) amplitude as measured by EMG root mean square (RMS) at 1067 m (solid circle; ●), 2438 m (solid square; ■), and 3810 m (solid triangle; ▲) of simulated altitudes. Mean values are presented. *Indicates statistically significant difference (p < 0.05). **Indicates statistically significant difference (p < 0.001).

For EMG MPF, there was no significant three-way interaction for altitude × set × percent of repetitions to failure (p = 0.067; η_p^2 = 0.147). There was no significant two-way interaction for altitude × set (p = 0.225; η_p^2 = 0.117) and no significant two-way interaction for altitude × percent of repetitions to failure (p = 0.736; η_p^2 = 0.047). There was no significant main effect for altitude (p = 0.115; η_p^2 = 0.165) and no significant main effect for set (p = 0.630; η_p^2 = 0.020) for

EMG MPF. There was, however, a significant main effect for EMG MPF percent of repetitions to failure ($p < 0.001$; ${\eta_p}^2 = 0.662$), which indicated that 75% was greater than 100% ($p < 0.001$).

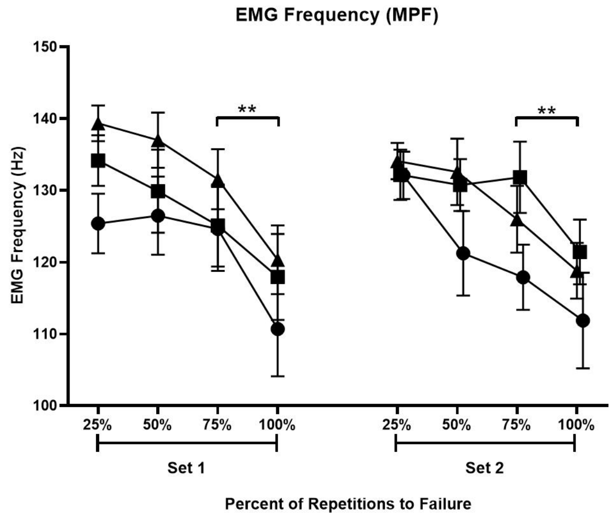

FIG 4. EMG FREQUENCY (MPF)

Biceps brachii electromyography (EMG) frequency as measured by EMG mean power frequency (MPF) at 1067 m (solid circle; ●), 2438 m (solid square; ■), and 3810 m (solid triangle; ▲) of simulated altitudes. Mean values are presented. *Indicates statistically significant difference ($p < 0.05$). **Indicates statistically significant difference ($p < 0.001$).

Discussion

Prolonged and repetitive heavy load bearing tasks lead to increased rates of fatigue development. These fatiguing factors are exacerbated in higher elevation such as when servicemembers are deployed to Afghanistan (elevation ranges from 1200 m to 7492 m), compromising physical performance and increasing injury risk. The main finding of this study indicated that altitude had no effect on that rate of fatigue development as measured by number of repetitions to failure, EMG Time, EMG RMS (amplitude), and EMG MPF (frequency) of the biceps brachii as a result of repeated DCER arm curl repetitions to failure at 70% of 1RM. 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), however, there were no differences between the normoxic and hypoxic conditions. Fatigue often results in an increased time to complete repetitions, EMG Time, which increased for each set at 50%, 75%, and 100% of repetitions to failure (Fig. 2). However, there was no difference in the repetition duration between altitude conditions. 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 (FIO2 = 0.21 or 0 m [sea level]?)), moderate hypoxia (FIO2 = 0.16 or 2134 m), and high hypoxia conditions (FIO2 = 0.13 or 3810 m).(49) These findings were in contrast with Peyrard et al., (2019) who reported a decrease in time to exhaustion during hypoxia (FIO2 = 0.13 or 3810 m; 250 ± 70 s) compared to normoxia (460 ± 220 s) following repeated 10 s arm-cycle ergometer sprints to volitional exhaustion.(45) In addition, Felici et al., (2001) reported decreased endurance time (22.4 ± 4 s to 18.3 ± 4.7 s) during fatiguing isometric muscle actions of the biceps brachii at 80% of maximal voluntary isometric contractions at high altitude (5050 m) compared to sea level.(17) 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.(17, 45, 49) That is, the current study and Scott et al., (2015) performed DCER exercises while Peyrard et al., (2019) and Felici et al., (2001) performed low resistance arm-cycle ergometer sprints and isometric muscle actions, respectively.(17, 45, 49) 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; however, the arm-cycle ergometer likely restricted blood flow to a lesser extent than DCER muscle actions.(45) 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 reducing or eliminating blood flow.(17) Therefore, the findings of the present study indicated that acute moderate- and high-altitude 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.

The present study indicated that altitude had no effect on motor unit activation measured by EMG RMS. These findings were in agreement with Casale et al., (2004) which report no differences in EMG amplitude during two voluntary contractions at 40% and 80% maximal voluntary isometric contraction (MVIC) of the biceps brachii at high altitude (FIO2 = 0.112 or 5050 m) compared to sea level.(13) Another study by Marillier et al., (2017) found no difference in biceps brachii EMG amplitude at sea level, following one or five days of exposure to high altitude (FIO2 = 0.12 or 4350 m) during intermittent submaximal isometric elbow flexions at 50% MVIC to task failure.(35) Muscle force production is modulated by increasing number of active MU to increase force output.(14) In the present study participants performed exercise at a constant load of 70% of 1RM until exhaustion in each altitude condition, requiring the same force production strategies throughout. Therefore, it is possible that despite acute exposure to different simulated altitudes, maintaining force output during high intensity arm curl repetitions at 70% of 1RM until volitional exhaustion may not alter force production strategies of MU.(38) The findings of the current and previous studies(13, 35) indicate that acute altitude exposure did not influence MU activation of the biceps brachii.

Although there were no effects of altitude on EMG RMS, there was a fatigue-induced decrease in motor unit 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 high altitude. 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.(29, 32, 44) For example, Kranz et al., (1985) reported a decrease in EMG amplitude during repeated MVICs of the elbow flexors that was attributed to a fatigue-induced decrease in neural drive.(29) 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.(32) Finally, Orizio (1992) also reported a decrease in EMG amplitude during sustained isometric muscle actions at 80% and 100% MVIC from the biceps brachii.(44) Changes in electromyographic 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.(15) Type II MU have a faster conduction velocity and depolarization/repolarization, as well as shorter action potential duration.(38) Maximal biceps brachii MU recruitment has been suggested to be achieved at 88% of MVIC,(31) and the present study utilizing 70% of 1RM it can be suggested that there is near maximal MU recruitment during the arm curl repetitions. The decrease in the recruitment and firing rates of these active mostly type II MU, evident by repetition failure or the loss of force production ability, may be independent of altitude exposure because of the consistent force production requirements. Therefore, the findings of the present study suggested that repeated arm curls in hypoxic and normoxic conditions resulted in similar patterns of responses for EMG RMS and that these decreases in EMG RMS were potentially due to fatigue-induced decreases in MU recruitment and firing rate.

The results of the present study indicated that fatiguing DCER arm curl repetitions at normal (1067 m), moderate (2438 m), and high (3810 m) altitudes resulted in similar patterns of responses in EMG frequency. These findings were in agreement with Kayser et al., (1994), who reported no differences in EMG frequency of the forearm flexors as a result of dynamic forearm exercise at high altitude (5050 m) compared to sea level.(27) The present study and other literature that examined the effects of single joint movements and indicated no differences in EMG frequency at altitude exposure compared to sea level,(17, 27) whereas other studies which did find differences in EMG frequency response between altitude exposure conditions, utilized multi-joint dynamic exercises of larger muscles of the lower body.(9, 54, 56) Acute altitude exposure combined with dynamic exercise has been shown to increase metabolic byproduct accumulation.(38) Potentially, smaller muscle groups involved in single joint movements increase metabolic byproduct accumulation to a lesser degree compared to larger muscle groups in multi-joint movements. Thus, smaller muscle groups may not provide sufficient stimulus to cause a large enough accumulation of metabolites compared to heavy exercise involving large muscle groups, preserving the normal altitude capacity to do work at high altitude.(38)

Furthermore, despite no effect of altitude 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.(29) Mottram et al. (2004) also reported a decrease in discharge rate at low intensity isometric muscle actions from the elbow flexor muscles.(40) The accumulation of metabolic byproducts (reduced Na+ and/or K+ accumulation) from anaerobic energy production (without oxygen) hinders signal propagation, due to a hostile extracellular environment reducing muscle membrane excitability.(38) Motor unit action potential conduction velocity is highly influenced by its extracellular environment, where an accumulation of metabolic byproducts such as hydrogen ions, inorganic phosphates, and lactate hinder signal propagation resulting in a decrease in EMG MPF.(38) Therefore, the findings of the present study indicated that fatiguing arm curl repetitions at normal (1067 m), moderate (2438 m), and high (3810 m) altitudes 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.

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 (1067 m), moderate (2438 m), and high (3810 m) altitude 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 higher altitudes. Despite similar performance and EMG time course changes to acute altitude exposure, the results of the present study demonstrated fatiguing DCER repeated arm curl repetitions at 70% of 1RM caused a decrease in both MUAP recruitment (EMG RMS) and MUAP CV (EMG MPF). Acute altitude exposure had no influence on rate of fatigue development or neuromuscular parameters of the biceps brachii.

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Vita

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