Acute Effects of Sprint Interval Training and Blood Flow Restriction on Neuromuscular and Muscle Function

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ACUTE EFFECTS OF SPRINT INTERVAL TRAINING AND BLOOD FLOW RESTRICTION ON NEUROMUSCULAR AND MUSCLE FUNCTION

by

DAVID HASSAM GONZALEZ ROJAS
B.S. University of Central Florida, 2021

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in the Department of Kinesiology in the College of Health Professions and Sciences at the University of Central Florida Orlando, Florida

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ABSTRACT

The purpose of this investigation was to examine the effects of continuous (CBFR) and intermittent (IBFR) blood flow restriction (BFR) applied during sprint interval training (SIT) on performance, muscle, and neuromuscular function. Fifteen men completed SIT with CBFR, IBFR, and No-BFR. Each SIT bout consisted of 2, 30-s maximal sprints on a cycle ergometer with a resistance of 7.5% of body mass. Concentric peak torque (CPT), maximal voluntary isometric contraction (MVIC) torque, and muscle thickness (MT) were measured before and after the SIT protocols during each visit. During the maximal strength assessments, surface electromyography (sEMG) was recorded and during each SIT, peak and mean RPM were measured, and power output was examined relative to the sEMG-based physical working capacity at the fatigue threshold (PWC_{FT}). CPT and MVIC torque decreased from pretest (220.3±47.6 Nm and 355.1±72.5 Nm) to posttest (147.9±27.7 Nm and 252.2±45.5 Nm), while MT increased (1.77±0.31 cm to 1.96±0.30 cm). There were no changes in sEMG amplitude assessed during the CPT (+6.5±22.5%) and MVIC (+7.7±24.1%) muscle actions, while sEMG mean power frequency decreased during the CPT (-12.8±10.5%) and MVIC (-8.7±10.2%) muscle actions. Collapsed across Sprint, %PWC_{FT} was greater during No-BFR (414.2±121.9%) than CBFR (375.9±121.9%). Peak and mean RPM decreased from Sprint 1 to Sprint 2 for No-BFR (157.7±12.5 and 110.4±7.1 RPM to 147.5±12.8 and 85.5±9.9 RPM), CBFR (153.9±14.5 and 105.2±11.5 RPM to 129.2±13.5 and 73.6±14.0 RPM) and IBFR (158.0±14.4 and 110.3±8.6 RPM to 134.1±15.7 and 81.2±12.5 RPM). During Sprint 1, mean RPM was greater for No-BFR than CBFR, while during Sprint 2, both No-BFR and IBFR were greater than CBFR. Collectively, the findings of the present study indicated that SIT with or without BFR did not
affect neuromuscular function and induced comparable reductions in neuromuscular fatigue and sprint performance across all conditions.
I dedicate this thesis to my family, thank you for your sacrifice and your support.
ACKNOWLEDGMENTS

It has been an honor and a privilege to work alongside you, thanks for everything.

Thesis Committee Chair and Advisor: Dr. Ethan C. Hill

Thesis Committee Members: Dr. Jeffrey R. Stout and Dr. Matt S. Stock
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I: INTRODUCTION

The application of blood flow restriction (BFR) during exercise has contributed to our understanding of the potential mechanisms mediating muscular adaptations. For example, BFR-studies have implicated that metabolites and/or muscle swelling facilitates muscular adaptations during low-load resistance training (Loenneke et al., 2012). Less is known, however, regarding the effects of BFR during maximal intensity activities. Specifically, BFR may provide a robust training stimulus when combined with sprint interval training (SIT). SIT is a form of high intensity interval training that utilizes maximal or supramaximal sprints interspersed with rest periods (Rodas et al., 2000; Skovgaard et al., 2018). SIT has been demonstrated to improve maximal aerobic speed, mean power, peak power, and time to exhaustion (Koral et al., 2018). Furthermore, there was a 4.7% increase in maximal oxygen uptake ($\text{VO}_{2\text{max}}$) following a 4-week intervention of SIT with BFR applied intermittently during passive rest, compared to a 1.1% increase with no BFR (Taylor et al., 2016). There was also an increase in hypoxia-inducible factor ($HIF$)-$\text{I} \alpha$ concentration, 3 hours post exercise following an acute bout of SIT with intermittent BFR (Taylor et al., 2016). Additionally, acute SIT with BFR applied continuously results in lower mean power ($530 \pm 160$ W vs. $543 \pm 135$ W), total work ($42 \pm 32$ kJ vs. $162 \pm 81$ kJ), maximal heart rate ($171 \pm 20$ bpm vs. $185 \pm 9$ bpm), and fatigue index ($-23.1 \pm 7.7\%$ vs. $-26.5 \pm 7.2\%$) than SIT without BFR (Willis et al., 2018). A greater rating of perceived exertion (RPE) for the legs ($19.5 \pm 0.6$) but a lower RPE for breathing ($15.5 \pm 2.5$) was observed during SIT with continuous BFR compared to no BFR (Willis et al., 2018). Together, these studies (Taylor et al., 2016; Willis et al., 2018) indicated that SIT with BFR, whether applied intermittently or
continuously, elicits both positive (increase in VO\textsubscript{2max}) and negative (decrease in mean power and total work) physiological and performance responses.

Other studies have also examined the acute responses of SIT with continuous and/or intermittent BFR (Kojima et al., 2021; Peyrard et al., 2019; Willis et al., 2019). For example, relative to non-restricted conditions, SIT combined with continuous BFR results in fewer completed 10-s cycling sprints, lower muscle excitation, and resting twitch force (Peyrard et al., 2019). Furthermore, SIT combined with intermittent (during rest) BFR reduced peak power, oxyhemoglobin concentration, and tissue saturation, but increased heart rate to a greater extent across five 10-s cycling sprints compared to SIT with no BFR (Kojima et al., 2021). Intermittent BFR may elicit comparable physiological responses as continuous BFR but achieved at a lower perceived effort (Schwiete et al., 2021). Therefore, it is important to examine the differences in physiological responses to SIT between intermittent and continuous BFR to develop more efficient training modalities to elicit desired adaptations.

The effects of SIT with and without BFR has been examined using a multitude of outcomes (Billaut et al., 2013; Kojima et al., 2021; Taylor et al., 2016; Willis et al., 2018). The application of BFR, however, induces unique sensations and physiological perturbations in the occluded limb that are typically quantified by systemic or subjective measures of fatigue or performance. Thus, a local measure of fatigue such as physical working capacity at the fatigue threshold (PWC\textsubscript{FT}) would provide valuable insight to the physiological responses associated with SIT and SIT combined with intermittent or continuous BFR. Specifically, surface electromyographic (sEMG) recordings of PWC\textsubscript{FT} tracks neuromuscular fatigue across incremental work bouts of progressively greater intensities and can demarcate training levels
(Camic et al., 2009, 2011). Thus, \( PWC_{FT} \) may aid in examining the effects of intermittent or continuous BFR, which has been associated with accelerated muscle fatigue (Karabulut et al., 2010). No previous investigations, however, have examined the effects of continuous or intermittent BFR during SIT training on \( PWC_{FT} \). Therefore, the purpose of this investigation was to examine the acute effects of SIT with continuous, intermittent, and no BFR on neuromuscular function and \( PWC_{FT} \). Based on previous findings (Kojima et al., 2021; Peyrard et al., 2019), it was hypothesized that SIT with continuous and intermittent BFR would result in greater neuromuscular fatigue and reduce the \% of \( PWC_{FT} \) achieved during SIT relative to unrestricted conditions.
II: REVIEW OF LITERATURE

SIT Protocols

2.1.1 (Mendez-Villanueva et al., 2007)

The purpose of this study was to compare muscle fatigue during two sets of an all-out repeated sprint exercise (RSE) protocol by examining mechanical output while being fatigued and not fatigued. Eight men (mean age 19.5 ± 0.9) were recruited to participate in the study and visit the laboratory for a total of 4 visits: three familiarization visits and one exercise visit. The repeated sprint exercise protocol consisted of 10, 6-second sprints on a cycle ergometer with 30-seconds of rest between sprints followed by another 5, 6-seconds sprints also with 30-seconds of rest between sprints. A passive recovery period of 6 minutes was allotted between the two sets of sprints. Prior to maximal sprinting, a 4-minute warm up was performed at a resistance of 100-120W, with three maximal standing-start accelerations lasting approximately 2 seconds followed by 3 minutes of rest before performing the RSE. All sprints were performed from the same pedal starting position with the right pedal located at 45° forward to the vertical axis. For each 6-second sprint, peak power output (PPO) and total work (TW) were calculated. EMG was examined from the vastus lateralis (VL) of the right leg and was recorded between the onset and the end of each sprint. Results showed that during the first 10 sprints, PPO and TW decreased by 24.1% and 27.2% from the maximal value. During the last five sprints, PPO and TW decreased by 17% and 20.3%. EMG amplitude (RMS) and frequency spectrum (MF) decreased during the 10 sprints by 14.3% and 10.6%. During the following 5 sprints, there was further significant decrease in RMS and MF (4.4% and 6.8%). Findings may implicate an opposite neuromuscular
response to fatiguing maximal exercise than is typically observed, when provided with passive recovery between maximal bouts of repeated sprinting.

2.1.2 (Mendez-Villanueva et al., 2008)

The purpose of this study was to determine the acute effects of repeated sprint exercise on neuromuscular activity and describe the relationship between each participant’s anaerobic power reserve (APR), the difference between maximum anaerobic and aerobic power. Eight recreationally active men volunteered to participate in the study (mean age 19.8 ± 0.8) where they visited the laboratory for seven exercise sessions with at least 48 hours between visits. First visit consisted of a familiarization followed by visits 2-5 where they performed a single 6-second sprint and practiced the main repeated sprint exercise protocol. On the sixth visit subjects performed a graded-exercise-test to determine $\text{VO}_2\text{peak}$. On the seventh and final visit subjects performed 10, 6-second sprints with 30 seconds between sprints to measure their repeated-sprint ability (RSA). EMG activity of the vastus lateralis (VL) of the right leg was recorded between the onset and end of each 6-second sprint. For each sprint, the RMS was normalized to the first sprint value of 100%. Results showed that on average, the maximum anaerobic power output displayed during the 6-second cycling sprints were 5.0 ± 0.2 times higher than maximum power outputs produced by aerobic power. EMG amplitude (RMS) decreased significantly across sprints with decrements ranging between 5.3 and 25.8%. It is noted that subjects with higher anaerobic power reserves saw greater power decrements across the sprints when compared to subjects with higher aerobic power reserves, accompanied by decrease in EMG amplitude of the VL muscle. These findings may be due to fiber type allocation in the VL as well as a decrease in
muscle excitation followed by possible motor unit derecruitment presented during maximal repeated sprints.

2.1.3 (Billaut & Basset, 2007)

The purpose of this study was to examine the effect different recovery patterns had on mechanical and neuromuscular responses during three separate repeated sprint ability (RSA) tests. Thirteen active men (mean age 23 ± 3) participated in the study for a total of four visits; a familiarization visit and three separate testing visits (at least 48 h in between) where they performed ten 6-s sprints with differing recovery patterns across the visits (constant 30-s, increasing 10 to 50-s, and decreasing 50 to 10-s). Peak power, mean power, and total work performed, were recorded for each sprint. Total work performed across the ten sprints was also calculated. Subjects completed maximal voluntary isometric contractions (MVIC), assessed on an isokinetic dynamometer (Biodex 3), 2-min before sprints, immediately after the tenth sprint, and 5 and 10 min after the tenth sprint. Electromyography (EMG) recordings of the vastus lateralis of the dominant leg were taken during the MVICs and analyzed on MATLAB (root-mean-square [RMS]). Results indicated that the highest peak power was achieved in sprint 1 (mean of recovery patterns = 797 W ± 203) followed by decrements across the rest of the sprints. The mean peak power across the three RSA tests was significantly lower in sprint 10 (-11.7%) compared to sprint 1. Total work calculated over the ten sprints was affected by recovery pattern, where the increasing recovery pattern exhibited the lowest total work (43.8 kJ) followed by the constant recovery pattern exhibiting lower total work (46.8 kJ) than the decreasing recovery pattern (48.5 kJ). The decreasing recovery pattern exhibited a higher fatigue index (-15.8%) than the increasing recovery pattern (-5.1%), with no difference compared to the constant recovery
pattern (-10.1%). Main effect of time between pre and post MVICs was observed, with post 5 and 10 min MVICs still being lower than pre MVIC but not significantly. Across the three recovery patterns, RMS did not vary significantly during the post MVICs compared to pre. There was however a significant interaction between MVIC repetition and recovery pattern, where RMS increased during the decreasing recovery pattern. These results suggest that decrements in peak and mean power are affected by recovery pattern including total work which was significantly lower for the increasing recovery pattern. Furthermore, decreases in MVIC force coupled with RMS increases suggests a neuromuscular response to fatigue that is attenuated as recovery intervals decrease.

2.1.4 (Billaut et al., 2013)

The purpose of this study was to determine if there is a relationship between peripheral muscle fatigue, muscle recruitment, and performance during repeated-sprint exercise (RSE). Ten male team-sport athletes (mean age 22.8 ± 4.4) volunteered to participate in the study for a total of three visits (one familiarization and two testing visits) and performed two RSEs consisting of fifteen, 5-s, cycling sprints, with 25-s of rest between sprints under normoxia and acute moderate hypoxia conditions. During familiarization, subjects practiced maximal sprinting to determine optimal cycling cadence, defined as the cadence for which maximal cycling power output was reached. After a 5 min self-paced warm up, subjects performed five maximal 5-s cycle sprints initiated with their dominant leg, at different resistances with 5 minutes of passive recovery in between each sprint. The repeated-sprint exercise for visits 2 and 3 was performed on an electronically braked cycle ergometer, where the pedaling rate was the same for every sprint in both trials (pre-determined individual cycling cadence of 128.7 ± 12.5 rpm). Arterial oxygen
saturation was estimated using pulse oximetry (Nellcor N-600) with optodes placed on the ears, shown to have a significant relationship with hemoglobin $O_2$ saturation. $\text{SpO}_2$ was recorded during baseline and 2-s after every sprint. Lactate concentration was measured using a catheter inserted in the antecubital vein, where blood was drawn at rest and immediately after the 5th, 10th and 15th sprints and 5 minutes post RSE. Cerebral and muscle oxygenation of the vastus lateralis (VL) was recorded using near infrared spectroscopy (NIRS) at 10 Hz, averaged over the last 2.5s of each sprint. Surface electromyography (EMG) was recorded from the VL, the vastus medialis (VM) and the rectus femoris (RF) with electrodes fixed longitudinally over the muscle bellies. The root mean square (RMS) of each of the three recorded muscles across each sprint was considered total EMG activity ($\text{RMS}_{\text{sum}}$). Subjects completed maximal voluntary contractions (MVC) of the leg extensors to evaluate changes in M-wave properties pre and post RSE. A reduction in the MVC RMS without a decrease in M-wave amplitude was interpreted as central activation failure. Peripheral magnetic stimulation was used to stimulate the quadriceps muscle and femoral nerve at a knee joint angle of 90° (full extension = 0°) of flexion with arms folded across the chest. The area between the quadriceps and femoral nerve was also stimulated during the MVCs. Neuromuscular assessments were performed before and immediately after the RSE with the subjects in the environmental chamber where the RSE was performed. Rating of perceived exertion was assessed using a Borg 15-point scale, taken at rest and immediately after each sprint. Results showed no significant change in performance for the first sprint during hypoxia, however total mechanical work was lower in this condition. A reduction in mechanical work (-23.9 ± 19.1%) during hypoxia was significantly larger than decrements observed during normoxia (20.2 ± 14.5%). There was an expected large difference in $\text{SpO}_2$ between the two conditions (normoxia: 96.9% vs hypoxia: 84.2%). Changes in muscle tissue saturation were not
significantly different between conditions (normoxia: 49.7% vs hypoxia: 43.4%), however cerebral tissue saturation was significantly lower in hypoxia (52.8%) compared with normoxia (70.6%). Changes in lactate concentration were similar for both conditions during every sprint and 5 minutes post exercise. Total EMG activity fell significantly in both conditions however $\text{RMS}_{\text{sum}}$ was lower in hypoxia (-13.7%). Muscle contractile function assessed with the twitch showed no significant difference between conditions. There was no significant effect of hypoxia observed for M-wave amplitude and duration post RSE. Mean maximal voluntary force was significantly lower in hypoxia compared to normoxia (-5.9%). No significant difference in RPE was observed between conditions. Overall, these results may indicate that performing RSE under hypoxic conditions exhibits greater physiological decrements compared to normoxia, possibly due to total oxygen concentration being lower, affecting multiple systems in the body.

2.1.5 (Koral et al., 2018)

The purpose of this study was to assess the acute effects of sprint interval training (SIT) on maximal shuttle run performance. Sixteen trained runners (12 men, 4 women, mean age: 21.1 6 3.6 years (18–28 years) participated in this study, where they performed a 2-week training intervention consisting of 4-7 bouts of 30-s maximal intensity sprints with 4 minutes of recovery between bouts, three times a week. Subjects were given a familiarization of the protocol and had their maximal aerobic speed (MAS), time to exhaustion at 90% MAS (TMAX90), and a 3,000m time trial evaluated pre and post training intervention. MAS test was as continuous running, multistage test where subjects ran on a 400m flat track with markers located every 50m along the track at 8km/h increasing speed by 1km/h every 2 minutes. Test is terminated once a participant falls 5m short of the designated marker. TMAX90 was measured on the same track with 50m
cone markings as subjects were instructed to run as long as possible. The 3km time trial was measured by having subjects run on the same 400m track as fast as possible until the 3km distance was reached. During the SIT protocol, mean (total distance covered divided by number of repetitions), peak (longest total distance covered in a 30-s period) power, and fatigue index (shortest distance divided by longest distance multiplied by 100) were assessed. Results showed a significant increase in MAS of 0.41 km/h reflecting a 2.8% improvement representing a small effect size. Similarly, TMAX90 showed a significant increase of 158.9 seconds, or a 42% improvement represented by a large effect size. There was also a significant decrease in the 3km time-trial of 50.4 seconds, reflecting a 5.7% improvement over a small-to-medium effect size. During SIT sessions, peak power improved by 3.06m and mean power improved by 13.9m however no significant changes in fatigue index were observed. These findings suggest that SIT is an effective method of improving MAS, TMAX90, 3km time trial performance, mean, and peak power acutely over a 2-week training period.

2.1.6 (Larsen et al., 2020)

The purpose of this study was to examine whether the mitochondrial oxygen affinity of the vastus lateralis (VL) and triceps brachii (TB) increases after completing a sprint interval training (SIT) protocol using both arm and leg cycling. Twelve untrained or moderately active men (mean age: 24.2 ± 3.8 years) participated in this study where they underwent muscle biopsies, blood sampling, and body compositions measurements, prior to and after a SIT protocol consisting of 4-6, 30-s isokinetic Wingate sprints, with 4 rests between sprints, of both arm and leg cycling separated by one hour. Prior to the training protocol, subjects completed an incremental exercise test of both arm and leg cycling (order randomized) separated by 2-h of rest
of four 4-min consecutive bouts with intensities ranging from 40% and 90% of VO$_{2\text{peak}}$. After 10 minutes of rest, an incremental exercise test used to determine VO$_{2\text{peak}}$ was performed, where arm cycling began at 20 W increasing by 10 W every 30-s and leg cycling starting at 60 W increasing by 25 W every 30-s. During the sprint protocol, order of which limbs went first was randomized and number of bouts would increase as the protocol progressed, from 4 sprints the first two days, 5 sprints the third and fourth day, and 6 sprints performed on the fifth, sixth, and seventh day. 6 days before the start of the training period, subjects reported to the lab following an overnight fast to provide a venous blood sample and muscle biopsy from the VL and TB. These procedures were repeated 48 hours after the 7th training visit. Results showed an increase in VO$_{2\text{peak}}$ from pre to post in arm (38.4 ± 7.5 to 43.1 ± 6.5) and leg (47.0 ± 7.5 to 49.9 ± 8.0) cycling. Isolated mitochondria from the VL and TB showed large inter-individual variations but were similar between muscles. Respiratory rate increased in the VL (5.8 ± 1.8 to 8.8 ± 2.2) and TB (5.3 ± 2.5 to 7.8 ± 3.7) which represented a higher respiratory flux increasing the oxygen pressure at the mitochondrial level where respiration is 50% of the maximal rate at saturating oxygen concentrations (p50$_{\text{mito}}$) to 77±7.7 in the VL and 77±7.8 in the TB. These findings suggest that p50$_{\text{mito}}$ and mitochondrial capacity share a role in determining mitochondrial function where p50$_{\text{mito}}$ can decrease with SIT and mitochondrial capacity can increase with SIT.

2.1.7 (Skovgaard et al., 2018)

The purpose of this study was to examine the effects of tapering after a period of high-volume sprint interval training (SIT) on running performance and muscular adaptations. Eleven moderately trained runners (8 men, 3 women, mean age: 29.2 ± 4.5) underwent a 40-day familiarization (HV) before testing, where 10 sessions of SIT (ten 30-s all-out running with 3.5
min of rest between sprints) were performed as well as 10 sessions of aerobic moderate-intensity running (30-60 minutes at 60-85% of max HR). Following the familiarization, an 18-day tapering period was completed with SIT where sets were reduced to four 30-s maximal sprints with 3.5 min of rest in between. On separate testing visits, subjects performed an incremental treadmill test (INC), a 10-km test, and a repeated running test (RRT) at 90% VO$_{2\text{max}}$ to exhaustion after a muscle biopsy and blood sample was collected. The INC consisted of walking for 2 min at 5 km/h, 6 min at 10 km/h, and 2 min at 14-15 km/h, then increasing by 1 km/h every minute until exhaustion. The 10-km test was performed on a running track with two bouts of 6-min treadmill running at 60% VO$_{2\text{max}}$. Muscle biopsies and blood sample were collected between 7 and 11 AM, at rest, from the vastus lateralis of the right leg. The RRT followed the biopsy and blood sampling and consisted of three bouts of running on a treadmill: 6 min of running at 10 km/h with 1 hour of recovery, 2 min of running at 90% VO$_{2\text{max}}$ with 5 min of recovery, running to volitional exhaustion at 90% VO$_{2\text{max}}$. Results showed that 10-km was 2.7% better after both 8 and 16 days of tapering. Time to exhaustion during RRT did not change during HV but was 22% longer after 18 days of tapering. VO$_{2}$ and running economy at 60% VO$_{2\text{max}}$ were lower after 16 days of tapering compared to HV. After 18 days of tapering, there was a higher expression of muscle NKA$\alpha$1, NKA$\beta$1, FXYD1, and SERCA. 3 min after RRT, plasma epinephrine, norepinephrine, sodium, blood lactate and glucose, were higher than before. These results suggest that SIT with tapering elicited improvements in short duration running performance as well as time-to-exhaustion, associated with increases in muscle protein expression.
Blood Flow Restriction

2.2.1 (Kojima et al., 2021)

The purpose of this study was to determine if implementing blood flow restriction (BFR) during rest periods of repeated sprint training would lead to accentuated deoxygenation levels while maintaining sprint performance and not compromising fatigue resistance. Seven active men (mean age 21.7 ± 0.8 years) performed repeated sprint exercises (5 x 10s maximal pedaling) on a cycling ergometer, resting 40 seconds in between each sprint bout with or without BFR throughout the duration of the rest. The load during pedaling was set to an equivalent of 7.5% of body weight. Muscle oxygenation was measured with near-infrared spectroscopy (NIRS). Blood lactate concentration was taken before, immediately after, and 5 minutes following BFR application. Data analyzed post-trials showed oxyhemoglobin levels were significantly lowered in BFR trials compared to the control group. A significant effect of time was noticed in total hemoglobin during sprints and rest periods. Tissue saturation levels were significantly decreased with BFR application. Mean power output was significantly reduced from the third to fifth sets of sprints in both BFR and control group however total power output did not differ. Blood lactate concentration did not show any variance between groups either. These findings indicate the BFR had no difference on blood lactate concentration as well as sprint power output while simultaneously lowering oxygenation of active muscle. This suggests that muscle oxygenation is not the only contributor to muscle power output.

2.2.2 (Willis et al., 2018)

The purpose of this study was to determine any changes in cerebral oxygenation as well as oxygenation of the vastus lateralis and neuromuscular fatigue across differing levels of blood
flow restriction (BFR) while completing a repeated cycling sprint test (RST) to volitional exhaustion. Eleven recreationally active volunteers took part in the study, (6 men and 5 women); mean age being 26.7 ± 4.2 years, where they were required to train at least 4 hours per week and be able to perform maximal intensity exercise. BFR was applied during the testing visits at differing intervals of 0, 45, and 60% of total arterial occlusion, measured in the first visit. Two maximal 10 second warm-up sprints were completed with three minutes of active recovery in between sprints. BFR cuff was kept inflated until the post-RST measurements were complete. Muscle oxygenation was assessed using near-infrared spectroscopy (NIRS). To assess neuromuscular fatigue, surface electromyography (EMG) electrodes were positioned on the vastus lateralis of the right upper leg. Results for the repeated sprint test reported that the fatigue index did not result in any significant differences between conditions. As far as peripheral oxygenation, lower concentration of deoxyhemoglobin in the vastus lateralis was reported when the values were compared between the three conditions (0, 45, 60). I suspect that the findings may indicate a greater attenuated performance during repeated sprints specifically due to BFR, when performed to total fatigue.

2.2.3 (Pignanelli et al., 2020)

The purpose of this study was to compare the structural and functional adaptations that occur when performing lower body low-load resistance exercise (LL-RE) compared to performing low-load blood flow resistance (LL-BFR) three times a week. Legs were randomly assigned to the BFR condition, matching for dominance. Whole muscle group adaptations were examined over a 6-week period of LL-RE and LL-BFR such as, muscle strength and endurance performance, skeletal muscle microvascular and morphological properties, and mitochondrial
protein content and function. 10 healthy men (mean aged 24), who previously participated in a single bout investigation of LL-RE and LL-BFR, were recruited to perform the 6 weeks of training intervention which included three sets of single leg squats at a load corresponding to 30% of their 1RM to task failure. Strength testing was performed at the baseline visit, at the start of weeks 3 and 5 and following the 6th week of training. Muscle biopsies were taken pre and post 6-week intervention, following at least 5 days since the last training intervention. To standardize post exercise nutrition all subjects consumed 25g of whey protein. The legs assigned to the LL-RE throughout the study performed more repetitions and had a greater load than the leg with the LL-BFR condition however even with total volume differences, both legs increased their respective training volume two-fold at the end of the intervention compared to the beginning. The study demonstrated how after the 6-week training program both muscle strength and size increases (~25% increase in 1RM) were similar despite that the LL-BFR intervention had ~33% lower training volume as well as greater sustained power output during muscle endurance tasks compared to the LL-RE leg. These findings indicate that it is possible to achieve the same muscular adaptations when completing LL-BFR at lower training volumes compared to performing LL-RE, which may provide insight on the mechanisms driving muscle adaptations when tasks are performed to failure under BFR conditions.

2.2.4 (Fahs et al., 2015)

The purpose of the study was to examine the muscular adaptations caused by performing low-load (20-50% of 1RM) resistance training to fatigue with and without blood flow restriction. 22 subjects aged 40-64 years, with 14 being men and 8 women, were recruited to perform unilateral knee extensions to volitional fatigue at a load of 30% 1RM over the course of 6 weeks.
Training volume increased as the intervention progressed, beginning with two sets of the exercise for the first 2 weeks, three sets for weeks 3 and 4, and four sets for weeks 5 and 6. sEMG was placed on each limb to record excitation of the vastus lateralis (VL) during the seventh training session, specifically because by this point the subjects were familiar with the protocol. 17 of the subjects did not reach arterial occlusion pressure at 300mmHg and were therefore occluded at 150mmHg during the first week and 240mmHg during the rest of the training weeks. At the end of the 6 weeks, adaptations were analyzed, and the results indicated increases in strength, and muscular endurance with no significant differences between the BFR and free-flow (FF) conditions however there was a significant increase in VL thickness observed in the leg that completed the protocol under BFR. The greatest adaptation was in muscular endurance, increasing significantly with both conditions. The findings indicate that performing low-load resistance exercise to volitional fatigue under BFR can significantly increase muscle endurance and muscle thickness with lower training volume than FF conditions. This may benefit populations like the one observed for the study in terms of maximizing adaptations but not having to perform greater loads, therefore minimizing chance of injury.

2.2.5 (Fatela et al., 2019)

The purpose of the study was to determine whether blood flow restriction (BFR) altered the characteristics of motor units during low-intensity exercise. Eight men (mean age 26 ± 3.8 years) completed 5 sets of 15 unilateral knee extensions at 20% 1RM with and without BFR. Three pre-evaluation protocols were completed by subjects in which they performed a maximal voluntary isometric contraction (MVIC) and two isometric trapezoidal contraction with a plateau of 40% MVIC for 12 seconds. The protocols were repeated in an inverse order after the low
intensity exercise with and without BFR. Measurements at pre 1 and post 2 time points were performed without BFR in both conditions. In the LI-BFR condition, measurement of pre 2 and post 1 were made with BFR. BFR arterial occlusion pressure (AOP) was set to 60% of their baseline measurements taken at rest during their familiarization visit. Results indicated that the low-intensity BFR intervention elicited the recruitment of motor units with higher motor unit action potential amplitudes as well as an increased firing rate. Motor units recruited at similar force levels during both conditions also expressed higher firing rate under BFR. There were no differences with the pre fatigue trapezoidal with either condition suggesting that neuromuscular function is not affected by relative BFR, however from Pre 2 trapezoidal to post 1 trapezoidal there was a significant decrease in greater motor unit recruitment threshold. Explanations may vary from the extra metabolic stress resulting from the increased blood pooling and metabolite build up which already causes increased firing rates, as well as the faster onset of fatigue leading to greater muscle recruitment in an attempt to preserve mechanical and force output.

2.2.6 (Oranchuk et al., 2020)

The purpose of this study was to observe the effects of blood flow restriction (BFR) on neuromuscular fatigue following sustained maximal isometric contractions. 12 active men (mean age 28.8 ± 8.4) performed 1-min maximal voluntary isometric contractions (MVIC) via leg extension with and without blood flow restriction measuring at 300mmHg. Neuromuscular testing was performed with transcranial magnetic stimulation (TMS) in which subjects performed an MVIC for approximately 5 seconds and then a TMS pulse was administered followed by peripheral nerve stimulation (PNS) before, immediately after contraction and throughout an 8-minute recovery period between contractions. Muscle oxygenation was
measured using near-infrared spectroscopy (NIRS). TMS derived voluntary activation was lower during the non-BFR condition during the recovery period. Muscle oxygenation was not different between conditions however force decreased for both conditions during the minute MVIC. A decrease in vastus lateralis (VL) root-mean-square was also present in both conditions. There was no difference in neuromuscular fatigue and recovery between the conditions. Findings indicated that MVIC with or without BFR induce complete or near-complete limb ischemia.

2.2.7 (Fatela et al., 2016)

The purpose of this study was to examine the acute effects of exercise on muscle activation and fatigue under different levels of blood flow restriction (BFR). Fourteen non-resistance trained healthy men (mean age 24.8 ± 5.4) performed unilateral leg extensions at 20% of their 1RM for a total of 75 repetitions under arterial occlusion at 40, 60, and 80%. Prior to the fatiguing protocol, 1RM was determined as well as maximal voluntary isometric contraction (MVIC). Electrodes were placed following SENIAM recommendations, and they recorded activity in the vastus medialis (VM) and rectus femoris (RF). Pre- and post-exercise measurements included mechanical output (MVC torque), neuromuscular function and fatigue (Median frequency of the EMG power spectrum) and muscular activation (Root Mean Square of the EMG signal). Results indicated no significant differences in MVC torque output except in the 80% BFR condition where there was a 5.2% decrease. There were no differences for either VM or RF median frequency but there were differences between conditions, however MF decreased in all conditions with -9.5% for 40%, -19.9% for 60% and -30.6% for 80%. For the RF there was an RMS decrease (-13.9%) during the 40% BFR condition however there was an increase (28.1%) during the 80% condition. For the VM there was an RMS increase in the 60 and 80%
conditions where cuff deflation only induced significant RMS decreases in the 80% condition however values remained persistently higher throughout. These findings indicate that increases in vascular occlusion may lead to relative increases in muscle activation as well as a decreases in fatigue tolerance.

2.2.8 (Peyrard et al., 2019)

The purpose of this study was to determine the effects of hypoxia and blood flow restriction (BFR) on a repeated sprint ability test (RSA) and its effects on elbow flexor neuromuscular function. Fourteen volunteers participated in this study (10 men and 4 women) with a mean age of 26 ± 4 years and trained throughout the week for at least 4 hours completed an RSA consisting of 10-second sprints with 20-seconds of active recovery in between sprints until task failure. Subjects had 5 total visits, one familiarization and 4 experimental visits where conditions were performed in a randomized order with 3-4 days between sessions, the experimental conditions being normoxia (NOR), normoxia with BFR (N_{BFR}), hypoxia (HYP), or hypoxia with BFR (H_{BFR}). At the beginning of each visit, electrical muscle stimulation (EMS), electrical nerve stimulation, (ENS) as well as transcranial magnetic stimulation (TMS) sites were assessed. Subjects completed an isometric warm up of 5-second isometric contractions and 5 seconds of rest to between contractions to reach maximal voluntary contraction (MVIC). After a 6-minute recovery period, subjects completed a neuromuscular function evaluation (NME) where TMS, EMS, and ENS were performed. Another 6 minutes of recovery was allotted before subjects then completed an arm-cycling repeated sprint ability test to exhaustion under one of the 4 conditions. A post-NME was conducted 2 minutes after the RSA. Arterial oxygen saturation, pre-frontal cortex (PFC) and biceps brachii (BB) oxygenation were measured using near-infrared
spectroscopy (NIRS). EMG signals of the BB and triceps brachii (TB) were recorded continuously for the entire duration of each visit. Results showed that mean power output was affected by BFR but not by hypoxia with or without BFR. Total number of sprints was affected by both BFR and HYP. Change in EMG\textsubscript{RMS} was not impacted by BFR or H\textsubscript{BFR} but was significantly less increased with HYP compared to NOR. BFR seemed to impair muscle excitation while hypoxia mainly affected corticospinal excitability. These findings suggest that BFR induces a greater peripheral fatigue through metabolic waste build up while hypoxia shows signs of central fatigue coupled with lower levels of cerebral oxygenation.

2.2.9 (Hotta & Ito, 2011)

The purpose of this study was to assess muscle fatigue using different electrode configurations for surface electromyography (sEMG) during low-load isometric contractions, with and without blood flow restriction (BFR). Center frequency (CF) of the power spectral density (PSD) and the Borg CR-10 scale were used as indices of fatigue. Four healthy male adults in their twenties participated in the study, where they performed three separate isometric muscle actions of the biceps brachii at 20% of their maximal voluntary isometric contraction (MVIC) torque, with each contraction lasting 8 minutes. In the BFR condition, subjects had their arterial blood flow occluded using a pneumatic cuff placed on the upper arm set at 200 mmHg. Blood flow was restricted only during the first 5 minutes of contraction, after which the cuff was deflated, and the subjects finished the remaining 3 minutes of contraction under non-BFR conditions. EMG was recorded using both a monopolar and bipolar configuration for signal acquisition comparison. For the monopolar configuration, the recording electrode was placed on the muscle belly of the long head of the biceps brachii, the ground electrode on the wrist, and the
reference electrode on the elbow, respectively. In the bipolar configuration, the recording electrodes were also placed on the long head of the biceps brachii with a center-to-center spacing of 20mm, parallel to the axis of the muscle fibers. Results showed that the CF values of the monopolar configuration were significantly lower than those of the bipolar configuration in both conditions and that RPE for the BFR condition was higher for the first 7 min of each contraction. These findings may indicate that since the monopolar configuration has a wide detection area, it may be more efficient in measuring muscle fatigue over a wider surface area, while BFR seems to elicit greater perception of muscle fatigue and possibly earlier onset.

2.2.10 (Abe et al., 2010)

The purpose of this study was to determine the effects of low-intensity cycle training with bilateral blood flow restriction (BFR) on thigh muscle volume and VO\textsubscript{2max}. Nineteen physically active men (aged 20-26) volunteered to participate in the study, where they were randomized between a BFR group (n=9) or a control (CON) non-BFR (n=10) group and performed the low intensity cycle training on an electrically braked cycle ergometer (Aerobike 900U) once a day, 3 days a week, for 8 weeks. The BFR group performed the cycle training at 40% of VO\textsubscript{2max} for 15 minutes while the CON group performed the cycle training also at 40% of VO\textsubscript{2max} but for 45 minutes. BFR occlusion pressure was measured each training day and was maintained for a total of 18 minutes (3 min preparation time and 15 min cycling) where the cuff was immediately deflated upon completion of the cycling. Heart rate was recorded at the 5\textsuperscript{th} and 15\textsuperscript{th} minute for both BFR and CON groups as well as ratings of perceived exertion (RPE) using a Borg 15 Point Scale at the end of each training session. Thigh muscle volume was measured via MRI multislice images taken while the participant rested in a supine position with their legs extended.
Continuous, transverse images were taken with a 1.0 cm slice thickness, originating from the greater trochanter to the lateral condyle of the femur for each participant. Muscle volume was defined as the sum of the slices of muscle captured and was calculated by multiplying the muscle tissue area by the slice thickness. Cross-sectional-area was digitized for each muscle slice. Maximal isometric strength of the knee extensors and flexors was determined using an isokinetic dynamometer (Biodex 3) ~1 week prior to the first training session and 3 days after the final training session. Maximal voluntary isometric leg extension muscle actions (MVIC) were performed at a knee joint angle of 75° and MVIC leg flexion muscle actions were performed at 60° (0° corresponded to full extension at the knee). To determine VO$_{2\text{max}}$, a graded exercise test (GXT) was performed on an electronically braked cycle ergometer during the subjects’ baseline visit and during post-training testing. The GXT began with a workload of 50 W and increased by 15 W every minute until volitional exhaustion (Increasing by 10W a minute if a workload of 200 W was reached). Results indicated a significant increase in mid-thigh girth for the BFR group but not the CON group. Muscle CSA increased by 3.4% for the thigh and 4.6% for the quadriceps while muscle volume increased by 3.8% and 5.1%, respectively. MVIC torque increased in the BFR group by 7.7% but not sufficiently in the CON group (1.4%). No change in isometric knee flexion was observed for either group. Heart rate was higher for the BFR group (mean heart rate reserve [HRR]: 59%) during training sessions compared to the control group (mean HRR: 42%) and RPE was also higher for the BFR group at the end of each session. (10.5 ± 1.4 and 13.6 ± 1.3). Absolute and relative VO$_{2\text{max}}$ increased in the BFR training group as well as time to exhaustion (15.4% increase) but these changes were not observed in the CON training group. These findings may indicate that performing low intensity cycling with BFR over 8 weeks,
elicits significant increases in maximal oxygen uptake and thigh muscle volume compared to no significant changes when performed with no BFR.

2.2.11 (Kim et al., 2016)

The purpose of this study was to compare the effects of vigorous to low intensity with blood flow restriction (BFR) cycle training and detraining on muscle mass, strength, and aerobic capacity over the course of 11 weeks. Thirty-one college aged men (22.4 ± 3.0 years, range: 19–30 years) participated in this study and were split into three groups where they performed 20-mins of either vigorous-intensity (70% HRR) cycling, low-intensity (30% HRR) cycling with BFR on a cycle ergometer, or the non-exercising group for 6 weeks. 1-RM testing of the knee extensors and flexors was performed on an isotonic leg extension machine and a separate leg curl machine, where 1-RM was achieved withing 4-6 attempts with 1-min of rest between attempts. Muscle cross-sectional area (mCSA) was assessed using a peripheral quantitative computed tomographic (pQCT) scanner, taken from 50% of the length of the femur then subtracting total fat area leaving just muscle and bone to determine mCSA. Body composition was measured using a DEXA to assess regional bone-free lean body mass and fat mass following height and weight measurements. VO$_{2peak}$ was determined using a cycle ergometer and an indirect spirometry metabolic cart, where subjects performed a graded exercise test consisting of 7 stages from 25 to 325 W with each stage increasing by 50 W every 3 minutes at a pedaling cadence of 50 RPM. Measurements were taken pre and post training intervention as well as 3-weeks post training. Results across the three time points showed an increase in knee extension and flexion strength across all three groups, increased lean leg mass in the low-intensity BFR group, increased mCSA, and increased VO$_{2peak}$ across all three groups. Even though all three groups had
similar increases across variables it is noteworthy how lean leg mass only significantly increased in the low-intensity BFR group, suggesting a potential additive effect of BFR on muscle size when cycling.

2.2.12 (Willis et al., 2019)

The purpose of this study was to examine the effects of blood flow restriction (BFR) and systemic hypoxia, either alone or in combination, during repeated sprint arm cycling on vascular and oxygenation responses. Sixteen active subjects (11 men, 5 women, mean age 26.4 ± 4.0 years old) completed 5 visits consisting of one familiarization and four testing visits where they performed 10-s maximal arm cycling sprints until volitional exhaustion with 20 seconds of rest between sprints, across 4 separate conditions (Hypoxia: 400m, 3800m, BFR: 0%, 45%). Number of sprints, mean power, total work, pulse oxygen saturation (SpO₂), maximal HR, tissue saturation, and VO₂, were measured for each condition. Results showed that number of sprints was lower in both hypoxic conditions (3800m,0%, and 3800m 45%). Mean power was unchanged across conditions. Total work decreased by 23% from hypoxia alone compared to control and 53% from hypoxia and 45% BFR compared to control. SpO₂ and VO₂ both decreased in both hypoxic conditions compared to normoxic. Maximal HR was lower in the combined hypoxia and BFR condition compared to control. Blood flow was 52% lower in the hypoxia with BFR condition compared to just hypoxia, and 48% lower with BFR only compared to hypoxia only. Tissue saturation index (ΔTSI) and absolute maximum TSI decreased with both BFR conditions compared to control and decreased further in both hypoxic conditions compared to BFR alone. These findings suggest that arm cycling performance is hindered by systemic
hypoxia with no differences between hypoxia with BFR or hypoxia only, potentially due to decreased maximal TSI and VO₂.

2.2.13 (Taylor et al., 2016)

The purpose of this investigation was a two-part study to examine the acute and chronic effects of performing sprint interval training (SIT) combined with post-exercise blood flow restriction (BFR). A total of 28 healthy trained men who cycled at least 120±66 km per week volunteered to participate across both studies (2 men participated in both). Study 1 was the training study where 20 subjects across two groups (mean age: 27±7 vs. 26±5) performed 4 weeks of SIT either with or without post-exercise BFR where VO₂max and 15 km time-trial performance, were assessed pre and post training intervention. Study 2 examined the acute responses of SIT where 8 subjects had muscle biopsies taken before exercise, immediately postexercise, and 3 hours post exercise. For study 1, pre and post training outcomes were conducted on a cycle ergometer where subjects completed an incremental test to exhaustion to determine VO₂max, pedaling at a freely chosen cadence for 5 min at 120 W, after which the resistance increased by 20 W every minute. On the same cycle ergometer subjects performed a 15-km time-trial 3 separate times to familiarize them with the protocol, with at least a week between attempts. The third time-trial effort was reported as their pretraining outcome measure. For the SIT protocol, subjects completed two sessions per week that consisted of repeated 30-s maximal sprints on a mechanically braked cycle ergometer at a resistance equivalent to 7.5% of total body mass. SIT was progressive as subjects performed 4, 5, 6, and 7 maximal sprints in week 1, 2, 3, and 4 with 4.5 min of recovery between sprints. Subjects in the BFR group immediately after the sprint, laid supine on a couch where they were subject to BFR at a pressure
of 130 mmHg for 2 min, after which the cuff was rapidly deflated, and subjects laid supine for another 2 min. For study 2, subjects reported to the lab for a total of three visits to perform the same incremental test described in study 1 and randomized maximal sprints at a fixed cadence (90, 100, 110, 120, and 130 RPM) followed by two experimental visits. The experiment visits consisted of subjects resting supine for approximately 20 min to obtain resting muscle biopsies of the vastus lateralis, followed by a 5 min warm up cycling at 120 W, whereby immediately after, they performed four 30-s maximal sprints separated by 4.5 min of rest. Subjects in the BFR group underwent the same procedures as in study 1 after their sprint was completed. Muscle biopsies were then taken within a minute after cessation of exercise, followed by another biopsy three hours later. Results of study 1 showed greater average power output (642 ± 10 W vs 618 ± 11 W) and total work (106 ± 22 kJ vs 102 ± 21 kJ) done in the control group compared to the BFR group. Absolute and relative VO$_{2\text{max}}$ increased after BFR but not in the control group as well as an increase in relative sprint peak power output for both groups with no significant differences between them. Results of study 2 showed an increase in phosphorylation of p38MAPKThr180/Tyr182 immediately after SIT with and without BFR (4.1-fold vs 3.2-fold) before returning to baseline 3 hours post-exercise. PGC-1α, VEGF and VEGFR-2 increased at 3 hours in both groups. HIF-1α mRNA expression increased at 3 h only after BFR. The combined findings of these studies demonstrate how performing SIT with BFR may elicit adaptations responsible for improving VO$_{2\text{max}}$ starting at the local level with changes in mRNA expression of the working muscle.
The purpose of this study was to examine the effects of 4 weeks of low-intensity blood flow restricted (BFR) training on time to exhaustion during severe-intensity cycling exercise. Thirteen recreationally active young adults (BFR Group: 7 men, 2 women, mean age: 22±5 years; CON Group: 3 men, 1 woman, mean age: 23 ± 2 years) participated in this study where they completed two exercise protocols pre and post the 4 week training intervention, consisting of an incremental cycling test until volitional exhaustion and a constant-load severe cycling test at a work rate (WR) corresponding to 110% of peak power (P_{peak}) determined pre training. The incremental cycling test began at 1.0 W/kg followed by an increase of 35 W for men or 25 W for women every 3 minutes until volitional exhaustion. Subjects performed a constant work-rate cycling test until exhaustion which began with a 5-minute warm up at 30% of P_{peak} followed by 5 minutes of rest, with subject continuing the test until they could no longer pedal at a cadence of 70 RPM. Both the BFR and CON groups performed three exercise sessions per week on a stationary cycle ergometer consisting of 2 sets of 5 repetitions lasting 2 minutes with 5 minutes of rest between sets (3 min active recovery at 30% of P_{peak} followed by 2 min of passive recovery) increasing up to 8 repetitions by the 4th week. The BFR group had the cuffs on both legs and were inflated to 140 mmHg during the repetitions and deflated during the rest periods between repetitions of 1 minute. Cuff pressure was increased by 20 mmHg after three sessions therefore having the last week’s occlusion be 200 mmHg. Results indicated that the BFR group showed a significant increase in time-to-exhaustion compared to the CON group at post-training while there was no difference in time-to-exhaustion in the CON group comparing pre and post training. These findings suggest that the addition of BFR to low-intensity exercise may cause adaptations locally in the muscle that attenuate fatigue during more intense exercise. These
adaptations may be due to increased metabolite build up resistance developed in the muscle over time with BFR training.

2.2.15 (de Oliveira et al., 2016)

The purpose of this study was compared the effects high and low intensity interval training with and without blood flow restriction on aerobic fitness and muscle strength. Thirty-seven recreationally trained adults (mean age: 23.8 ± 4 years, 22 men, 15 women) were placed in 4 different groups of either high-intensity interval training with or without BFR (HIT/HIT+BFR) or low-intensity interval training with or without BFR (BFR/LOW). Total duration of the study was 6 weeks in which all subjects visited the laboratory on two occasions; before and after the 4 weeks of training, where their anthropometric measures were recorded, familiarization of maximal voluntary isometric contractions (MVIC) and an incremental exercise test to determine onset blood lactate accumulation (OBLA), VO\textsubscript{2max}, maximal power output (P\textsubscript{max}) and isometric muscle strength. Incremental exercise test began at 0.5 W/kg and increased by 35 W for men and 25 W for women every 3 minutes until volitional exhaustion. Strength measurements were assessed with two 5-s bilateral MVIC at a 60° knee joint angle (0° full extension) with 5 minutes of rest between attempts, on load cell. All 4 groups performed the same three exercises per week on a cycle ergometer consisting of two sets of five repetitions for the first three sessions after which one repetition per set was added each week. Each repetition lasted 2 min with 1 min of passive rest between repetitions and 5 min (3-min active recovery at 30% P\textsubscript{max} followed by 2-min passive rest) of rest between sets. The BFR group wore cuffs during all training sessions with the pressure set to 140 mmHg during the 2-min repetitions and deflated during the 1-min rest. Cuff pressure was increased by 20 mmHg after three sessions, reaching 200 mmHg by the final week.
of training. The HIT group completed a variable power output training protocol beginning at 110% $P_{\text{max}}$ with a progressive 5% decrease in intensity every 30 seconds. For the HIT+BFR group, one set was performed as “BFR” and the other as “HIT” with set order alternated every session. Results showed that work session volume and total training volume in HIT was ~340% higher than BFR and LOW groups and was ~171% higher than HIT+BFR. Peak lactate concentration was similar between HIT and HIT+BFR and both were greater than BFR and LOW. VO$_2$ during HIT was higher than HIT+BFR but was higher in both compared to LOW and BFR however VO$_2$ did not increase for the LOW group. Isometric muscle strength only showed a significant increase for the BFR group, with no differences demonstrated for the other groups. These findings suggest that low-intensity interval training with BFR may elicit adaptations to both aerobic fitness and muscular strength compared to high-intensity interval training with or without BFR.

2.2.16 (Keramidas et al., 2012)

The purpose of this study was to investigate the effect of interval training with blood flow restriction (BFR) on maximal and submaximal cycling performance. Twenty (6 men, 14 women) untrained adults participated in this study consisting of three separate phases: a pre-training testing visit, a 6-week interval training, and a post-training testing period. During pre and post training visits, subjects completed an incremental exercise test to exhaustion, a 6-min submaximal test at 80% of pretraining VO$_{2\text{max}}$ and a maximal constant-power test to exhaustion (TF$_{150}$). Only during the pre-training period did subjects perform an incremental test to exhaustion with BFR (VO$_{2\text{max} \text{Press}}$). VO$_{2\text{max}}$ testing was performed on an electromagnetically braked cycle ergometer beginning with a 4-min warm up at 30 W with workload increasing by
20 Watts every minute. VO$_{2\text{max}}$ testing with BFR had subjects sit idly for 2-min with the cuffs inflated to 90 mmHg before pedaling at 70 rpm until volitional exhaustion. 48 hours after VO$_{2\text{max}}$ testing, subjects performed the submaximal and maximal constant power test. Training protocol consisted of 3 days per week for 6 weeks, pedaling at a cadence of 70 RPM with 2 min of work and 2 min of active recovery bouts from 90% to 50% VO$_{2\text{max}}$ for control group and 90% of VO$_{2\text{max}}$ Press to 50% of VO$_{2\text{max}}$ for the BFR group. Heart rate, peak power output, RPE, blood sampling, and muscle oxygenation were recorded during the testing and training sessions. Results showed a significantly higher VE$_{\text{max}}$ and PPO during the post-training period. Post-training VO$_2$ did not change in either group at the same relative PPO however in the BFR group oxygenation was significantly reduced at 80% and 100% PPO while only being reduced at 100% in the CON group. Only the BFR group had a greater reduction in total hemoglobin at 100% of post-training PPO. The mean power output during the submaximal test was 146±42 W with CON group being 151±55 W and BFR group being 140±28 W. Mean power of the timed ride to fatigue (TF$_{150}$) was 288±76 with both groups significantly improving their post-training performance. Hemoglobin and hematocrit did not change in both groups after the training regimen. These findings suggest that interval training with BFR does not improve maximal and submaximal performance more than regular interval training without BFR.
EMG and Fatigue

2.3.1 (Miller et al., 2020)

The purpose of this study was to compare motor unit activation rates from maximal voluntary contractions (90% of MVIC) to submaximal (50% of MVIC) isometric contractions performed to fatigue. Subjects included 9 healthy adults who volunteered to be in the study. (mean ± SD, 7 men, 2 women, age = 22.78 ± 4.15 years). Training varied from recreationally active (∼1–3 h·wk⁻¹) to resistance trained (4–8 h·wk⁻¹). Subjects completed three MVICs in which the peak force between them was used to normalize force requirements for the trapezoidal muscle actions at 90% of MVIC as well as the isometric muscle actions performed until to fatigue. Trapezoidal contractions ramped up at 10%MVIC/s for a total of 9 seconds and were then held for 12 seconds at a force of 90%MVIC in which the contraction would de-ramp at 10%MVIC/s once again. Subjects completed an average of 10 ± 5 repetitions for the fatiguing protocol. A total of 576 motor units were analyzed in which the data indicated that the later recruited higher threshold motor units were larger and had lower firing rates at a steady force for each contraction. EMG amplitude was greater for both the MVIC and the last submaximal fatiguing contraction in comparison to the first. Observed motor unit action potentials (MUAP) were largest during the MVIC however the MUAP were greater for the last submaximal contraction compared to the first. It is suggested that as muscles get closer to fatigue, excitation and recruitment increase until all motor units achieve maximal stimulation. Further analyses suggest greater excitation for the MVIC compared to the last submaximal isometric contraction of the fatiguing protocol. The greater motor unit action potential amplitudes found during the 90% MVIC may indicate larger motor units were active as well as greater motor unit activation
rates may indicate greater neural drive when performing MVIC compared to the final submaximal isometric contraction while fatigued.

2.3.2 (Babault et al., 2006)

The purpose of this study was to examine the effects of performing maximal concentric and isometric knee extensions on neuromuscular fatigue. Nine recreationally active men (mean age 21.2 ± 1.1) performed maximal concentric or isometric knee extensions between two laboratory visits. The first visit consisted of two series of three concentric maximal voluntary contractions (MVC) at a velocity angle of 60°/s with 2 minutes of rest in between. During the second visit, three 5-second isometric MVC were performed with one minute of rest in between. Both sessions performed fatiguing protocols post MVC. During the concentric session subjects performed 3 sets of 30 maximal concentric leg extensions and had two doublet twitches delivered at rest. During the isometric session subjects completed three isometric contractions until torque reductions were similar to those obtained during the concentric session. For both sessions, a one-minute rest period was allowed between each set and MVC. Torque decreases following the three fatiguing series was similar for both the concentric and isometric protocols. Pre-fatigue, the interpolated twitch demonstrated similar activation levels during MVC for both contraction types. Post-fatigue it was demonstrated that isometric actions yielded a significantly greater reduction in muscle activation than concentric contractions for all three sets. There was no significant difference in doublet twitch contraction time between isometric and concentric actions. The study examined inverse fatiguing profiles based on the contractions performed in which central fatigue was stated to have occurred first during Isometric contractions compared to concentric contractions where peripheral fatigue was achieved first.
2.3.3 (Muddle et al., 2018)

The purpose of this study was to compare motor recruitment and firing rates of the vastus lateralis (VL) when performing high (70% MVIC) vs low-torque (30% MVIC) isometric exercise to failure. 18 resistance trained men (mean age 23.1 ± 3.8) performed a series of fatiguing unilateral trapezoidal contractions on an isokinetic dynamometer in a randomized order of high and low torque. Prior to completion of the fatiguing protocol subjects performed two 5-sec maximal voluntary contractions (MVIC) with about a minute rest between contractions as well as a single maximal isometric trapezoidal contraction at 100% MVIC held for 6-sec with ramp up and de-ramp time of 20% MVIC/s. Torque trajectories increased linearly in both high and low load conditions, increasing at a rate of 10% MVIC/s. Contractions were held for 7 seconds and approximately 6-7 seconds of rest were given between contractions. There was no difference in MVIC strength prior to the high and low load exercise as well as no difference in the largest predicted motor unit action potential amplitude (MUAP). Subjects had a greater time to task failure during the low-load session where MVIC strength was inversely related to time to task failure during both sessions. Firing rates increased throughout both high and low load sessions however mean firing rates (MFR) were higher during the high-load exercise. Significant changes in recruitment threshold were observed during the low-load session but not the high-load. Regardless, both high and low-load exercise performed to fatigue resulted in additional recruitment of larger motor units. These findings align with our current understanding of the mechanisms of muscular fatigue when regulating torque production.
2.3.4 (Harmon et al., 2021)

The purpose of this study was to analyze motor unit action potential amplitude (MUAP) during low torque fatiguing vs high torque non-fatiguing contractions. 11 untrained men (mean age 24 ± 4) performed three 3-sec maximal voluntary contractions (MVC), two sets of trapezoidal contractions at 50 and 80% with 10% MVC/s ramp up and de-ramp, followed by a fatiguing protocol consisting of trapezoidal contractions at 30% MVC until volitional exhaustion on an isokinetic dynamometer. Surface electromyographic (sEMG) signals of the vastus lateralis (VL) were decomposed to quantify the peak-to-peak amplitude of individual MUAPs. Mean MUAP amplitude for 50% (0.0969 mV) and 80% (0.1580 mV) MVC showed significant variation between subjects as well at the beginning (0.0563 mV), middle (0.0782 mV), and end (0.1053 mV) measurements taken throughout the fatiguing protocol. The 80% MVC MUAP amplitude had a higher mean MUAP amplitude as compared to either beginning fatigue or middle fatigue however the total MUAP amplitude values were similar for the low torque fatiguing contractions. There was greater recruitment of higher threshold motor units with greater action potential amplitudes throughout the submaximal fatiguing protocol which increased as torque levels increased. These findings suggest that the motor unit recruitment profile of the VL is similar during maximal contraction as well as towards the end of fatigue, in which motor unit recruitment and firing rates were both similar.

2.3.5 (Adam & De Luca, 2003)

The purpose of the study was to determine changes in motor-unit-recruitment behavior of the vastus lateralis (VL) when performing fatiguing muscle activity. Five healthy men participated in the study (mean age 21.4 ± 0.9) where they performed trajectory traced isometric
contractions at 20% of their maximal voluntary isometric contraction (MVIC), ramping up to 50% MVIC momentarily and then deramping back to 20% MVIC and held for 50-s with 6-s of rest between contractions, repeating until volitional exhaustion. Surface electromyography (EMG) was recorded, using a bipolar surface electrode placed on the VL, vastus medialis (VM), rectus femoris (RF), and biceps femoris (BF). Intramuscular EMG was only recorded on the VL of the dominant leg, using a quadrifilar fine wire electrode inserted into the muscle via a 25-gauge hypodermic needle to decompose the signal of individual motor units. Electrical stimulation was also used on three of the five subjects to measure the contractile properties of the VL, administered using electrical square-wave pulses (0.2 ms in duration) at a supramaximal (110%) intensity. The precision decomposition technique was used to construct motor unit action potential trains showing individual motor unit firing characteristics in which similar shapes across successive contractions confirmed that the same motor units were used throughout. Results indicated a recording of 55 distinct motor units with successive contractions ranging from 6 to 10 (mean 8.20 ± 2.05) and an increase in surface EMG amplitude across all muscles examined excluding the biceps femoris which showed minimal activity during the fatigue protocol. New motor units were recruited during the 50% MVIC ramp up and progressively increased during the 20% 50-s hold in all subjects. The data showed that to generate the same rate of torque increase, motor units were recruited earlier and in larger numbers as fatigue began to onset, suggesting a decrease in motor unit excitation thresholds.

2.3.6 (Stock et al., 2012)

The purpose of this study was to determine the effects of fatigue on the relationship between motor unit firing rates and their recruitment thresholds. Twelve men (mean age 22.1 ±
1.4) and seven women (mean age 21.6 ± 1.2) volunteered to participate in the study for a total of two visits, the first being a familiarization visit, followed by a testing visit where they performed isometric trapezoidal contractions prior to and immediately after completing a fatiguing protocol of maximal voluntary isometric contractions (MVIC) of their dominant leg extensors. During the testing visit maximal isometric torque was determined by performing two 3-s unilateral MVICs separated by 3 minutes of rest at a joint angle of 120° (180° being full knee extension). Isometric trapezoidal muscle actions were performed with a 4-s ramp up from 0% to 50% MVIC, a 12-s hold at 50% MVIC, followed by a 4-s decrease in force from 50% to 0% MVIC. The fatigue protocol consisted of ten 10-s MVICs performed intermittently with 10-s of rest in between each contraction. A 3-s MVIC was performed after the fatiguing protocol to examine force decrements in the quadriceps muscles, followed by a second trapezoidal contraction with MVIC percentages referenced to fresh muscle output (force output when not fatigued). Surface electromyography (sEMG) was recorded from the vastus lateralis (VL) and vastus medialis (VM) during the MVICs and trapezoidal contractions for later signal decomposition to determine motor unit action potential trains (MUAPT). Decomposition was carried out with the PD III algorithm to examine the MUAPT in order to calculate a mean firing rate curve for each detected motor unit. Only motor units that were decomposed with >85.0% accuracy were used for analysis. Results indicated a significant increase in the linear slope coefficients from the fatiguing protocol for the VL but not for the VM. Decreases in the y-intercepts were significant in the VL but not for the VM. The fatiguing protocol resulted in a significant decrease in mean firing rate for all motor units recruited at 30-40% MVIC of fresh muscle for the VL as well as motor units recruited at 0-10%, 10-20%, and 50-60% of fresh muscle MVIC for the VM. The data also showed a significant decrease in unilateral isometric muscle strength with an 18.6%
reduction in MVIC values from pre to post. These findings indicate that fatigue may cause a significant decrease in firings rates in both the VL and the VM but at different MVIC percentages, suggesting adaptive neuromuscular mechanisms present to maintain force output and increase motor unit recruitment.

2.3.7 (Camic et al., 2014)

The purpose of this study was to determine torque, mechanomyographic (MMG), and electromyographic (EMG) response patterns of the leg extensors when performing fatiguing eccentric muscle actions. Eleven moderately trained women (mean age 21.2 ± 1.4) volunteered to participate in the study for two visits, one orientation visit and one testing visit. Visit 1 consisted of an orientation of the testing protocols where subjects practiced ten submaximal eccentric isokinetic muscle actions at 30°·s⁻¹ on an isokinetic dynamometer (Cybex 6000) at an estimated 50% of their maximum force. To determine peak eccentric torque, subjects completed ten maximal eccentric contractions at 30°·s⁻¹. Visit 2 was the fatigue session, where subjects performed thirty consecutive, maximal, eccentric, muscle actions of the leg extensors with passive leg extension movements. Range of motion was set from 0° to 90° of leg flexion at the knee. During visit 2, EMG and MMG were recorded from the vastus lateralis using a bipolar surface electrode arrangement and an accelerometer placed between the EMG electrodes. Results indicated a significant decrease for mean torque and EMG frequency across the 30 eccentric muscle actions. There was an increase in MMG amplitude but no change in EMG amplitude. These findings may suggest that as fatigue began to onset, more motor units were recruited across the contractions however muscle excitation did not change during the eccentric contractions.
The purpose of this study was to examine the torque, electromyographic (EMG) and mechanomyographic (MMG) responses of the leg extensors when performing repeated maximal isometric (ISO) and concentric (CON) muscle actions. Twelve moderately trained women (mean age 21.1 ± 1.4) volunteered to participate in this study for a total of 4 visits, consisting of a familiarization visit, a determination of muscle fiber long axis visit, and two testing visits. During visit 1 subjects practiced isometric and concentric muscle actions of the leg extensors on an isokinetic dynamometer (Cybex 6000). Five, 3-s, submaximal and three, 3-s, maximal ISO contractions were completed along with five submaximal and three maximal CON isokinetic contractions at 30°·s⁻¹. Visit 2 consisted of determining the long axis of the vastus lateralis muscle fibers on the subjects’ dominant leg with surface EMG using a 16-channel linear electrode array. The long axis of the fibers was determined by rotating the probe around the innervation zone until the slopes of the two lines connecting the EMG waveforms were approximately equal. During visits 3 and 4, subjects performed a warm-up of five, 3-s ISO muscle actions or five CON isokinetic muscle actions at 50% of maximal force. The warm-up was followed by subjects performing randomly ordered, intermittent, ISO and CON isokinetic fatigue protocols with 72 hours between testing visits. The ISO protocol consisted of 30 repeated maximal ISO contractions of the leg extensors, sustained for 3-s with 3-s of rest between contractions. The CON protocol involved 30 consecutive maximal CON leg extension muscle actions at 30°·s⁻¹ where the joint angle was 120° between the thigh and leg and the range of motion was set from 90° to 180° of flexion at the knee. Surface electrodes were placed in a bipolar arrangement over the vastus lateralis to record EMG, with an accelerometer to record...
MMG placed between the electrodes, having the reference electrode placed over the iliac crest. Results showed a significant decrease in torque, EMG amplitude, EMG mean power frequency, and MMG mean power frequency for both ISO and CON muscle actions, however there was only a significant decrease in MMG amplitude for the CON muscle actions. These findings may indicate that when performing CON and ISO muscle actions, EMG is a useful indicator of muscular fatigue, however MMG amplitude responses in the VL may only be a useful indicator for fatigue when performing continuous CON muscle actions but not intermittent ISO muscle actions.

2.3.9 (Hautier et al., 2000)

The purpose of this study was to examine the influence of fatigue on EMG/force ratio and co-contraction during repeated sprint cycling. Ten subjects (8 men, 2 women, mean age: 26.4 ± 4.0 years old) trained four times a week for 9 weeks and detrained for 7 weeks, where during training visits they performed two sets of fifteen 5-s maximal sprints with 55 seconds of rest between sprints and 15 minutes between sets on a cycle ergometer at a resistance of ~8% of body mass. During the exercise protocol, each participant performed one set of fifteen repeated 5-s sprints with 25 seconds of rest in between. Cycling performance was recorded during the first and 13th sprint to allow time for data storage before a 2-min constant cycling period completed prior to and immediately after the set of 15 sprints. EMG signals were obtained from the gluteus maximus (GM), rectus femoris (RF), vastus lateralis (VL), gastrocnemius lateralis (GL), and biceps femoris (BF), recorded during the sprints and the 2-min continuous cycling period except for the GM. Subjects completed maximal voluntary isometric contractions (MVIC) of each of the five muscles prior to the sprinting protocol to achieve 100% EMG normalization. Results
showed a decrease in maximal mean power from the first to the 13\textsuperscript{th} sprint as well as maximal pedaling cadence decrease from 125±1.5 rpm to 119±1.3 rpm. EMG results showed a constant EMG signal throughout the maximal sprints with changes in activation level compared to 100% MVIC which followed as: 86\% for the GM, 126.2\% for the VL, 99.9\% for the RF, 75.7\% for the BF, and 80.8\% for the GL. EMG changes during the continuous submaximal 2-min cycling period showed a significant increase in RMS EMG during the last cycling period in the VL (50 rpm pre: 155±88\textmu V, 50 rpm post: 180±101\textmu V) compared to the first, with the activation of other muscles not as affected. Based on the significant changes in activation levels of the VL, these findings may suggest that the VL and RF are prime movers and the first muscles to fatigue during maximal repeated cycling sprints as their activations were maximal and supramaximal compared to their recorded MVICs and the other muscles involved.
The purpose of this study was to compare electromyography (EMG) and physical working capacity at the fatigue threshold (PWC\textsubscript{FT}) recorded in three different bipolar arrangements during incremental cycling. Thirteen men (n = 8) and women (n = 5) (mean age 22.4 ± 3.4) of varying training status (untrained to moderately trained) volunteered to participate in the study, where they performed a graded exercise test (GXT) to volitional exhaustion to determine VO\textsubscript{2peak}, with three bipolar electrode arrangements placed simultaneously on different sections of the vastus lateralis of the dominant leg to compare EMG signal recordings and determine PWC\textsubscript{FT}. The arrangements were: parallel to the muscle pennation angle (MPA), parallel to the long axis of the femur, and over the innervation zone (IZ). Three reference electrodes were placed over the iliac crest. Amplitude and mean power frequency (MPF) were calculated for each pedal thrust using 0.45 epochs and were estimated from the average of the last three. To determine PWC\textsubscript{FT}, during each 2 min power output of the GXT, six 10-s EMG segments were recorded for each electrode arrangement using 10-s epochs. The amplitude values for each of the 10-s epochs were plotted versus time for each power output. PWC\textsubscript{FT} was defined as the average of the highest power output that resulted in a non-significant slope coefficient for the EMG versus time plot, and the lowest power output that resulted in a significant positive slope coefficient. Results showed no significant mean differences between the three electrode arrangements for PWC\textsubscript{FT}, EMG amplitude, or MPF, however there were significant correlations (r = 0.75-0.91) for the PWC\textsubscript{FT} values for all three arrangements. This finding suggests that PWC\textsubscript{FT} may be subject to having its values affected by electrode placement arrangement such as EMG amplitude and MPF.
2.4.2 (deVries et al., 1987)

The purpose of this study was to evaluate physical working capacity at the fatigue threshold (PWC<sub>FT</sub>) during an incremental, submaximal, cycle ergometry test. PWC<sub>FT</sub> was determined as the midpoint between the highest non-significant workload and the lowest significant workload. Blood lactate (OBLA), percentage heart rate range (%HRR) at PWC<sub>FT</sub>, heart rate-workload relation (HR-WL), critical power (CP) and rating of perceived exertion (RPE) were also measured. Surface electromyography (sEMG) was recorded from the lateral aspect of the rectus femoris of the right leg with a unipolar lead system electrode, and a reference electrode over the anterior superior iliac spine. Thirty-two men (mean age 23.4 ± 3.1) of differing training status (highly trained to sedentary) volunteered to participate in the study, where they performed four discontinuous work bouts on a cycle ergometer to determine PWC<sub>FT</sub>. The first work bout was performed at 420 kpm/min which produced an electrical output of 110μV with no slope. Following sufficient rest to reduce heart rate (HR) to within 10 beats/min of resting, the second work bout was completed at 840 kpm/min, resulting in an output of 180μV with no slope. The third work bout, performed at 1260 kpm/min, showed an increasing amount of electrical output to sustain work (slope of 1.16μV/s) indicating neuromuscular fatigue. Therefore, the fourth bout was completed at 1050 kpm/min (the midpoint between 840 and 1260 kpm/min) resulting in a slope of 0.80μV/s which was still significant compared to zero. An interpolation was completed at 945 kpm/min resulting in a slope of 0.61μV/s, allowing PWC<sub>FT</sub> to be estimated as (840+945)/2 (892.5 kpm/min) with an error of ± 6%. Results indicated that power output at PWC<sub>FT</sub> was moderately correlated with OBLA (r= 0.569) and %HRR (r= 0.702). There was only a 9.9% common variance between PWC<sub>FT</sub> and HR-WL. Twelve subjects of the
thirty-two performed a CP test to determine if there was any correlation with PWC$_{FT}$, resulting in a partial correlation of $r=0.670$ with no significant differences between means. There was a significant correlation ($r=0.690$) between RPE and PWC$_{FT}$ where RPE was greater for the fit group compared to the unfit group. PWC$_{FT}$ was determined to be highly reproducible with a test-re-test correlation of $r=0.947$ and a standard error of 145.6 kpm/min. Mean difference between power outputs of OBLA and PWC$_{FT}$ for all 32 subjects was 464 kpm/min however for the highly trained subjects, the difference was 760 kpm/min, while for the sedentary subjects there was a small and non-significant difference of 47.9 kpm/min. These findings suggest that for fit subjects there were central neuromuscular limitations when performing work compared to unfit subjects where local muscular fatigue may be a more limiting factor. PWC$_{FT}$ was moderately correlated with OBLA, suggesting a possible interaction between the neuromuscular and cardiovascular system.

2.4.3 (deVries et al., 1989)

The purpose of this study was to estimate physical working capacity and examine training changes in elderly adults at the fatigue threshold (PWC$_{FT}$). 27 elderly adults (11 men, 16 women) participated in this study (3 groups; CON: mean age 69.1±5.2, LOW: mean age 67.9±5.3, HIGH: 64.9±6.2) where they exercised on a cycle ergometer for 30 minutes, pedaling at a cadence of 50 RPM, at an intensity reflecting their group (HIGH: 85% PWC$_{FT}$, LOW: 70% PWC$_{FT}$, CON: no exercise). The two training groups completed three sessions per week for 10 weeks and had their PWC$_{FT}$ retested. Over the first 5-weeks, the 30 min sessions were separated as 3 sets of 10-min bouts with 2 minutes of rest in between, after which in the last 5 weeks the protocol became 2 sets of 15-min bouts also with 2 minutes of rest between sets. EMG was recorded in a unipolar
lead setup from the right rectus femoris. During the exercise, power output was increased between 10 to 20 W for each stage of the discontinuous protocol where once the first significant slope coefficient for the regression line was determined, two interpolations were made between both power output differences. Rating of perceived exertion (RPE) was asked at each work bout using the Borg 6-20 scale. Heart rate was measured during the last 15 seconds of each stage where heart rate above and below the PWC_{FT} were averaged to determine a ratio between heart rate (BPM) and PWC_{FT} (W). Results showed an average RPE of 14.2 where only three subjects reported and RPE above 17 during testing, most likely due to them being physically fit and requiring power outputs between 150 and 200 W to elicit a significant slope change. 16 subjects volunteered for retesting one week after the post-test PWC_{FT} which measured 108.8±53.3 W and the repeat test was 109.1±49.4 W which was not significantly different. PWC_{FT} of the control group decreased from 78.8 W to 78.5, high intensity group increased from 83.6 W to 115.7 W (38.4% improvement), and the low intensity group improved from 81.0 W to 105.0 W (29.8% improvement). Control groups HR/PO ratio went up from 1.88 to 1.94 bpm/W, low intensity group improved from 1.80 to 1.47 bpm/W and the high intensity group improved from a mean of 1.65 to 1.11 bpm/W. These findings suggest that a discontinuous incremental exercise bout is reliable for estimating PWC_{FT} in the elderly as well as training may improve PWC_{FT} whether low or high intensity, potentially due to improvements in neuromuscular function.

2.4.4 (Bremer et al., 2021)

The purpose of this study was to determine if repeated incremental work-bouts separated by 1 hour, would increase the electromyographic fatigue threshold (EMG_{FT}). Nine recreationally active men (mean age: 23.8 ± 0.6) participated in the study where they performed single leg knee
extensor ergometry on a custom-made device, consisting of the subjects kicking at ~70 RPM preceded by an initial 2-minute warm up at 4 W followed by an increase of 4 W every minute after. Hear rate and RPE was recorded for each stage using a polar heart rate monitor and a modified Borg 0-10 scale. Electromyography (EMG) was recorded from the rectus femoris using a bipolar surface electrode arrangement, digitized at 1,000 Hz, and processed through a custom written LabVIEW program using a fourth order Butterworth filter at 10-500 Hz, with amplitude reported in microvolts root-mean-square (µV RMS). Subjects completed the same incremental protocol an hour after volitional exhaustion was determined. Results showed no significant differences across physiological outcomes (maximal power output, end-exercise heart rate) however there was a significant difference in EMG_{FT} between trials [EMG_{FT} (W): 27±1 vs. 34±2, EMGFT (% maximal power output): 51.2±2.6 vs. 60.0±3.7]. The slope coefficient in trial 2 was significantly different compared to trial 1 (trial 1: y=3.1944x + 22.97, trial 2: y=2.509x + 22.68). These findings suggest that performing 2 consecutive incremental exercise bouts separated by an hour may influence EMG_{FT} where the first bout causes an increase in the 2^{nd} bout’s EMG_{FT}.

2.4.5 (Briscoe et al., 2014)

The purpose of this study was to determine the electromyographic fatigue threshold (EMG_{FT}) from a single incremental cycle test and then validate the recorded EMG_{FT} across a constant workload cycle test. Eleven healthy college aged adults (5 men, 6 women, mean age: 23.6±0.7) participated in this study where they performed an incremental test to volitional exhaustion on an electronically braked cycle ergometer, pedaling at a cadence of 70 RPM, beginning at 50 W for a 2-min warm up then increasing by 25 W every 2 minutes. To determine
EMGFT, EMG amplitude was recorded every 20-s from the vastus lateralis (VL) and plotted vs time, where a linear regression was used to determine if there was a significant increase in amplitude. EMGFT was defined as the highest power output that resulted in a non-significant slope coefficient and the lowest power output that resulted in a significant slope coefficient. Following the estimation of EMGFT, subjects performed the incremental cycle ergometer test that corresponded to 70, 100, and 130% of their EMGFT. The intensities of the exercise were randomized, and subject were asked to maintain a pedaling cadence of 70 RPM for up to 1 hour. EMG was recorded using a bipolar surface electrode configuration, positioned over the longitudinal axis of the vastus lateralis. Results showed no statistically significant differences between the slopes for 70 and 100% EMGFT but a significant increase in the slope for 130% EMGFT with a difference in maximal power output between men and women (290±24 W vs. 192±10 W). The results suggest that estimating EMGFT from a single cycle ergometry test is valid since there were no differences between the 70 and 100% slopes measured during the incremental test.

2.4.6 (Camic et al., 2009)

The purpose of this investigation was a two-part study with the goal of determining if the model used for estimating physical working capacity at the fatigue threshold (PWCFT) from EMG amplitude can be applied to derive a new fatigue threshold called the mean power frequency (MPFT) and to compare power outputs associated with the PWCFT, MPFT, ventilatory threshold (VT) and respiratory compensation point (RCP). Sixteen healthy men (mean age: 23.4±3.2) participated in this study where they had their VO2peak, VT, RCP, PWCFT and MPFT measured by performing an incremental test to exhaustion on an electronically
braked cycle ergometer. During the incremental test, resistance began at 80 W and increased by 30 W every 2 minutes until voluntary exhaustion. EMG was measured from the vastus lateralis (VL) using a bipolar surface electrode configuration. $\text{PWC}_{\text{FT}}$ and $\text{MPF}_{\text{FT}}$ were determined by measuring six, 10-s samples of EMG amplitude of the VL during each 2-min stage of the incremental cycle test. $\text{PWC}_{\text{FT}}$ was determined by averaging the highest power output that resulted in a non-significant slope coefficient with the lowest power output that resulted in a significant positive slope coefficient. The $\text{MPF}_{\text{FT}}$ was determined in the same way, instead examining the EMG MPF versus time relationship. Results showed significant mean differences in power outputs between $\text{PWC}_{\text{FT}}$ (168±36 and $\text{MPF}_{\text{FT}}$ (208±37), $\text{PWC}_{\text{FT}}$ and RCP (205±84 W), $\text{MPF}_{\text{FT}}$ and VT (152±33 W) and VT and RCP. There were also significant mean differences between the slope coefficients for the EMG MPF versus time relationships where MPF decreased linearly with time. These findings suggest that as power outputs increase there is a proportional decrease in EMG MPF. Furthermore, results indicate that the onset of fatigue induced changes in the EMG signal occur at a lower output for time compared to frequency which is shown by the power output values of $\text{MPF}_{\text{FT}}$ and $\text{EMG}_{\text{FT}}$ (208±37 vs. 168±36).

2.4.7 (deVries et al., 1990)

The purpose of this study was to determine potential improvements in estimating physical working capacity at the fatigue threshold ($\text{PWC}_{\text{FT}}$) by examining four different methods of obtaining $\text{PWC}_{\text{FT}}$. 20 subjects (16 men, 4 women, mean age: 29.1±12.3 years) were involved in one or more of the four experiments presented in the study. Surface electrodes were used for all experiments however for experiments 1 and 4 a unipolar configuration was used and for experiments 2 and 3 a bipolar configuration was used over the vastus lateralis and/or the gastroc-
soleus muscles. Across all four experiments, testing order was randomized, and the EMG curves were recorded over 2-min periods with alternating 10-s display and integration periods. Power output increased by 12-25 W during each stage of the bicycle ergometer experiments and by one to two percent increases in grade on the treadmill. Results of experiment 1 showed mean $\text{PWC}_{\text{FT}}$ as $222\pm83$ W for the discontinuous protocol compared to the $210\pm73$ W for the continuous test. Experiment 2 consisted of $\text{PWC}_{\text{FT}}$ estimation on a treadmill versus a cycle ergometer using a discontinuous protocol where heart rate was assessed since there is no direct measurement of work or power for exercise on a treadmill to compare $\text{PWC}_{\text{FT}}$ obtained from a cycle ergometer. No significant difference between heart rate means for the gastroc-soleus test (164±10 bpm) and the quadriceps test (167±12 bpm). There were no significant differences between the heart rate values for $\text{PWC}_{\text{FT}}$ on the bicycle ergometer versus the treadmill. Experiment 3 attempted to estimate $\text{PWC}_{\text{FT}}$ using both unipolar and bipolar leads resulting in the mean voltages for different power outputs on the cycle ergometer being significantly different (unipolar = $152\pm45\mu$V, bipolar= $80\pm33\mu$V), however the mean $\text{PWC}_{\text{FT}}$ values were not significantly different (unipolar = $188\pm79$ watts; bipolar=210±60 watts). Experiment 4 was a repeated estimation of $\text{PWC}_{\text{FT}}$ 24 hours after an initial estimation using a discontinuous cycle ergometer test. There were no residual effects of fatigue for the discontinuous $\text{PWC}_{\text{FT}}$ test performed 24 hours later. Mean $\text{PWC}_{\text{FT}}$ values were not significantly different (198±60 versus 191±63). Overall, these results indicate that a continuous incremental test is a valid way to determine $\text{PWC}_{\text{FT}}$, as well as $\text{PWC}_{\text{FT}}$ is not affected by a unipolar or bipolar arrangement, or a repeated test performed 24 hours later.
The purpose of this study was to examine a relationship between critical power and the onset of fatigue estimated from EMG data. Eleven recreationally trained adults (5 men, 6 women, age range: 19-32) participated in this study where they performed a critical power (CP) test with a drop pedal from 70-60 RPM on an electrically braked ergometer. The ergometer was calibrated to increase in torque by 16.7% as RPM drops. Power stages for men were 400, 350, 300, and 275 W and 350, 300, 250, and 225 W for women. All testing was accomplished in one laboratory visit with rest periods between work bouts being a minimum of 30-min or longer to return to within 5 beats of resting heart rate. Surface electrodes in a unipolar arrangement were place on the rectus femoris to record EMG. The EMG signal was counted using an alternating signal which made it possible to measure a direct integral of electrical activity of the muscle over 10-s periods. These 10-s periods were used to estimate EMG at the fatigue threshold. Results from a typical subject showed a rise in EMG rate at 400 W (2.48 µV/s), 350 W (2.28 µV/s), 300 W (1.53 µV/s) and at 250 W (0.74 µV/s). This subject's EMGFT in this case would be 185±25 W determined from the from plotting the power loads as a function of the fatigue slope coefficient. Plotting the relationship between power output and rate of EMG rise or each subject showed an EMGFT of 124-284 W with the mean being 190.5±14.0 W. Critical power across the eleven subjects were 115-262 W with a mean of 169.5±12.8 W. Power output achieved during anaerobic threshold (AT) was a range 113-288 W with a mean of 187.1±15.9 W. Examining the difference in values obtain from CP, AT, and EMGFT, the relation between AT and EMGFT is stronger (R= 0.903) than that between EMGFT and CP (R= 0.877). These findings suggest that AT may have a greater effect on EMGFT estimation compared to CP.
2.4.9 (Duff et al., 2016)

The purpose of this study was to determine if pedaling cadence during an incremental cycle ergometer test affects the estimation of electromyography at the fatigue threshold. Eight healthy recreationally trained men (mean age: 25.5±0.6) participated in this study where they each performed an incremental cycling ergometer test to volitional exhaustion. On separate occasions they performed a randomized order and combination of cycling cadences: 1) 25 W at 70 RPM, 2) 13 W at 70 RPM, and 3) 25 W at 100 RPM. Exercise began at 50 W and increased by the randomized rate every 2-min. EMG was recorded from the vastus lateralis of the non-dominant leg using a bipolar configuration. To determine EMG<sub>FT</sub>, EMG amplitude (root-mean-square) was calculated from 10-s epochs in 20 second intervals for each stage and then plotted versus time. A linear regression was performed to determine a significant increase in EMG amplitude across time for each power output. The EMG<sub>FT</sub> was defined as the average of the highest power output that resulted in a nonsignificant slope coefficient and the lowest power output that resulted in a significant positive slope coefficient. Results showed that the mean maximal power output achieved for the 13 W at 70 RPM bout was significantly lower compared to the other two conditions. No significant differences however were present for the EMG<sub>FT</sub> values across the three pedaling cadences. The percentage of maximal power output for the EMG<sub>FT</sub> of the 13 W/70 RPM condition was significantly higher than the percentage of maximal power of the 2 other conditions. EMG<sub>FT</sub>: 25 W/70 RPM = 166±9, 13 W/70 RPM = 158±6, 25 W/100 RPM= 156±10. These findings suggest that different pedaling cadences and power outputs had no effect on estimating EMG<sub>FT</sub> with values for all three showing no significant differences.
The purpose of this investigation was a two-part study to determine the effect of increasing the duration of the work-bouts during an incremental cycle test on PWC\textsubscript{FT} and two examine the time to exhaustion during continuous work-bouts at the PWC\textsubscript{FT}. Twelve healthy adult men (mean age: 22.4±3.0) participated in the study where they performed three PWC\textsubscript{FT} tests, randomly utilizing different work-bouts at 2, 3, and 4 minutes and 9 of the 12 returned to perform continuous cycle work-bouts. EMG was recorded from the vastus lateralis of the right leg, using a bipolar surface electrode arrangement. PWC\textsubscript{FT} was determined using a continuous protocol with subjects pedaling at 70 RPM at 60 W with the power output increasing by 30 W every 2, 3, or 4 minutes until a significant slope coefficient for voltage versus time was observed. After the first significant slope coefficient was observed. The power output at the fatigue threshold PWC\textsubscript{FT} was defined as the mean of the lowest significant and highest nonsignificant power outputs. Subjects that returned for the continuous cycle bouts were told to maintain the power output assigned for as long as possible until 60 minutes was reached. Results indicated a significant difference between the mean values for the 2, 3, and 4-minute bouts. Mean PWC\textsubscript{FT} for the 4 min group was 168.8±45.1 W which was 19.1\% less than that of the 2-minute group (208.9±59.0 W). No significant differences were observed between group 2 vs 3, or 3 vs 4. There were no significant differences among the mean slope coefficient values for the EMG voltage-time relationship at 150 W for the 2-minute group (mean = 0.042±0.074 µV/s), 3-minute group (0.021±0.044 µV/s) and the 4-minute group (0.027±0.022 µV/s). For the continuous cycle tests only two subjects were able to complete 60 min during the 4-min stages with no subjects completing 60 min during the 2-min stages. These results suggest that there is no evidence that
extending the duration of the work-bout at each power output results in greater neuromuscular
fatigue and/or greater slope coefficient.

2.4.11 (Galen & Malek, 2014)

The purpose of this study was to determine if a single EMG testing point is valid to monitor
neuromuscular fatigue during continuous exercise. Seven healthy men (mean age: 25.0±0.7)
visited the lab on 5 separate occasions and performed knee-extensor tests. One visit consisted of
an incremental test to determine maximal power output to estimate EMG_{FT} and the 4 other visits
consisted of various workload tests to estimate EMG_{FT} across multiple visits. A bipolar surface
electrode arrangement was used to measure EMG of the rectus femoris. Single visit EMG_{FT}
consisted of subjects kicking on a custom-made chair with a special ankle boot placed on the
dominant leg at 5 W for 2 minutes. Power output increased by 5 W every 2 minutes throughout
the test until volitional exhaustion. Subjects were asked to maintain a cadence of 70 RPM. EMG
amplitude was calculated from 10-s epochs in 20-s intervals for each 2-minute stage and plotted
vs time. Linear regression was performed to determine if EMG amplitude increased for each
power output across time. The EMG_{FT} for the single-visit test was defined as the average of the
highest power output that resulted in a nonsignificant slope coefficient and the lowest power
output that resulted in a significant positive slope coefficient. Determining multiple visit EMG_{FT}
consisted of an incremental knee-extensor test consisting of 4 randomly ordered protocols
ranging from 80-95% of the participant’s maximal incremental test result. Subjects began at 30%
of maximal power for 5-minutes and then increased to a constant workload intensity at a cadence
of 70 RPM. EMG amplitude was recorded every minute until termination of the test where it was
calculated as the average of the completed kick thrusts from 10-s epochs during the last 10-s of
each minute of the constant power work-bout. For each participant, the slope coefficient was calculated for each constant power output, whereafter, the power outputs were plotted as a function of the slope coefficient for the EMG amplitude vs. time relationships. EMG\textsubscript{FT} was defined as the y-intercept of the power output vs. slope coefficient plot. Results of a paired-sample t-test showed a significant mean difference between the 2 protocols (40.5±4.7 W vs 31.8±3.4 W). These findings suggest that estimating EMG\textsubscript{FT} using a multiple visit test compared to a single visit test yields significantly difference results which may determine which test would be more advantageous to carry out specifically the single visit since it takes less time to complete.

2.4.12 (Mahmutović et al., 2016)

The purpose of this study was to determine the reliability of estimating electromyographic fatigue threshold (EMG\textsubscript{FT}) for cycle ergometry between sessions. Ten healthy college aged men (mean age: 27.3±1.4) participated in this study where they performed an incremental test to voluntary exhaustion on a cycle ergometer with the EMG recorded from the vastus lateralis (VL), the vastus medialis (VM), and the rectus femoris (RF). All three EMG signals were recorded using 3 separate bipolar surface electrode configurations place in accordance with SENIAM guidelines. On two separate occasions, each participant performed an incremental test beginning with a warm-up of 50 W for 2 minutes followed by an increasing rate of 20 W every 2 minutes. To determine EMG\textsubscript{FT}, the EMG amplitude (µV RMS) was calculated from 10-second epochs in 20-second intervals for each 2-minute stage and then plotted vs. time. Linear regression was then performed to determine whether there was a significant increase in EMG amplitude across time for each power output. The EMG\textsubscript{FT} was defined as the average of the
highest power output that resulted in a non-significant slope coefficient and the lowest power output that resulted in a significantly positive slope coefficient. There were no significant mean differences between the 2 trials and the EMGFT values for the VL, VM, and RF, were identical for each trial. The reliability of the EMGFT for the three examined muscles (ICC2,1 = 0.85; 95% confidence interval 0.49-0.096) was considered “excellent” for the 10-participant sample size. Results from a linear regression indicated that the mean score did not contribute to the prediction of the difference score suggesting no proportional bias with the standard error of measure being 14.6 W. Because there were no significant mean differences between daily values of EMGFT it may suggest that EMGFT is a stable assessment of neuromuscular fatigue and can be measured daily if needed.
III: METHODS

Experimental Approach

College aged men performed a graded exercise test on a cycle ergometer (Visit1) and then randomly completed on separate days (≥ 48 hours), 3 separate SIT protocols with CBFR, IBFR, and No-BFR (Visits 2-4). Each SIT protocol consisted of 2, 30s sprints with 2 minutes of rest between sprints at a resistance of 7.5% of body mass. Prior to (pretest) and after (posttest) each SIT protocol, maximal strength, neuromuscular function, and muscle thickness were measured. During each sprint, peak and mean RPM as well as % of PWC<sub>FT</sub> were determined.

Subjects

Fifteen actively trained men (mean age ± SD = 22.5 ± 2.4 yrs; height = 175.6 ± 6.2 cm; body mass = 78.8± 13.0 kg) participated in this study and performed SIT with continuous BFR, intermittent BFR, and without BFR. sEMG Data from 11 of the 15 subjects was used for analysis as there were 4 incomplete datasets (Subjects: 7,9,10, and 15) due to hardware malfunction. Subjects had no known cardiovascular, pulmonary, metabolic, muscular, and or coronary heart disease, as well as no daily use of prescription medications or dietary supplements. Actively trained was defined as a tier 2 on the participant classification framework, described as regularly training ~3 times per week, identify with a specific sport, and train with a purpose to compete (McKay et al., 2021). Subjects visited the laboratory on 4 separate occasions: one familiarization and baseline graded exercise test (GXT) and three randomly allocated testing visits. All subjects completed a health history questionnaire and signed a written informed consent prior to all testing. Subjects were told to refrain from exhaustive lower body exercise at least 48 hours prior to testing and asked at the beginning of their visit if they felt physically able to perform maximal
intensity exercise, if unable, their visit was rescheduled. This study was approved by the University of Central Florida Institutional Review Board in compliance with their regulations.

Procedures

**Familiarization and Baseline, Visit 1**

The first laboratory visit consisted of a written informed consent and health history questionnaire followed by a familiarization of the testing protocols. During the familiarization, subjects’ BFR arterial occlusion pressure was determined using Doppler ultrasound and a rapid-cuff-inflator (Hokanson E20 Rapid Cuff Inflator; Hokanson Inc., Bellevue, WA, USA). Subjects then performed maximal strength testing on an isokinetic dynamometer (Biodex system 3, Shirley, NY, USA) and practiced performing maximal sprints on a cycle ergometer (894 E, Monark, Vansbro, Sweden). Subjects then performed a GXT to determine both PWC$_{FT}$ and aerobic capacity.

**Maximal Isometric Strength Familiarization**

Following a 5-minute warm up on a cycle ergometer (Corval 400, Groningen, The Netherlands), subjects completed three maximal voluntary isometric contraction (MVIC) leg extension muscle actions on an isokinetic dynamometer (Biodex system 3, Shirley, NY, USA). For each MVIC attempt, the leg was positioned at a knee joint angle of 90°, where 180° corresponded to full extension at the knee and a 90° hip angle. Each MVIC muscle action was initiated as rapidly and forcibly as possible and maintained for a duration of three seconds. A rest period of 90 seconds was provided between attempts and the highest MVIC torque produced in Nm of the three attempts was used for further analyses.
Maximal Sprinting Familiarization

Following the assessment of MVIC torque, subjects were seated on a mechanically braked ergometer (894 E, Monark, Vansbro, Sweden) and practiced performing maximal sprints. Each practice sprint was performed for a duration of four seconds at a resistance of 7.5% of total body mass (Kojima et al., 2021; Taylor et al., 2016). Subjects performed 2-5 sprints until they were comfortable with the SIT protocol.

Graded Exercise Test

Subjects were equipped with a heart rate monitor (Polar H10, Polar Electro Oy, Kempele, Finland) and fitted to a silicone facemask (7450 V2, Hans Rudolph, Inc., Shawnee, KS, USA) with a two-way non-rebreathing valve prior to being seated and fitted on a cycle ergometer (Corval 400, Groningen, The Netherlands). Maximal aerobic capacity was examined using a breath-by-breath gas analysis (10-second rolling average) recorded on a metabolic cart (TrueMax 2400, ParvoMedics, Sandy UT, USA) that was used to determine the maximum volume of oxygen consumption in ml/kg/min (VO$_{2\text{max}}$). sEMG sensors were placed on the subjects’ dominant leg to determine the sEMG-based PWC$_{FT}$. The GXT began at 90 watts with a pedal cadence of 70 ± 5 rpm and increased by 30 watts every three minutes until volitional exhaustion, that was determined when subjects could no longer sustain the pedal cadence for a 5-second period despite strong verbal encouragement.
Sprint Interval Training and Assessments, Visits 2-4

Muscle Thickness

Upon entering the laboratory and a brief rest period, subjects lied supine on a padded table to measure the thickness of the vastus lateralis (VL) muscle of their dominant leg. Muscle thickness (MT) was measured using a portable brightness mode Doppler ultrasound imaging device (Logiq e, General Electric, Chicago IL, USA) and a multifrequency linear-array probe. All ultrasound assessments were determined at 50% of the distance of the subjects’ greater trochanter to the lateral aspect of their patella with their leg internally rotated (Miyatani et al., 2004). The ultrasound images were captured using a gain of 50 dB and a frequency of 12 Hz with a default depth of 5 cm. These settings were kept consistent across subjects, only adjusting depth on a subject-by-subject basis. To enhance acoustic coupling and reduce near-field artifacts, water-soluble transmission gel was applied to the skin for each of the ultrasound assessments. Assessments of MT was also determined following post SIT strength testing for each visit.

Maximal Strength Testing

Following a 5-minute warm up on a cycle ergometer (Corval 400 Groningen, The Netherlands), subjects performed maximal concentric leg extension muscle actions followed by MVIC muscle actions on an isokinetic dynamometer (Biodex system 3, Shirley, NY, USA) to determine concentric peak torque (CPT) and MVIC torque, respectively. Subjects completed one set of three maximal concentric leg extension and flexion muscle actions at a velocity of 90°/s, performed through a 90° range of motion (90°-180° of knee extension, where 180° corresponded to full extension at the knee). Following a 60-s rest period, subjects then completed three MVIC muscle actions performed at 90° sustained for a period of 3-s, each separated by 90-s of rest.
Prior to post ultrasound assessments, maximal strength testing was performed immediately following each SIT protocol but rest between attempts were limited to 3-5 seconds to minimize recovery.

*Sprint Interval Protocol*

The SIT protocol consisted of two, 30-second sprints performed on a mechanically braked cycle ergometer (894 E, Monark, Vansbro, Sweden) with two minutes of rest between the first and second sprint. Specifically, two sprints were chosen as during the pilot for the study, subjects were physically incapable of performing more than two sprints with both continuous and intermittent BFR due to accumulated fatigue and discomfort. Each sprint utilized a resistance of 7.5% (Kojima et al., 2021; Taylor et al., 2016) of the subjects’ body mass and was initiated from a rolling start that progressively increased in pedal cadence in the three seconds preceding each sprint. The participant remained seated on the ergometer during each sprint and the passive rest period. Specifically, during each rest period, subjects were instructed to remain seated with their dominant foot extended and to avoid pedaling. Maximum revolutions per minute (RPM) were recorded for each sprint for all conditions. Mean RPM was derived from six, 5-s averages recorded during each 30-s sprint for each condition as well.

>Data Analysis*

*Blood Flow Restriction, Visits 2-4*

Subjects completed a SIT protocol with three randomly ordered BFR conditions: continuous (CBFR), intermittent (IBFR), and No-BFR. During the continuous intervention, bilateral BFR was applied for the duration of the 2, 30-second sprints and during the 2-minute rest period allotted between sprints. Intermittent bilateral BFR was applied during the 2-minute
rest period between sprints but not applied during the sprints. For the No-BFR condition, bilateral BFR was not applied during the sprints or rest period. Both the intermittent and continuous BFR conditions were performed at 60% of arterial occlusion pressure that was determined during each visit (Patterson et al., 2019). Specifically, Doppler ultrasound was used to examine muscle blood flow from the posterior tibial artery and to determine when total arterial occlusion was reached. Total arterial occlusion pressure was achieved by rapidly inflating (increments of 1-30 mmHg) and deflating (completely) the cuff until total arterial occlusion was identified. Each inflation and deflation was approximately five seconds in duration to avoid accentuated vasodilation from an increase in arterial nitric oxide secretion that is enhanced under ischemic/hypoxic conditions (Pearson & Hussain, 2015).

Electromyography, Visits 1-4

sEMG was assessed from the dominant leg using a Delsys Avanti Trigno sensor (Delsys Inc., Natick MA, USA). Before electrode placement, the area was shaved and cleaned with an alcohol swab. The sensor was placed on the VL muscle in accordance with SENIAM recommendations (Hermens et al., 2000). Specifically, the sensor was placed at 66% of the distance from the anterior superior iliac spine to the lateral aspect of the patella and oriented towards the pennation angle of the muscle (20°) with the leg internally rotated (Camic et al., 2011). The analog sEMG signals were digitized at 2,148 Hz with EMGworks-acquisition software (Delsys Inc., Natick MA, USA) and stored on a personal computer for subsequent offline analysis. The signals were amplified x1,000,000 and digitally bandpass filtered (zero-phase shift, fourth-order Butterworth) at 10-500 Hz (Basmajian, 1978). sEMG amplitude (RMS) and mean power frequency (MPF) were processed offline using a custom-written LabVIEW,
2021 (National Instruments, Austin TX, USA) program. RMS was calculated and normalized to the MVIC and CPT attempts that produced the highest torque. MPF was derived using a Hamming window on the power density spectrum and using discrete Fourier transform algorithm.

*Physical Working Capacity at the Fatigue Threshold (PWC_{FT})*

PWC_{FT} was determined from the graded exercise test performed during visit 1. During each 3-min stage of the GXT, intermittent 10-s epochs were selected for a total of nine 10-s samples collected during each stage (deVries et al., 1990). To determine PWC_{FT}, sEMG amplitude (µV) was determined for each 10-s epoch. The nine 10-s epochs for each stage were then plotted across time and a slope coefficient was determined via linear regression (W/s). PWC_{FT} was identified as the combined average of the power output from the last stage that resulted in a non-significant increase in the slope coefficient of the linear regression analysis with the power output from the first stage that resulted in a significant increase in the slope coefficient of a linear regression analysis (deVries et al., 1987).

*Statistical Analysis*

To examine the acute effects of each SIT protocol, separate 3-way (Condition [Continuous BFR, Intermittent BFR, No-BFR]) x 2 (Time [Pretest, Posttest]) repeated measures analyses of variance (ANOVA) were used to analyze CPT, MVIC torque, MT, as well as sEMG RMS and MPF responses during the CPT and MVIC muscle actions. During each sprint, %PWC_{FT}, peak RPM, and mean RPM were examined using separate 2-way (Sprint [Sprint 1, Sprint 2]) x 3 (Condition [Continuous BFR, Intermittent BFR, No-BFR]) repeated measures ANOVAs. Greenhouse–Geisser corrections were used if sphericity was not met according to
Mauchly’s test of sphericity. Significant interactions were decomposed, if appropriate, using Bonferonni-corrected repeated measures ANOVAs. Partial eta squared effect sizes ($\eta^2_p$) were calculated for each ANOVA, and classified as small ($\eta^2_p = 0.01$), medium ($\eta^2_p = 0.06$), and large ($\eta^2_p = 0.14$) (Richardson, 2011). All statistical analyses were performed using IBM SPSS v. 27 (Armonk, NY) and an alpha of $p \leq 0.05$ was considered statistically significant for all comparisons.
IV: RESULTS

Muscle Thickness and Maximal Strength

There were no significant Condition × Time interactions for MT ($p = 0.792$, $\eta^2_p = 0.016$), CPT ($p = 0.203$, $\eta^2_p = 0.111$), or MVIC torque ($p = 0.519$, $\eta^2_p = 0.039$). There were, however, main effects for Time, but not Condition for MT ($p < 0.001$, $\eta^2_p = 0.591$), CPT ($p < 0.001$, $\eta^2_p = 0.761$) and MVIC torque ($p < 0.001$, $\eta^2_p = 0.793$). Specifically, collapsed across Condition, MT increased from pretest ($1.77 \pm 0.31$ cm) to posttest ($1.96 \pm 0.30$ cm), while CPT and MVIC torque decreased from pretest ($220.3 \pm 47.6$ Nm and $355.1 \pm 72.5$ Nm, respectively) to posttest ($147.9 \pm 27.7$ Nm and $252.2 \pm 45.5$ Nm, respectively).

sEMG Amplitude and sEMG Mean Power Frequency

There were no significant interactions for sEMG amplitude (RMS) or sEMG mean power frequency (MPF) during the CPT ($p = 0.894-0.976$, $\eta^2_p = 0.002-0.011$) or MVIC ($p = 0.155-0.344$, $\eta^2_p = 0.101-0.170$) muscle actions. There were, however, main effects for Time, but not Condition for MPF during the CPT ($p < 0.001$, $\eta^2_p = 0.778$) and MVIC ($p = 0.005$, $\eta^2_p = 0.564$) muscle actions. Specifically, collapsed across Condition, CPT and MVIC MPF decreased (-12.8±10.5 and -8.7±10.2 %, respectively) from pretest to posttest.

%PWC$_{FT}$

There was no significant interaction ($p = 0.258$, $\eta^2_p = 0.092$) for %PWC$_{FT}$, but there were significant main effects for Sprint ($p < 0.001$, $\eta^2_p = 0.784$) and Condition ($p < 0.001$, $\eta^2_p = 0.409$). Specifically, collapsed across Condition, %PWC$_{FT}$ was greater during Sprint 1 (461.2±126.9%) than Sprint 2 (330.7±72.7%). Furthermore, collapsed across Sprint, %PWC$_{FT}$ was greater during
No-BFR (414.2±121.9%) than CBFR (375.9±121.9%) with no difference between IBFR (397.7±123.2%) and No-BFR.

RPM

There were significant interactions for peak ($p=0.005$, $\eta_p^2=0.315$) and mean ($p=0.030$, $\eta_p^2=0.221$) RPM. Follow-up analyses of simple main effects indicated that peak RPM decreased from Sprint 1 to Sprint 2 for No-BFR (157.7±12.5 to 147.5±12.8 RPM), CBFR (153.9±14.5 to 129.2±13.5 RPM) and IBFR (158.0±14.4 to 134.1±15.7 RPM). Similarly, Mean RPM also decreased from Sprint 1 to Sprint 2 for No-BFR (110.4±7.1 to 85.5±9.9 RPM), CBFR (105.2±11.5 to 73.6±14.0 RPM) and IBFR (110.3±8.6 to 81.2±12.5 RPM). Additionally, during Sprint 1, mean RPM was greater for No-BFR than CBFR, while during Sprint 2, both No-BFR and IBFR were greater than CBFR (i.e., Sprint 1, No-BFR > CBFR; Sprint 2, No-BFR and IBFR > CBFR). Furthermore, there were no differences between conditions for peak RPM during Sprint 1, while during Sprint 2 No-BFR was greater than IBFR and CBFR (i.e., No-BFR > IBFR and CBFR).
V: DISCUSSION

The application of intermittent and continuous BFR elicits similar acute physiological responses as a non-BFR condition when applied during SIT. Specifically, there were similar fatigue-induced reductions in maximal strength (i.e., CPT and MVIC) and an increase in muscle swelling (i.e., muscle thickness) among all three conditions. The reductions in maximal strength were unrelated to changes in muscle excitation (sEMG amplitude), but may have been due, in part, to excitation-contraction coupling failure as evidenced by the reduction in sEMG frequency. Despite a lack of differences among these physiological responses, %PWC\textsubscript{FT} as well as peak and mean RPM were higher during No-BFR relative to CBFR. Collectively, these findings suggested that SIT with or without CBFR and IBFR elicited comparable physiological responses, although there were differences in some of the performance measures (i.e., %PWC\textsubscript{FT} and RPM) among conditions.

Performance Measures

In the present study, SIT elicited comparable reductions in CPT (-31.0±14.2%) and MVIC torque (-27.6±12.6%) and similar increases in MT (11.4±11.0%) from pretest to posttest across all 3 conditions. Furthermore, there were reductions in peak and mean RPM from Sprint 1 to Sprint 2 for all conditions that, in general, decreased by a greater extent for CBFR than No-BFR (Figure 9.) The findings of the present study were partially consistent with previous investigations (Kojima et al., 2021; Peyrard et al., 2019) that have examined the acute effects of SIT with and without BFR. For example, like the present investigation, MVIC torque decreased similarly for CBFR (-10.5±12.1%) and No-BFR (-16.5±9%) from pretest to posttest following 10-s sprints of arm cycling to exhaustion with 20 seconds of active recovery between sprints.
(Peyrard et al., 2019). Contrarily, following three separate sessions of 10-s maximal cycling sprints to exhaustion (cadence < 70RPM), MVIC torque was lower for CBFR (138±82 Nm) than No-BFR (255±114 Nm) relative to pretest values (263±124 Nm and 279±140 Nm, respectively) (Willis et al., 2018). Additionally, Kojima et al. reported decreases (approximately 16-23%) in mean power output relative to body mass after three to five 10-s sprints (40-s passive rest), although there were no differences between BFR and No-BFR conditions. The inconsistency among the performance measures between the present study and previous investigations (Kojima et al., 2021; Peyrard et al., 2019; Willis et al., 2018) are likely due, in part, to the heterogeneity among protocols (number of sprints, duty cycle), modality, and BFR pressure (45%, 60%, 140 mmHg).

**Neuromuscular Responses**

In the present study, SIT with and without BFR did not affect sEMG RMS, but elicited similar reductions in sEMG MPF assessed during the CPT and MVIC muscle actions. Specifically, there were no changes in sEMG RMS during the CPT (+6.5±22.5% change from pretest) or MVIC (+7.7±24.1% change from pretest) muscle actions, while sEMG MPF decreased by 12.8±10.5% during the CPT and 8.7±10.2% during the MVIC muscle actions across all 3 conditions. The lack of change in sEMG RMS suggested that the SIT intervention did not adversely affect muscle excitation or the ability to maximally excite all available motor units (De Luca, 1997). The reduction in sEMG MPF, however, suggested there were fatigued-induced decreases in action potential conduction velocity (APCV) possibly due to the build-up of metabolites. For example, fatigue-induced reductions in sEMG MPF have been attributed to the build-up of metabolites which has been shown to adversely affect APCV (Edwards, 1981; Maclaren et al., 1989; Sadoyama et al., 1983). Specifically, sEMG MPF is sensitive to changes
in APCV which is inversely related to metabolic increases of H+ and lactate, while higher muscle temperatures (29-38°C) increase APCV, approximately 5% per degree (Kiernan et al., 2001; Waxman, 1980). Collectively, the findings of the present study indicated that SIT with or without BFR did not affect muscle excitation but did induce comparable reductions in APCV across all conditions.

\%PWC_{FT}

In the present study, collapsed across condition, \%PWC_{FT} was greater during sprint 1 (461.2±126.9%) than sprint 2 (330.7±72.7%) which was consistent with the fatiguing nature of repeated sprint exercise (Billaut & Basset, 2007; Hautier et al., 2000; Mendez-Villanueva et al., 2007, 2008). Furthermore, collapsed across Sprint, \%PWC_{FT} was greater during No-BFR (414.2±121.9%) than CBFR (375.9±121.9%) with no difference between IBFR (397.7±123.2%) and No-BFR. The sEMG-based PWC_{FT} has been applied to examine neuromuscular function during progressive exercise bouts to demarcate the onset of neuromuscular fatigue (i.e., linear increase in muscle excitation possibly due to increased recruitment of additional motor units). Thus, theoretically, 100% of PWC_{FT} represents the highest power output that could be achieved prior to power- and/or fatigue-induced increases in muscle excitation. Therefore, in the present study, regardless of condition, each 30-s sprint achieved approximately 3-5 times the power output of the PWC_{FT}, likely eliciting a potent stimulus on neuromuscular, muscle, and cardiovascular function. Furthermore, despite lower \%PWC_{FT} for CBFR than No-BFR, collapsed across Sprint, all sprints substantially exceeded the PWC_{FT} threshold suggesting that all SIT protocols necessitated robust increases in muscle excitation which were not augmented in either BFR protocol. Collectively the results of the present study suggested that SIT exhibits a potent effect on muscle function and achieved a power output that of 3 to 5-fold larger than PWC_{FT}. 
VI: CONCLUSION

In the present study, SIT elicited comparable reductions in leg extension strength and similar increases in MT from pretest to posttest across all 3 conditions. There were also differences in reductions in peak and mean RPM from Sprint 1 to Sprint 2 for all conditions. Specifically, during Sprint 2 peak RPM was greater during No-BFR than IBFR and CBFR while mean RPM was greater for No-BFR and IBFR than CBFR. Regardless of condition, each 30-s sprint achieved approximately 3-5 times the power output of the PWC_{FT}. SIT with and without BFR did not affect sEMG RMS but elicited similar reductions in sEMG MPF during both CPT and MVIC muscle actions although %PWC_{FT} was greater during sprint 1 than sprint 2 and greater during No-BFR than CBFR. Collectively, the findings of the present study indicated that SIT with or without BFR did not affect neuromuscular function and induced comparable reductions in neuromuscular fatigue across all conditions. Power output, however, may be lower when SIT is combined with BFR.
APPENDIX A: IRB APPROVAL
December 14, 2022

Dear Ethan Hill:

On 2/8/2022, the IRB reviewed the following submission:

<table>
<thead>
<tr>
<th>Type of Review:</th>
<th>Initial Study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Title:</td>
<td>The Acute Effects of Continuous and Intermittent Blood Flow Restriction on Sprint Interval Performance and Muscle Oxygen Responses</td>
</tr>
<tr>
<td>Investigators:</td>
<td>Ethan Hill, PI David Gonzalez-Rojas, Co-I Christopher Proppe, Co-I Paola Rivera, Co-I Aaron Wizenberg, Co-I</td>
</tr>
<tr>
<td>IRB ID:</td>
<td>STUDY00003812</td>
</tr>
<tr>
<td>Funding:</td>
<td>None</td>
</tr>
<tr>
<td>Grant ID:</td>
<td>None</td>
</tr>
<tr>
<td>IND, IDE, or HDE:</td>
<td>None</td>
</tr>
<tr>
<td>Documents Reviewed:</td>
<td>• Email Script Repeated Sprints.docx, Category: Recruitment Materials; • Flowchart for muscle mitochondrial protocol.docx, Category: Other; • Medical and Activity History Questionnaire.docx, Category: Survey / Questionnaire; • RPE scale, Category: Survey / Questionnaire; • SIT Consent v9.pdf, Category: Consent Form; • SIT Data Sheet.xlsx, Category: Other; • SIT Flyerv2.pptx, Category: Recruitment Materials; • SIT IRB v7.docx, Category: IRB Protocol;</td>
</tr>
</tbody>
</table>

The IRB approved the protocol on 2/8/2022. This study was closed on 7/25/2022.

In conducting this protocol, you are required to follow the requirements listed in the Investigator Manual (HRP-103), which can be found by navigating to the IRB Library within the IRB system. Guidance on submitting Modifications and a Continuing Review or Administrative Check-in is detailed in the manual. If
continuing review is required and approval is not granted before the expiration
date, approval of this protocol expires on that date.

If you have any questions, please contact the UCF IRB at 407-823-2901 or
irb@ucf.edu. Please include your project title and IRB number in all
correspondence with this office.

Sincerely,

[Signature]

Renea Carver
UCF IRB
APPENDIX B:
MEDICAL HEALTH AND ACTIVITY QUESTIONNAIRE
Confidential Medical Health and Activity Questionnaire

Participant # __________
(investigator will assign you a number)

When was your last physical examination? _____ / _____ / _______

1. Have you ever been hospitalized? If yes, please explain. □ N/A
   Year of Hospitalization | Reason for Hospitalization
   ______________________ | ______________________
   ______________________ | ______________________
   ______________________ | ______________________

2. List any chronic (long-term) illnesses that have caused you to seek medical care. □ N/A

3. Have you undergone major surgery within the previous 16 weeks? If yes, please explain. □ No

4. Have you ever had (or do you have now) active malignant disease or cancer? If yes, please explain. □ No
5. Please place a check in the appropriate box.

**Symptoms or Signs Suggestive of Disease**

<table>
<thead>
<tr>
<th>Yes</th>
<th>No</th>
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<tbody>
<tr>
<td>Are you a male over age 45 or female over age 55?</td>
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<tr>
<td>Have you experienced any unusual pain or discomfort in your chest, neck, jaw, arms, or other areas that may be due to a heart problem?</td>
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<tr>
<td>Have you experienced unusual fatigue or shortness of breath at rest, during usual activities (e.g., climbing stairs, carrying groceries, walking briskly), or during mild or moderate exercise?</td>
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<tr>
<td>Have you had any problems with dizziness or fainting?</td>
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<td>When you stand up, do you have difficulty breathing?</td>
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<td>Do you have difficulty breathing while sleeping?</td>
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<td>Do your ankles swell (ankle edema)?</td>
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<td>Have you ever experienced an unusual or rapid heartbeat or fluttering of the heart?</td>
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<td>Have you experienced severe pain in your legs while walking?</td>
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<td>Have you ever been told by a doctor that you have a heart murmur?</td>
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<td>Has anyone in your family died before the age of 40 (excluding accidental death)?</td>
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<tr>
<td>Are you a cigarette smoker, quit smoking within the past 6 months, or are exposed to tobacco smoke?</td>
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<tr>
<td>Do you have a history of drug or alcohol dependency?</td>
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<tr>
<td>Has your doctor ever said you have a heart condition and that you should only do physical activity recommended by a doctor?</td>
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<tr>
<td>Are you physically inactive (perform little physical activity on the job or during your leisure time)?</td>
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<tr>
<td>Do you feel any pain in your chest when you do physical activity?</td>
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<td>Are you ever bothered by racing of your heart?</td>
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<td>Do you ever notice abnormal or skipped heartbeats?</td>
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<td>Do you ever have any arm or jaw discomfort, nausea, or vomiting associated with cardiac symptoms?</td>
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<td>Do you ever have difficulty breathing?</td>
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<td>Do you ever experience shortness of breath?</td>
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<td>Have you ever had any tingling or numbness in your arms or legs?</td>
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<td>Yes</td>
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<tr>
<td>Condition</td>
<td>Comments</td>
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<td>-----------------------------------------------</td>
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<tr>
<td>Alzheimer’s</td>
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<tr>
<td>Claudication</td>
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**Cardiovascular Disease**

<table>
<thead>
<tr>
<th>Condition</th>
<th>Comments</th>
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<tbody>
<tr>
<td>Peripheral vascular disease</td>
<td></td>
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<tr>
<td>Hypercholesteremia (high cholesterol)</td>
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<td>Carotid vascular disease</td>
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<tr>
<td>Coronary artery disease</td>
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<td>Aortic stenosis</td>
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<td>Congestive heart failure</td>
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<td>Arterial fibrillation</td>
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<tr>
<td>“Heart block”</td>
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<td>Myocardial infarction (Heart attack)</td>
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<td>Hypertension</td>
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<td>Heart pacemaker</td>
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<tr>
<td>High blood pressure</td>
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<tr>
<td>Heart murmur</td>
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**Pulmonary**

<table>
<thead>
<tr>
<th>Condition</th>
<th>Comments</th>
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<tbody>
<tr>
<td>Chronic obstructive pulmonary disease</td>
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<tr>
<td>Asthma</td>
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<tr>
<td>Intestinal lung disease</td>
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<tr>
<td>Emphysema</td>
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<tr>
<td>Metabolic disorder</td>
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<tr>
<td>Diabetes mellitus (type 1, type 2)</td>
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<tr>
<td>Diabetes insipidus</td>
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<tr>
<td>Thyroid disorders</td>
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<tr>
<td>Yes</td>
<td>No</td>
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- Do you have a bone or joint problem that could be made worse by a change in your physical activity? 
- Is your doctor currently prescribing drugs (for example, water pills) for your blood pressure or heart condition? 
- Are you presently taking any nutritional supplements or ergogenic aids? 
- Has a health care practitioner ever denied or restricted your participation in sports for any problem? 
- Are you pregnant? 
- Is there a chance that you may be pregnant? 
- When was the first day of your last menstrual cycle (period)? 
- Do you know any other reason why you should not do physical activity?
6. Please check any of the medications or supplements that you currently take regularly. Also give the name of the medication.

<table>
<thead>
<tr>
<th>Type of Medication</th>
<th>Name of the Medication</th>
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<tbody>
<tr>
<td>Heart medicine</td>
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<tr>
<td>Blood pressure medicine</td>
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<td>Blood cholesterol medicine</td>
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<td>Hormones</td>
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<tr>
<td>Birth control pills</td>
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<td>Medicine for breathing or lungs</td>
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<tr>
<td>Insulin</td>
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<tr>
<td>Other medicine for diabetes</td>
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<td>Arthritis medicine</td>
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<td>Medicine for depression</td>
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<td>Medicine for anxiety</td>
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<td>Thyroid medicine</td>
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<td>Medicine for ulcers</td>
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<td>Painkiller medicine</td>
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<td>Allergy medicine</td>
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<td>HIV/AIDS medicine</td>
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<td>Hepatitis medicine</td>
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**Other medicine or supplement**

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7. Are you allergic to any medications? If yes, please list medications and reaction. □ No

8. Please list any allergies, including food allergies that you may have? □ N/A

__________________________________________________________

INTERNATIONAL PHYSICAL ACTIVITY QUESTIONNAIRE

We are interested in finding out about the kinds of physical activities that people do as part of their everyday lives. The questions will ask you about the time you spent being physically active in the last 7 days. Please answer each question even if you do not consider yourself to be an active person. Please think about the activities you do at work, as part of your house and yard work, to get from place to place, and in your spare time for recreation, exercise or sport.

Think about all the vigorous and moderate activities that you did in the last 7 days. Vigorous physical activities refer to activities that take hard physical effort and make you breathe much harder than normal. Moderate activities refer to activities that take moderate physical effort and make you breathe somewhat harder than normal.

PART 1: JOB-RELATED PHYSICAL ACTIVITY

The first section is about your work. This includes paid jobs, farming, volunteer work, course work, and any other unpaid work that you did outside your home. Do not include unpaid work you might do around your home, like housework, yard work, general maintenance, and caring for your family. These are asked in Part 3.

1. Do you currently have a job or do any unpaid work outside your home?
   □ Yes
   □ No  ➔ Skip to PART 2: TRANSPORTATION

The next questions are about all the physical activity you did in the last 7 days as part of your paid or unpaid work. This does not include traveling to and from work.

2. During the last 7 days, on how many days did you do vigorous physical activities like heavy lifting, digging, heavy construction, or climbing up stairs as part of your work? Think about only those physical activities that you did for at least 10 minutes at a time.

   ____ days per week
3. How much time did you usually spend on one of those days doing **vigorous** physical activities as part of your work?

   _____ hours per day
   _____ minutes per day

4. Again, think about only those physical activities that you did for at least 10 minutes at a time. During the last 7 days, on how many days did you do **moderate** physical activities like carrying light loads as part of your work? Please do not include walking.

   _____ days per week

   □ No moderate job-related physical activity  ➔  Skip to question 6

5. How much time did you usually spend on one of those days doing **moderate** physical activities as part of your work?

   _____ hours per day
   _____ minutes per day

6. During the last 7 days, on how many days did you **walk** for at least 10 minutes at a time as part of your work? Please do not count any walking you did to travel to or from work.

   _____ days per week

   □ No job-related walking  ➔  Skip to PART 2: TRANSPORTATION

7. How much time did you usually spend on one of those days **walking** as part of your work?

   _____ hours per day
   _____ minutes per day

**PART 2: TRANSPORTATION PHYSICAL ACTIVITY**

These questions are about how you traveled from place to place, including to places like work, stores, movies, and so on.

8. During the last 7 days, on how many days did you **travel in a motor vehicle** like a train, bus, car, or tram?

   _____ days per week

   □ No traveling in a motor vehicle  ➔  Skip to question 10

9. How much time did you usually spend on one of those days **traveling** in a train, bus, car, tram, or other kind of motor vehicle?
____ hours per day
____ minutes per day

Now think only about the bicycling and walking you might have done to travel to and from work, to do errands, or to go from place to place.

10. During the last 7 days, on how many days did you bicycle for at least 10 minutes at a time to go from place to place?
____ days per week

☐ No bicycling from place to place  
⇒  Skip to question 12

11. How much time did you usually spend on one of those days to bicycle from place to place?
____ hours per day
____ minutes per day

12. During the last 7 days, on how many days did you walk for at least 10 minutes at a time to go from place to place?
____ days per week

☐ No walking from place to place  
⇒  Skip to PART 3: HOUSEWORK, HOUSE MAINTENANCE, AND CARING FOR FAMILY

13. How much time did you usually spend on one of those days walking from place to place?
____ hours per day
____ minutes per day

PART 3: HOUSEWORK, HOUSE MAINTENANCE, AND CARING FOR FAMILY

This section is about some of the physical activities you might have done in the last 7 days in and around your home, like housework, gardening, yard work, general maintenance work, and caring for your family.

14. Think about only those physical activities that you did for at least 10 minutes at a time. During the last 7 days, on how many days did you do vigorous physical activities like heavy lifting, chopping wood, shoveling snow, or digging in the garden or yard?
____ days per week

☐ No vigorous activity in garden or yard  
⇒  Skip to question 16

15. How much time did you usually spend on one of those days doing vigorous physical activities in the garden or yard?
16. Again, think about only those physical activities that you did for at least 10 minutes at a time. During the last 7 days, on how many days did you do moderate activities like carrying light loads, sweeping, washing windows, and raking in the garden or yard?

   □ No moderate activity in garden or yard. — Skip to question 18

   ___ days per week

17. How much time did you usually spend on one of those days doing moderate physical activities in the garden or yard?

   ___ hours per day
   ___ minutes per day

18. Once again, think about only those physical activities that you did for at least 10 minutes at a time. During the last 7 days, on how many days did you do moderate activities like carrying light loads, washing windows, scrubbing floors and sweeping inside your home?

   □ No moderate activity inside home — Skip to PART 4: RECREATION, SPORT AND LEISURE-TIME PHYSICAL ACTIVITY

   ___ days per week

19. How much time did you usually spend on one of those days doing moderate physical activities inside your home?

   ___ hours per day
   ___ minutes per day

**PART 4: RECREATION, SPORT, AND LEISURE-TIME PHYSICAL ACTIVITY**

This section is about all the physical activities that you did in the last 7 days solely for recreation, sport, exercise or leisure. Please do not include any activities you have already mentioned.

20. Not counting any walking you have already mentioned, during the last 7 days, on how many days did you walk for at least 10 minutes at a time in your leisure time?

   ___ days per week

   □ No walking in leisure time. — Skip to question 22

21. How much time did you usually spend on one of those days walking in your leisure time?

   ___ hours per day
   ___ minutes per day
22. Think about only those physical activities that you did for at least 10 minutes at a time. During the last 7 days, on how many days did you do vigorous physical activities like aerobics, running, fast bicycling, or fast swimming in your leisure time?

   ____ days per week

   [ ] No vigorous activity in leisure time  
   [ ] Skip to question 24

23. How much time did you usually spend on one of those days doing vigorous physical activities in your leisure time?

   ____ hours per day
   ____ minutes per day

24. Again, think about only those physical activities that you did for at least 10 minutes at a time. During the last 7 days, on how many days did you do moderate physical activities like bicycling at a regular pace, swimming at a regular pace, and doubles tennis in your leisure time?

   ____ days per week

   [ ] No moderate activity in leisure time  
   [ ] Skip to PART 5: TIME SPENT SITTING

25. How much time did you usually spend on one of those days doing moderate physical activities in your leisure time?

   ____ hours per day
   ____ minutes per day

PART 5: TIME SPENT SITTING

The last questions are about the time you spend sitting while at work, at home, while doing course work and during leisure time. This may include time spent sitting at a desk, visiting friends, reading or sitting or lying down to watch television. Do not include any time spent sitting in a motor vehicle that you have already told me about.

26. During the last 7 days, how much time did you usually spend sitting on a weekday?

   ____ hours per day
   ____ minutes per day

27. During the last 7 days, how much time did you usually spend sitting on a weekend day?

   ____ hours per day
   ____ minutes per day

This is the end of the questionnaire, thank you for participating.
14. I have answered these questions honestly and have provided all past and present health and exercise information to the best of my knowledge.

Yes  No
☐  ☐

_________________________  __________/_______/_______
Participant #  Date
APPENDIX C: FIGURE OF EXPERIMENTAL PROCEDURES
Visit 1

Graded Exercise Test (GXT)

Determine PWCft*

Visit 2-4

SIT

Ultrasound → CPT & MVIC

No-BFR

CPT & MVIC → Ultrasound

CBFR → IBFR

Conditions randomized per visit*
APPENDIX D: GRAPHS
Figure 1 Muscle Thickness

Figure 1. Mean ± SD values (cm) for muscle thickness (MT). MT was measured prior to (PRE) and after (POST) maximal strength testing and sprint interval training (SIT). SIT was performed with continuous blood flow restriction (CBFR), intermittent blood flow restriction (IBFR), and no blood flow restriction (No-BFR).

†Significant ($p \leq 0.05$) main effect for Time (POST > PRE).
**Figure 2.** Mean ± SD values (Nm) for concentric peak torque (CPT). CPT muscle actions were performed prior to (PRE) and immediately after (POST) sprint interval training (SIT). SIT was performed with continuous blood flow restriction (CBFR), intermittent blood flow restriction (IBFR), and no blood flow restriction (No-BFR).

*Significant ($p \leq 0.05$) main effect for Time (POST < PRE).
Figure 3. Mean ± SD values (Nm) for maximal voluntary isometric contraction (MVIC) torque. MVIC muscle actions were performed prior to (PRE) and immediately after (POST) sprint interval training (SIT). SIT was performed with continuous blood flow restriction (CBFR), intermittent blood flow restriction (IBFR), and no blood flow restriction (No-BFR).

*Significant ($p \leq 0.05$) main effect for Time (POST < PRE).
Figure 4 Concentric Peak Torque sEMG Amplitude

Figure 4. Mean ± SD values (%Δ) for surface electromyographic (sEMG) amplitude obtained during the concentric peak torque (CPT) muscle actions. CPT sEMG amplitude was recorded prior to (PRE) and immediately after (POST) sprint interval training (SIT). SIT was performed with continuous blood flow restriction (CBFR), intermittent blood flow restriction (IBFR), and no blood flow restriction (No-BFR).
Figure 5 Maximal Voluntary Isometric Contraction sEMG Amplitude

Figure 5. Mean ± SD values (%Δ) for surface electromyographic (sEMG) amplitude obtained during the maximal voluntary isometric contraction (MVIC) torque muscle actions. MVIC sEMG amplitude was recorded prior to (PRE) and immediately after (POST) sprint interval training (SIT). SIT was performed with continuous blood flow restriction (CBFR), intermittent blood flow restriction (IBFR), and no blood flow restriction (No-BFR).
Figure 6 Concentric Peak Torque sEMG Mean Power Frequency

Figure 6. Mean ± SD values (%Δ) for surface electromyographic (sEMG) mean power frequency (MPF) obtained during the concentric peak torque (CPT) muscle actions. CPT sEMG MPF was recorded prior to (PRE) and immediately after (POST) sprint interval training (SIT). SIT was performed with continuous blood flow restriction (CBFR), intermittent blood flow restriction (IBFR), and no blood flow restriction (No-BFR). *Significant \((p ≤ 0.05)\) main effect for Time (POST < PRE).
Figure 7. Mean ± SD values (%Δ) for surface electromyographic (sEMG) mean power frequency (MPF) obtained during the maximal voluntary isometric contraction (MVIC) torque muscle actions. MVIC sEMG MPF was recorded prior to (PRE) and immediately after (POST) sprint interval training (SIT). SIT was performed with continuous blood flow restriction (CBFR), intermittent blood flow restriction (IBFR), and no blood flow restriction (No-BFR).

*Significant \( p \leq 0.05 \) main effect for Time (POST < PRE).
Figure 8. Mean ± SD values (%) for physical working capacity at the fatigue threshold (PWC\textsubscript{FT}) determined during sprint interval training (SIT). PWC\textsubscript{FT} was determined for both Sprint 1 and Sprint 2. SIT was performed with continuous blood flow restriction (CBFR), intermittent blood flow restriction (IBFR), and no blood flow restriction (No-BFR).

*Significant ($p \leq 0.05$) main effect for Sprint (Sprint 1 > Sprint 2).

†Significant ($p \leq 0.05$) main effect for Condition (No-BFR > CBFR).
Figure 9. Mean ± SD values for Peak and Mean revolutions per minute (RPM) determined during sprint interval training (SIT). Peak and Mean RPM were determined for both Sprint 1 and Sprint 2. SIT was performed with continuous blood flow restriction (CBFR), intermittent blood flow restriction (IBFR), and no blood flow restriction (No-BFR).

*Significant ($p \leq 0.05$) simple main effect for Sprint (Sprint 1 > Sprint 2).

a. Significant ($p \leq 0.05$) simple main effect for Condition (> CBFR & IBFR).

b. Significant ($p \leq 0.05$) simple main effect for Condition (> CBFR).
REFERENCES


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