A COMPARISON OF TRADITIONAL BLOOD FLOW RESTRICTION VERSUS BAND TISSUE FLOSSING FOR INDUCTION OF MUSCULAR FATIGUE

by

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A THESIS

Submitted in partial fulfillment of the requirements
for the degree of Master of Arts in the
Department of Kinesiology
in the Graduate School of
The University of Alabama

TUSCALOOSA, ALABAMA

2021

ABSTRACT

Resistance training with blood flow restriction (BFR) exaggerates metabolic stress and increases the number of muscle fibers recruited, resulting in greater improvements in muscular strength. An alternative method for occluding blood flow is band tissue flossing (BTF), in which an elastic band is wrapped around the limb. PURPOSE: The purpose of this study was to compare the effects of BTF to BFR on muscular fatigue. METHODS: Fifteen subjects (6 females; mean ± SD: age = 23.3 ± 0.1y, BMI = 25.7 ± 0.9kg/m^2, thigh circumference = 59.9 ± 1.6cm) completed 3 sessions on separate days, each under a different condition: control (CON), BFR at 50% limb occlusion pressure, and BTF. During each session, participants performed maximal effort leg extension and flexion for 3 sets of 20 repetitions using an isokinetic dynamometer. At the start of each session, baseline heart rate (HR), lactate, glucose, and blood flow were recorded. During the BFR and BTF sessions, HR and blood flow were recorded before and 1-minute after occlusion. HR, glucose, and lactate were recorded immediately post- and 1-minute post-exercise for all sessions. Repeated measures ANOVAs were used to compare outcome measures between time points as well as between conditions. RESULTS: BFR and BTF both caused significant increases in HR compared to baseline (4.67 ± 2.14 BPM and 6.07 ± 2.56 BPM, both $p < 0.01$, respectively), with no significant differences between conditions. BTF significantly decreased arterial distance (-0.04 ± 0.04cm, $p = 0.001$), volume flow (-7.56 ± 6.88 cc/min, $p = 0.001$), and arterial area (-0.02 ± 0.01cm^2, $p < 0.001$). Whereas BFR significantly decreased time-averaged mean velocity (-1.03 ± 1.65cm/s, $p = 0.001$). BTF caused a greater reduction in arterial distance compared to BFR ($p = 0.006$). However, no differences were observed in all dynamometry, electromyography, glucose, or lactate measures between occlusion conditions. CONCLUSION: BTF occluded more blood flow and yielded comparable changes in muscular fatigue when compared to BFR, providing an inexpensive training alternative when more sophisticated laboratory techniques are unavailable.

DEDICATION

This manuscript is lovingly dedicated to my parents,
who unwaveringly supported every crazy dream and spontaneous change of
plans that brought me here.

And to my precious fiancé,
who constantly fibs and tells me I’m way more brilliant than I actually am.

My inflated ego is the fault of all three of you.
Thank you all for consistently leading by example and practicing what you preach.

LIST OF ABBREVIATIONS AND SYMBOLS

*	Denotes significant difference within the condition
#	Denotes significant difference from control condition
†	Denotes significant difference from BFR condition
‡	Denotes non-parametric testing performed
Δ	Difference/change in
1minPost(Ex)	1-minute post-exercise
1RM	1 repetition maximum
ACSM	American College of Sports Medicine
ANOVA	Analysis of variance
Asympt	Asymptotic
Avg	Average
AvgPow(PerRep)	Average power per repetition
BFR	Blood flow restriction
BMI	Body mass index
BTF	Band tissue flossing
cm	Centimeters
cc	Cubic centimeters
CON	Control condition
COVID-19	Coronavirus disease 2019

Delfi PTS	Delfi personal tourniquet system
df	Degrees of freedom
Dist	Distance
dL	Deciliter
DOMS	Delayed-onset muscle soreness
EMG	Electromyography
EPR	Exercise pressor reflex
Ext	Extension portion of the exercise
F	F-statistic
Flex	Flexion portion of the exercise
ft-lbs	Foot-pounds
HbA1c	Hemoglobin a1c
HR	Heart rate
HRPre	Baseline/resting heart rate
IL-6	Interleukin-6
ImmPost(Ex)	Immediately post-exercise
InPeakTorq	Initial peak torque
kg	Kilograms
LOP	Limb occlusion pressure
mg	Milligrams
min	Minute
mmHg	Millimeters of mercury
mV	Millivolts

N	Number/count
PercChange	Percent change
PostOcc	Post-occlusion
RMS	Root mean square
s	Second
SD	Standard deviation
SEM	Standard error of the mean
Set(#)Avg	Average of RMS values for all 9 recorded reps within a set
Set(#)First3	Repetitions 1, 2, and 3
Set(#)Last3	Repetitions 18, 19, and 20 of the set
Set(#)Middle3	Repetitions 9, 10, and 11 of the set
Sig	Statistical significance
TAMV	Time-averaged mean velocity
TotWork(Done)	Total work done/performed
VolFlow	Volume flow
vs	Versus
y	Years

ACKNOWLEDGMENTS

This project would not have been possible without the support of my advisor, Dr. Winchester. To say that nothing over the past two years has gone as expected would be an understatement. With your guidance, though, I'd say we made the best out of a bad situation. I will forever be grateful for the growth as a student, teacher, and human that I've gained under your mentorship. Thank you for constantly reminding me of my worth and challenging me to expect nothing but the best from myself. I know that even though I am moving, our research together doesn't end here, and I can't wait to continue on this academic journey with you in my corner.

I will also be forever grateful for my lab group: Abby, Keith, and Björn. Thank you for taking in the little biology nerd and making an exercise physiologist out of her. Not only were you all so helpful with my project, you also made the lab a very fun place to be. I can't wait to take on this field together and see what awesome projects you come up with in the years to come.

To my committee members, thank you so much for the time and energy invested into this both project and my understanding of statistics and physiology. I know this process could have been a daunting one, but I count myself grateful to have been under the guidance of such joyous and generous mentors. Working with you all was an absolute delight.

Finally, to my participants – thank you for trusting me to try something new and unresearched on you. I am so grateful for your perseverance and optimism!

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INTRODUCTION

Resistance exercise, defined by the American College of Sports Medicine (ACSM) as "exercising a muscle or a muscle group against external resistance" is highly effective at protecting the body by increasing strength and bone mineral density, reducing blood pressure, and decreasing the risk of sarcopenia as well as several pathological states rooted in chronic inflammation (1). The increased muscle mass resulting from resistance exercise can also reduce hemoglobin A1c (HbA1c) levels, indicating better glycemic control over the course of several months, which directly correlates to a reduced risk for all-cause mortality (Salem et al., 2010; Stratton et al., 2000; Tonoli et al.; Yardley et al., 2013). Therefore, resistance exercise is recommended by the ACSM to be performed 2-3 times per week (Fiataraone Singh et al., 2019).

Resistance exercise only produces muscle hypertrophy when the loads are >65% of the individual's one repetition maximum (1RM) (Fiataraone Singh et al., 2019; Schoenfeld, 2010). On the contrary, resistance exercise with blood flow restriction (BFR) induces hypertrophic mechanisms with loads as low as 20% 1RM (Pearson & Hussain, 2015; Wilson et al., 2013). For this reason, BFR resistance exercise has been popularized in recent years for its ability to, at low intensities, mimic the hypoxic environment seen during exercising at high intensities. Because veins are much more pliable than arteries, BFR fully occludes venous return of waste products and partially occludes oxygenated arterial inflow (Scott et al., 2015). BFR application during exercise promotes significantly greater intramuscular metabolite accumulation than observed with intense resistance exercise alone (Marliss & Vranic, 2002). This local stress on the muscle induces a cascade of cell signaling events related to muscle hypertrophy.

There are two likely mechanisms responsible for BFR induced hypertrophy: neurological effects and metabolic accumulation. The neurological effects of hypoxia result in accelerated fatigue, and therefore the need to recruit more muscle fibers, as demonstrated by greater EMG activity under BFR conditions (Moore et al.). The other, more complicated mechanism is metabolite accumulation due to restricted venous return. The metabolic stress created by anaerobic exercise is an established physiological promoter of cellular anabolism (Schoenfeld, 2013). Since BFR increases hypoxic- and metabolic stress-induced hypertrophy, lower resistance loads can produce gains in strength similar to heavy loads without the associated mechanical strain (Park et al., 2015). Because of this, low-intensity resistance exercise with BFR results in greater post-exercise concentrations of growth hormone, norepinephrine, IL-6, and lactic acid when compared to low-intensity resistance exercise without BFR.

Though significantly less studied than traditional blood flow restriction using a pressurized cuff, another technique to induce vascular occlusion is band tissue flossing (BTF). These bands are commercially-available rubber wraps that are tightly applied around the limbs in order to restrict blood flow to the tissue. The application of BTF is now common practice in the weightlifting and CrossFit realms and is advertised as a blood flow restriction device, though it is largely marketed as a means of warming up joints. Regardless of terminology, BTF provides a more affordable and accessible version of its BFR device counterparts. BTF manufacturers and advocates make claims similar to the benefits of BFR, insisting on reduced soreness, improved recovery, and increased hypertrophy through use of their products (*Physiopedia*, 2019). Because of its accessibility and portability, BTF is commonly used in sports medicine to increase muscular function and mobility (Cheatham & Baker, 2019). Unlike BFR devices, however, there is little supporting research regarding BTF's efficacy for improving health. In the limited available research, BTF has shown some small range of physiological successes. One study applying BTF around the ankle demonstrated an increase in range of motion and an apparent increase in athletic performance, determined by single-leg vertical jump height (Driller & Overmayer, 2017). Unfortunately, researchers failed to report time under occlusion, making this protocol difficult to replicate. BTF application during exercise has also been reported to significantly reduce post-exercise delayed-onset muscle soreness (DOMS) in healthy individuals (Prill et al., 2019).

To the best of our knowledge, BTF has yet to be compared directly to a traditional BFR device. It would be valuable information for therapeutic and athletic endeavors to discern differences in the efficacies of these methods for occluding blood flow and inducing muscular fatigue. Furthermore, there is no standardized protocol for BTF application. The common application is "50% wrap, 50% overlap" translating to roughly overlapping the band each time around the body part by 50%, while tensing the band to 50% more than its unstretched resistance (Cheatham & Baker, 2019). While Cheatham and Baker (Cheatham & Baker, 2019) were able to quantify the tension force at different band elongation lengths, there has yet to be a technique or design that aids the user in determining whether or not this tension has actually been achieved, nor has there been a correlation between these measurements and percent vascular occlusion.

Though less studied, BTF could prove to be a more successful method for occlusion than traditional BFR devices due to pressure application across a greater surface area. This was suggested by Weatherholt *et al* (2019), in which two types of BFR devices with different sized cuffs were compared. The results indicated the wider cuff (Delfi) was capable of completely occluding arterial blood flow at a lower pressure then the more narrow cuff (KAATSU), which required maximum device pressure and never reached full occlusion (Weatherholt et al., 2019).

The combination of BTF's popularity and accessibility with all of the unknowns regarding efficacy creates an essential need for additional research. The purpose of this study was to address this evidence gap in the literature, both by quantifying the physiological effects of BTF in comparison to BFR, as well as potentially establishing a protocol for consistent BTF application.

METHODS

Experimental Design

The study was conducted using a randomized, crossover repeated measures experimental design, as displayed in Figure 1. Recruited participants engaged in three different data collection sessions over a 2-3 week period. The sessions were no less than 72 hours apart to ensure adequate recovery time, but no more than two weeks apart. Each of the sessions involved exercise under only one of the three conditions (control (CON), BFR, and BTF) to limit interference of the effects of occlusion as well as exercise. The order for the occluding applications was randomized using Microsoft Excel v.16.48. A summary of the resultant ordering from the randomization procedure is provided in Appendix A. During all of the sessions, participants performed three sets of 20 repetitions of knee extensions/flexions (90 degrees per second) on the Humac Norm isokinetic dynamometer (Stoughton, MA, USA) with their dominant leg. The data for this study were collected between October 21, 2020 and April 19, 2021.

Participants

A power analysis conducted in G*Power v.3.1.9.6 revealed a need for 15 participants in order to observe a large effect size ($f = 0.4$, $\alpha = 0.05$, $\beta = 0.9$) based on means and SEM's from data for total work performed from the first three participants of this study. Participants numbered 15 healthy males (n=9) and females (n=6). In order to prevent the spread of COVID-19, participants were only recruited from the University of Alabama. Inclusion criteria required all participants to be non-smokers between the ages of 18 and 35 and pass the ACSM preparticipation screening to initiate exercise without medical clearance (American College of Sports Medicine, 2015). This designation translates to the participant having no signs, symptoms, or diagnoses of cardiovascular, metabolic, or renal disease that would have affected the study's results. Exclusion criteria for this study included, but was not limited to: requiring medical clearance prior to initiating exercise according to the ACSM preparticipation screening tool, having known cardiovascular, metabolic, renal, or musculoskeletal complications that would have prevented or impaired the subject from safely completing the study, and having a positive test for COVID-19 within the past 30 days. In order to limit the influence of external factors on the study's results, participants were asked to abstain from vigorous exercise and caffeine, 24 and 4 hours prior to each session, respectively. Participants were also asked to maintain social distancing and limit exposure to COVID-19 to prevent attrition due to the need to self-quarantine once the study was initiated.

Procedures

During the first session, participants were provided written formal consent, screened for participation, and evaluated for ability to engage in resistance exercise activity using a standardized Physical Activity Readiness Questionnaire+ (Warburton et al., 2011) and a 24-hour recall form detailing recent consumption of foods, drinks, and supplements as well as physical activity and sleep. Anthropometric measurements, including height (via stadiometer), weight (via digital scale), and body composition using the ImpediMed SFB7 bioimpedance spectroscopy device (Carlsbad, CA, USA) were also obtained. Thigh length and circumference were measured using a soft tape for body measurement.

During all three conditions, resting heart rate and baseline glucose and lactate measurements were taken following completion of the 24-hour recall form while the participant remained seated. The participant then moved to be seated on the Humac Norm isokinetic dynamometer (Stoughton, MA, USA). The skin surface above the rectus femoris was shaved when necessary, then cleaned with alcohol wipes to apply two gel electrodes in a bipolar configuration. The first ultrasound measurement was then taken at the tibial artery, occlusion applied (BFR and BTF conditions only), and the second ultrasound measurement taken 1-minute following occlusion. Procedures for application of the occlusion devices are detailed below. Immediately following a successful post- ultrasound measurement, the participant began the exercise protocol on the isokinetic dynamometer, consisting of three sets of 20 reps of maximal knee extension and flexion, with 30 seconds of rest between each set. After completion of the third set, the immediately-post lactate, glucose, and HR measurements were recorded, followed by removal of occlusion and the recording of the 1-minute post-exercise measurements. For additional precaution, no occluding application was in place for more than 8 minutes at a time.

B-mode ultrasound imaging using the Philips iU22 Ultrasound (Bothell, WA, USA) was performed to determine lumen distance and area as well as volume and time-averaged mean velocity of blood flow at the tibial artery on the participant's dominant (therefore involved) leg. Participants were seated in the upright position with their dominant leg propped up with a slight bend in the knee, and measurements of the tibial artery were taken adjacent to the medial malleolus for consistency. For all of the conditions, a 'pre-' ultrasound measurement was obtained. For the occlusion conditions, a 'post-occlusion' measurement was obtained after blood flow was occluded for at least 30 seconds, allowing time for physiological adaptations to occur. For the control condition, a 'post-' measurement was obtained at 30-60 seconds following the ‘pre-‘ measurement, to account for potential human error when taking two ultrasound measurements at the same site.

Circulating lactate and glucose levels were obtained from capillary blood droplets and analyzed via the Lactate Plus handheld lactate analyzer (Nova Biomedical, Waltham, MA, USA) and the ReliOn Prime handheld glucose analyzer (Novo Nordisk, Bagsværd, Denmark), respectively. Three total finger pricks occurred during each session. Baseline lactate and glucose measurements were obtained prior to exercise. The second measurement occurred immediately after the last set of exercise, and the third measurement occurred 1-minute after removal of occlusion (or 1-minute following the immediately post- measurement for the control condition).

For further indication of fatigue, participants were outfitted with gel electrodes on the rectus femoris (as proximal as possible) for surface electromyography (EMG) during the extension portion of the exercise. The participant was also outfitted with a heart rate monitor chest strap (Polar Electro Oy, Kempele, Finland). Heart rate was recorded at rest, 1-minute after occlusion, immediately post-exercise, and 1-minute post-removal of occlusion.

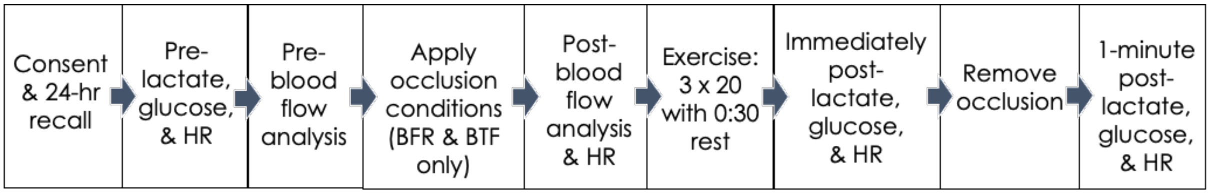

Figure 1. Chronological procedures common to each visit (excludes body composition measurements taken only during initial visit). All values were obtained with the participant seated in the upright position. *HR = heart rate; BFR = blood flow restriction; BTF = band tissue flossing*.

Blood flow restriction application

The BFR device used in this study was the Delfi PTS (Owens Recovery Science, San Antonio, TX, USA), which is FDA approved and commonly used in physical therapy, athletic training, and research settings. The BFR cuff was applied to the proximal thigh of the participant's dominant limb and inflated to 50% of the participant's predetermined personal limb occlusion pressure (LOP). In order to establish 50% of the participant's LOP, the Delfi must first perform a "personal tourniquet pressure" test. During this, the cuff self-inflates until it has determined 100% arterial occlusion, then immediately releases the pressure and saves the value in mmHg so the researcher can use 50% of that value. The cuff remained inflated for the duration of the 3 exercise sets and was deflated approximately 30 seconds after completion of the third set, as soon as all immediately-post measures were recorded.

Band tissue flossing application

The bands used were seven-foot long, two-inch wide, heavy strength WOD Nation Compression Muscle Floss, made of natural latex rubber (Suring, WI, USA). Though there is no standardized protocol yet for BTF application, this study used the "50% wrap, 50% overlap" common practice referenced in the sports medicine and fitness industries (Cheatham & Baker, 2019). This entails the band being stretched an additional 50% of its length, then wrapped around the limb, overlapping the segments below it by 50% of the width. Also, according to this practice, wrapping started distally and ended proximally and was wrapped clockwise from the participant's perspective. The free end of the band was secured by tucking the end under the final layer of the band.

To maintain consistency in this study, the following procedure for BTF application has been designed (see Figure 2 for visual reference). The length of the participants thigh was measured from the top of the patella to the inguinal crease. This length was then divided into thirds. At a distance 1/3 the length of the thigh from the top of the patella, a line was drawn with washable marker on the participant's quadriceps to mark where wrapping of the BTF band would begin. At a distance 2/3 the length of the thigh from the top of the patella, thigh circumference was measured. The circumference measurement (x) was then divided into quarters, and lines were drawn down the participant’s leg delineating these quarter-markings. While seated, but with the thigh not touching the chair, the band was then placed atop the participant's leg at the first quarter mark. The band was then wrapped unstretched around 2/4 of the participant’s thigh, and the researcher’s thumb placed at that position on the band, marking 0.5x circumference. The band was then lifted slightly off of the participant’s skin (to prevent pinching), and that length of the band (0.5x) was stretched around 3/4 of the participant’s thigh. This procedure was repeated for the entire length of the band. The overlap the band had with the piece of band underneath it was 0.5y, where "y" is the width of the band. To maintain consistency in the tension applied from person-to-person, each participant used a new, unused band.

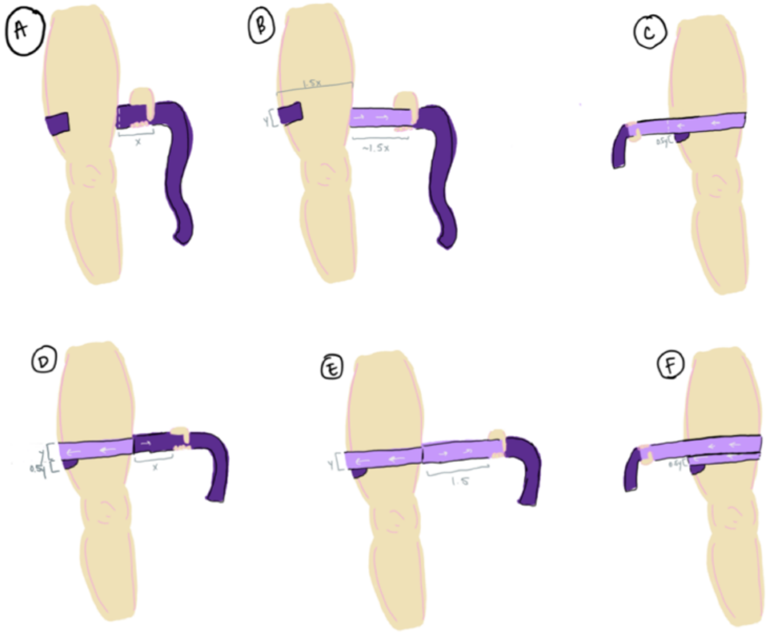

Figure 2. Diagram for BTF wrapping protocol. *x = thigh circumference; y = width of the band.*

Data Processing

For the isokinetic dynamometry data, three different measurements from the isokinetic dynamometer were analyzed: initial peak torque, average power per rep, and total work performed. Values were provided for both the extension and flexion components of the repetition. Repeated measures ANOVAs were first performed between the three sets within each condition. Then, repeated measures ANOVAs were performed analyzing differences within each set between the conditions. Finally, repeated measures ANOVAs were performed analyzing mean percent change in each measurement between conditions.

Surface EMG data was analyzed using Acqknowledge v.27 (BIOPAC Systems Inc). Root mean square (RMS) was calculated for the peak amplitude (in 0.25s intervals) of the first three reps (1-3), middle three reps (9-11), and last three reps (18-20) of each set. These 3 reps were averaged together to represent a single data point (Yasuda et al., 2008), denoted as “first3,” “middle3,” and “last3.” First, repeated measures ANOVAs were performed on the average of these values for all 9 reps in each set between conditions, denoted as “set1avg,” “set2avg,” and “set3avg.” Repeated measures ANOVAs were then performed comparing the first, middle, and last three reps within each set between the conditions. Then, repeated measures ANOVAs were performed on the change values calculated between the averages of each of the repetition groupings within a set. For example, “EMGChange1” corresponds to the difference in the average values between the first 3 reps and middle 3 reps of set 1. Because there are 9 total groupings of reps for each condition, 8 total change values were calculated for each condition.

Statistical Analyses

All statistical analyses were performed using SPSS for Windows v.27 (IBM Corporation, Somers, NY, USA). Mean values and standard deviations were generated for all of the outcome measures. Paired-samples t-tests were conducted to test the significance of mean differences in pre-/post- measures of arterial between conditions due to the unequal sample size in the control condition, as well as pre-exercise changes to heart rate caused by application of the two occlusion conditions. Cohen's d was used to determine effect sizes for t-tests, where η2 was used for repeated measures ANOVAs (Bakeman, 2005; Cohen, 1988). For variables being used in paired-samples t-tests, normality was determined using the Shapiro Wilk test. When the normality assumption was violated, nonparametric tests were used. Repeated measures ANOVAs were used for the other continuous variables to compare raw values and change scores of measures between and within conditions. Sphericity was tested using Mauchly's *W*. If sphericity was violated, the non-parametric Kruskal-Wallis independent samples test was used. If a main effect was found, a post-hoc analysis with Bonferroni correction was utilized to determine between condition differences. Sample characteristics are detailed in Appendix A and B. An alpha level of 0.05 was used for all tests.

RESULTS

Participants

Fifteen participants volunteered for this study. Participant characteristics are listed in table 1. Randomized assignment of conditions is provided in Appendix A.

Table 1. Descriptive characteristics for all participants (M ± SD)

Female (N)	Male (N)	Age (y)	Weight (kg)	Height (cm)	BMI (kg/m^2)	% Body Fat	Thigh Length (cm)	Thigh Circumference (cm)
6	9	23.27 ± 2.69	81.73 ± 17.38	177.25 ± 9.16	25.72 ± 3.62	26.27 ± 6.37	42.07 ± 4.23	59.93 ± 6.04

Responses to Occlusion Conditions Prior to Exercise

Heart rate

Analysis of resting HR data (HRpre) between conditions revealed no significant differences. Application of BFR and BTF caused moderate increases in HR, t(14) = 2.19, p = 0.001, d = 0.56 and t(13) = 2.37, p = 0.003, d = 0.63, respectively. No significant differences were found in change scores for each pre-/post-occlusion pair between the conditions. Analyses regarding post-exercise measurements will be discussed in a later section. HR data is summarized in Figure 3.

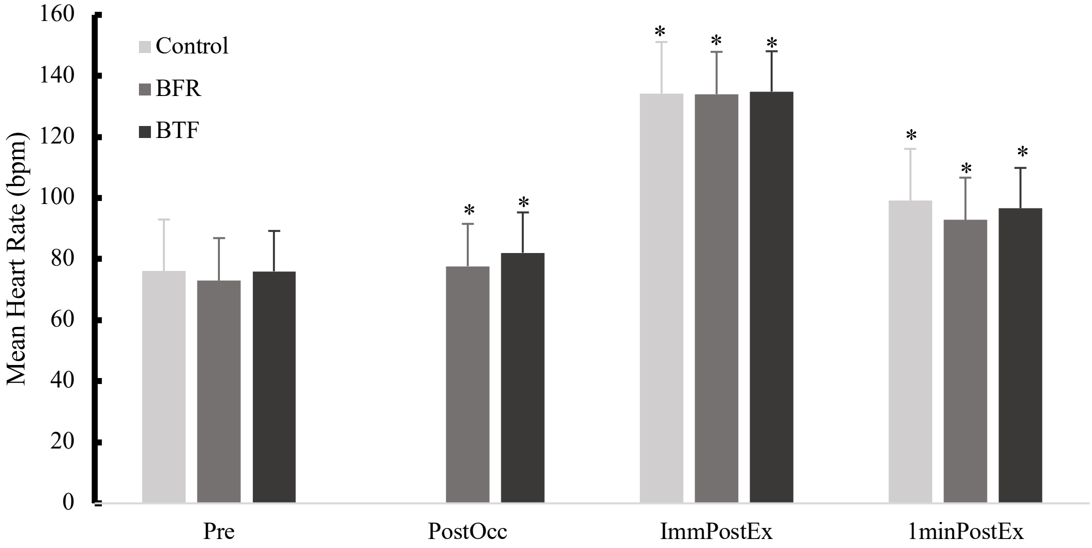

Figure 3. HR in each condition across different time points (M ± SD). No post-occlusion HR data exists for the CON condition, as no occlusion was applied. * = *Significantly different from pre-measurement within condition. BFR = blood flow restriction; BTF = band tissue flossing.*

Arterial flow

Analysis of raw values for pre- and post-measures of arterial blood flow revealed no significant differences between conditions. Mean, difference in mean, and mean percent change values are discussed below and summarized in Appendix D. Mean percent change values are displayed in Figure 4.

Distance: Only the BTF condition caused significant reductions in distance, t(14) = 4.43, $p < 0.001$, d = -1.14. No significant differences were identified in mean percent change scores for distance between conditions. However, this analysis uses only 8 of the 15 data points for the occlusion conditions, as post- measurements were a late addition to the study for the CON condition and only 8 of those exist. When comparing the mean percent change from all 15 data points in each of the occlusion conditions, BFR and BTF were significantly different from each other, t(28) = -2.99, p = 0.006, d = -1.09. On average, BTF caused a 14% greater reduction in arterial distance than BFR.

TAMV: TAMV moderately decreased from pre- to post- in all conditions, though this reduction was only significantly different in the BFR condition**,** t(14) = -2.43, p = 0.029, d = -0.63. No significant differences were identified in mean percent change between conditions.

Volume Flow: Volume flow also decreased from pre- to post- in all conditions, though the change was significant only during BTF, t(13) = -4.11, p = 0.001, d = -1.20. No significant differences were identified in mean percent change between conditions.

Area: The only condition in which area as significantly reduced is BTF, t(14) = -5.33, p < 0.001, d = -1.38. There were no significant differences in mean percent change between CON and BFR nor BFR and BTF. However, BTF caused significantly greater reductions in area than both CON, t(7) = -2.41, p = 0.047, d = -0.85 and BFR, t(14) = -5.50, p < 0.001, d = -0.04. On average, BTF caused a 20% greater reduction in area than CON and a 14% greater reduction in area than BFR.

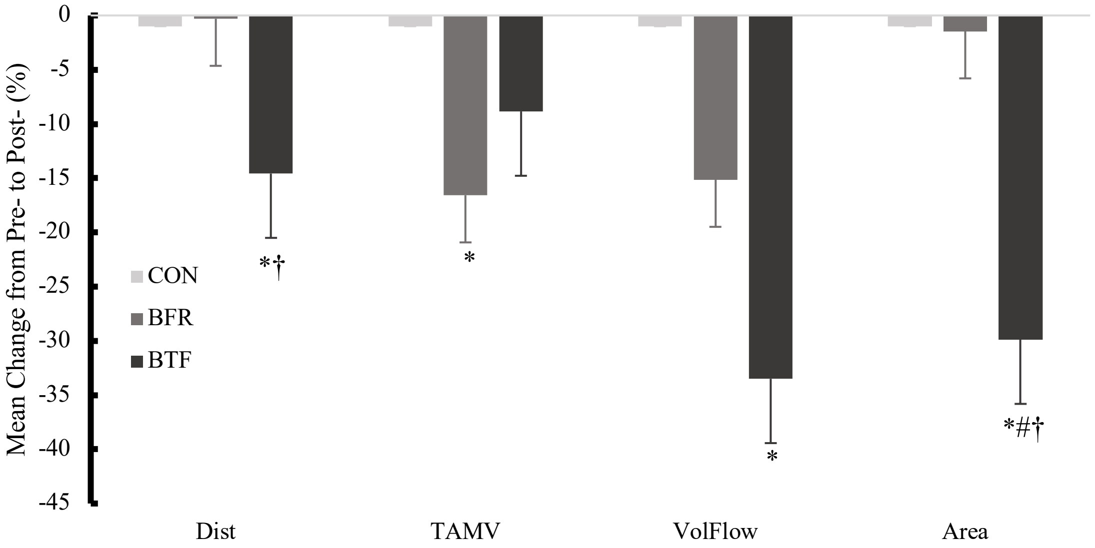

Figure 4. Mean percent change in arterial flow measurements between conditions. SEM displayed as error bars. N = 8 for CON because post- measurements for this condition were a late addition to the protocol.*# = Significantly different from CON; † = Significantly different from BFR; * = Significant difference in pre-/post-measures within condition. TAMV = Time-averaged mean velocity; VolFlow = volume flow; CON = control; BFR = blood flow restriction; BTF = band tissue flossing.*

Responses to Conditions During Exercise

Isokinetic dynamometry

Means and standard deviations for each outcome measure are provided in Appendix E.

Initial peak torque: between sets, within conditions

Extension: There were no significant differences between sets during CON or BFR. A main effect was found within the BTF condition, F(2, 26) = 10.53, $p < 0.001$, $\eta 2 = 0.448$. Pairwise comparisons revealed initial peak torque during set 3 is significantly less than during sets 1 and 2 within the BTF condition, $p = 0.011$ and $p = 0.002$, respectively.

Flexion: There were no significant differences between sets during any of the conditions.

Initial peak torque: within sets, between conditions

Extension: There were no significant differences in initial peak torque during set 1 between the conditions. In set 2, mean initial peak torque during BTF was significantly less than during CON, F(2, 26) = 3.88, $p = 0.033$, $\eta 2 = 0.230$. Similarly, mean initial peak torque during set 3 was significantly less in BTF compared to CON, F(2, 26) = 6.59, $p = 0.004$, $\eta 2 = 0.336$. There were no significant differences in raw values between BTF and BFR or BFR and CON during sets 2 and 3. The mean percent change from set 1 to 2 in initial peak torque was significantly different between CON and BFR as well as CON and BTF, $p = 0.002$ and $p < 0.001$, respectively. During the control condition, initial peak torque increased, on average, by 22%. During the occlusion conditions, though, initial peak torque decreased: 10% in BFR and 12% in BTF. There were no significant differences in mean percent change from set 1 to set 2 between the occlusion conditions. There were no significant differences between any conditions in mean percent change from set 2 to set 3.

Flexion: There were no significant differences in initial peak torque within any of the sets between the conditions. Further, there were no significant differences in mean percent change from set 1 to 2 as well as set 2 to 3 in initial peak torque between any conditions. Means are displayed in Figure 5a, while mean percent change values are displayed in Figure 5b.

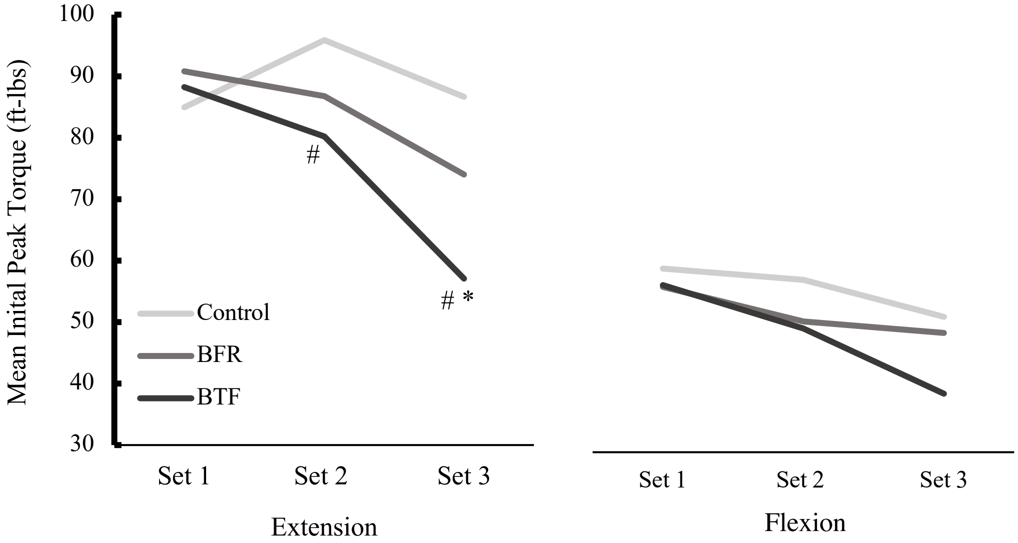

Figure 5a. Initial peak torque during extension and flexion. # = *Significantly different from CON; * = Significant difference within condition. BFR = blood flow restriction; BTF = band tissue flossing.*

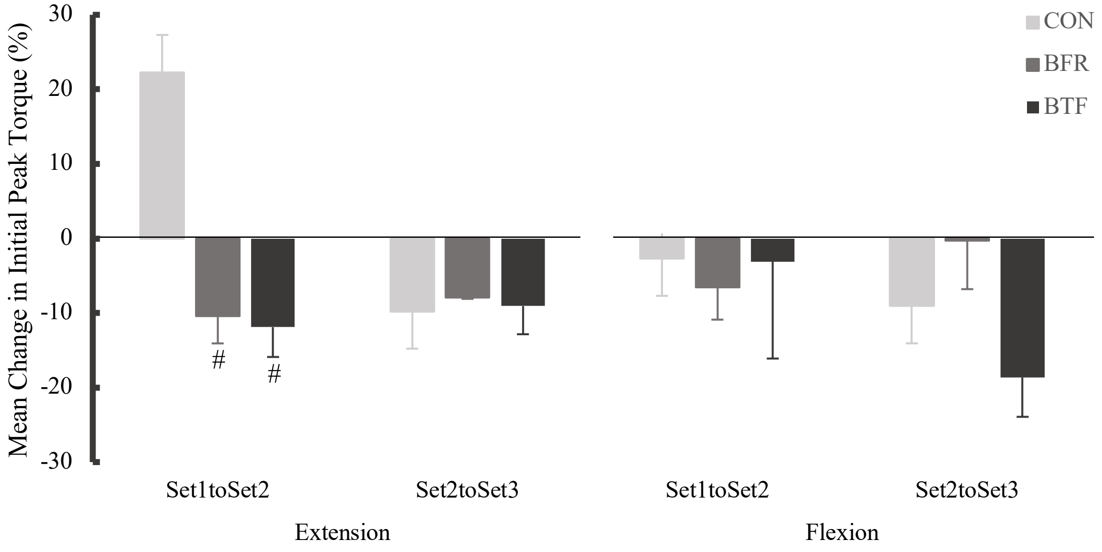

Figure 5b. Mean percent change in initial peak torque between sets during extension and flexion. *# = Significantly different from CON. CON = control; BFR = blood flow restriction; BTF = band tissue flossing.*

Average power per rep: between sets, within conditions

Extension: There were no significant differences in average power per rep between sets during both the CON and BFR conditions. However, a main effect was found during the BTF condition, F(2, 26) = 27.16, η2 = 0.676 in which average power per rep is significantly less in sets 2 and 3 than during set 1, p = 0.035 and p < 0.001, respectively.

Flexion: There were no significant differences during flexion within any of the conditions.

Average power per rep: within sets, between conditions

Extension: There were no significant differences between the groups during set 1. In set 2, mean average power per rep during BTF was significantly less than during CON, F(2, 26) = 6.95, p = 0.004, η2 = 0.348. Similarly, mean average power per rep during set 3 was significantly less in BTF compared to CON, F(2, 26) = 9.19, p < 0.001, η2 = 0.414. There were no significant differences between BTF and BFR or BFR and CON during sets 2 and 3. There were no significant differences in mean percent change from set 1 to set 2 between CON and BFR or BFR and BTF. However, mean percent change from set 1 to set 2 was significantly greater in BTF than in CON, p = 0.012, as BTF produced a 20% greater reduction in average power per rep. There were no significant differences in mean percent change from set 2 to set 3 between any conditions.

Flexion: There were no significant differences between conditions during sets 1 and 3. In set 2, mean average power per rep was significantly less in BTF compared to CON, mean difference, F(2, 26) = 5.63, p = 0.009, η2 = 0.302. There were no significant differences between BTF and BFR or BFR and CON during set 2. There were no significant differences in mean percent change scores between sets during flexion within any of the conditions. Means are displayed in Figure 6a, while mean percent change values are displayed in Figure 6b.

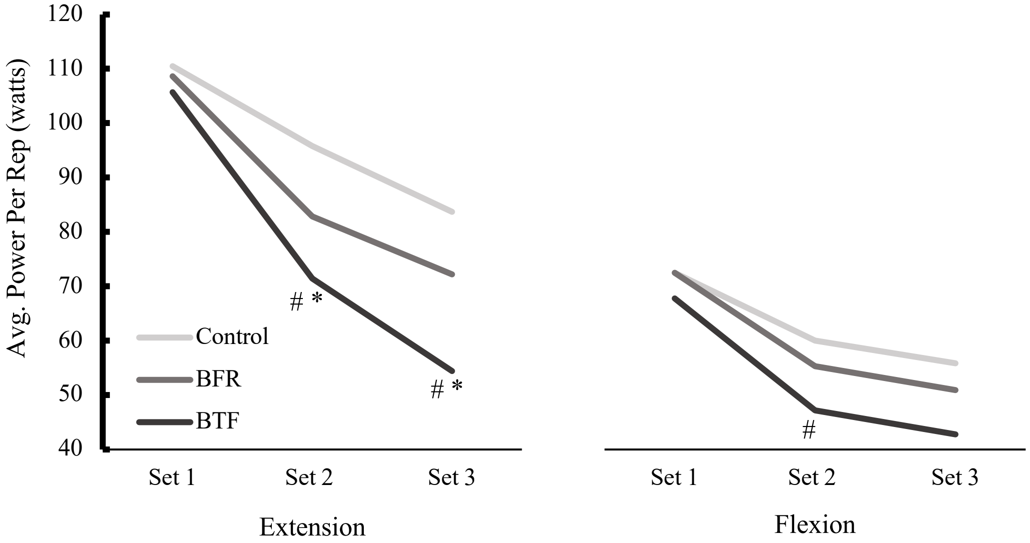

Figure 6a. Average power per rep during extension and flexion. # = *Significantly different from CON; * = Significant difference within condition. CON = control; BFR = blood flow restriction; BTF = band tissue flossing.*

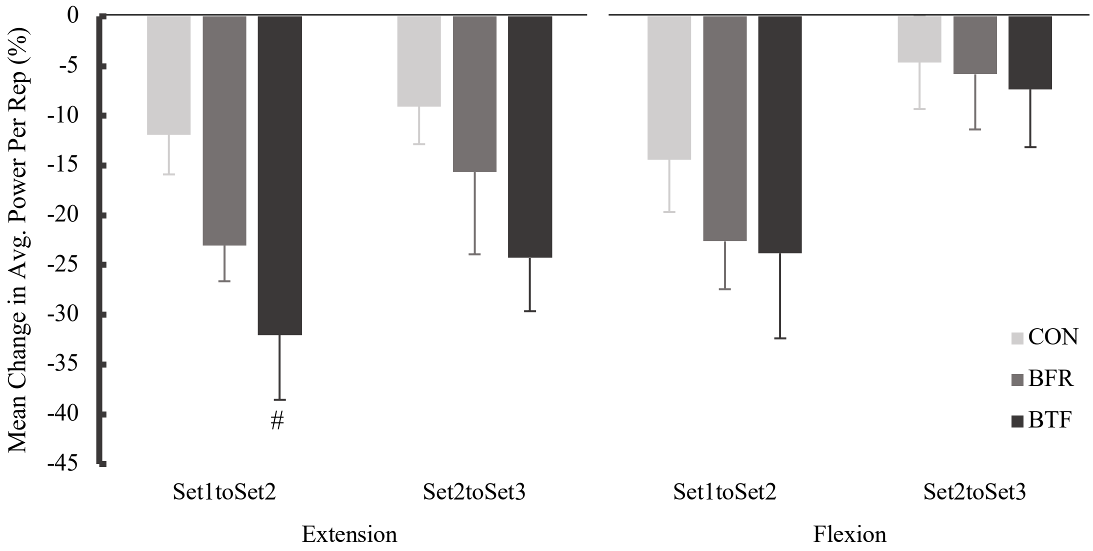

Figure 6b. Mean percent change in average power per rep between sets during extension and flexion. *# = Significantly different from CON. CON = control; BFR = blood flow restriction; BTF = band tissue flossing.*

Total work performed: between sets, within conditions

Extension: There were no significant differences in total work performed between sets during either the CON or BFR conditions, though differences between sets 1 and 3 were nearing significance, $p = 0.055$ in the BFR condition. During BTF, a main effect was found, $F(2, 26) = 14.39$, $\eta 2 = 0.662$. Total work performed during BTF was significantly less during sets 2 and 3 than during set 1, $p = 0.028$ and $p < 0.001$, respectively.

Flexion: No significant differences were found between sets during flexion for any of the conditions, though the difference between set 1 and 3 was approaching significance in the BTF condition, $p = 0.060$.

Total work performed: within sets, between conditions

Extension: There were no significant differences in total work performed during set 1 between conditions. During set 2, a main effect was found, $F(2, 26) = 22.91$, $\eta 2 = 0.421$. Means were significantly less in BFR than CON, $p = 0.046$, as well as during BTF and CON, $p = 0.004$, though not significantly different between BFR and BTF. During set 3, means were significantly less during BTF than CON, $F(2, 26) = 21.99$, $p < 0.001$, $\eta 2 = 0.479$, though not significantly different between BFR and CON or BTF and BFR. There were no significant differences in mean percent change in total work done from set 1 to set 2 between CON and BFR as well as between BFR and BTF. However, mean percent change during BTF was significantly greater than during CON, $p = 0.022$, as BTF caused an average 19% greater reduction in work performed than CON. There were no significant differences in mean percent change from set 2 to 3 between conditions, though the difference between CON and BTF was approaching significance, $p = 0.078$.

Flexion: There were no significant differences in total work performed during sets 1 or 3 between conditions. During set 2, means were significantly less during BTF than CON, $F(2, 26) = 6.13$, $p = 0.040$, $\eta 2 = 0.320$. The difference in means between BFR and BTF was approaching significance, $p = 0.053$. Differences between BFR and CON were not significant. During set 3, difference in means between BTF and CON was approaching significance, $p = 0.082$. There were no significant differences in mean percent change in total work done from set 1 to set 2 as well as set 2 to 3 during flexion between any of the conditions. Means are displayed in Figure 7a, while mean percent change values are displayed in Figure 7b.

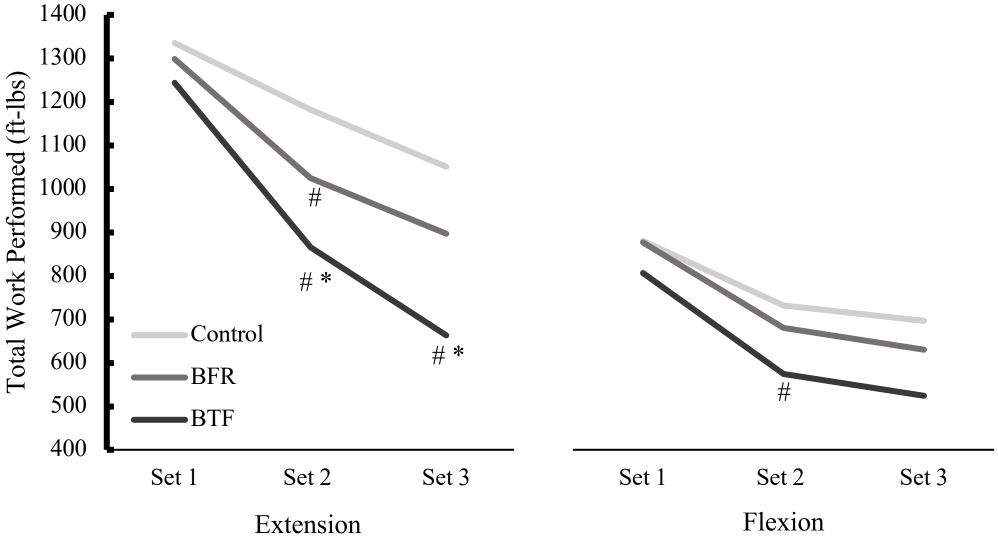

Figure 7a. Total work performed during extension and flexion. # = *Significantly different from CON.* * = *Significant difference within condition. CON = control; BFR = blood flow restriction; BTF = band tissue flossing.*

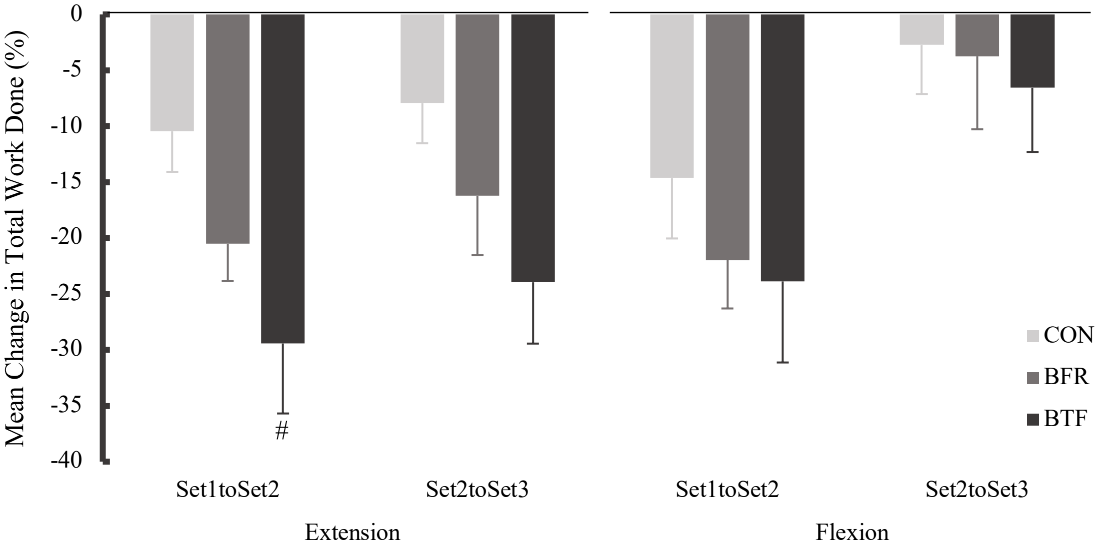

Figure 7b. Mean percent change in total work done between sets during extension and flexion. # = *Significantly different from CON. CON = control; BFR = blood flow restriction; BTF = band tissue flossing.*

Electromyography

No significant differences were identified between the average amplitudes of all 9 reps within each set between conditions, nor within any of the separate groupings of reps between the conditions. There were also no significant differences in any of the change values between conditions.

Analysis of the average amplitudes between sets within conditions revealed significant differences. In the control condition, set1avg was not significantly different than set 2, nor set 2 from set 3. However, set1avg was significantly greater than set3avg, $F(2, 13) = 5.45$, $p = 0.027$, $\eta2 = 0.280$. In the BFR condition, set1avg was significantly greater than set2avg, $F(2, 11) = 13.22$, $\eta2 = 0.524$, $p = 0.012$, as was set2avg than set3avg, $p = 0.038$, and set1avg than set3avg, $p = 008$. Similar to the BFR condition, set averages within the BTF condition also showed significant differences, though set2avg was not significantly different from set3avg. Set1avg was significantly greater than set2avg, $F(1, 13) = 21.91$, $\eta2 = 0.628$ $p = 0.005$, as was set1avg than set3avg, $p < 0.001$. Means are displayed in Figures 8a and 8b.

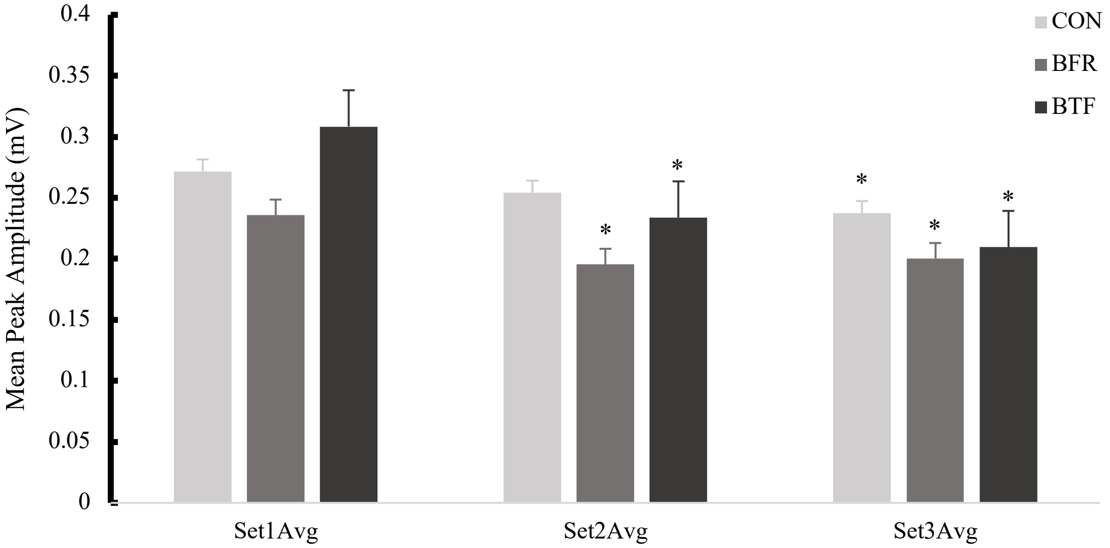

Figure 8a. Mean peak amplitudes for all 9 reps within a set. SEM displayed as error bars. * = *Significant difference within condition. CON = control; BFR = blood flow restriction; BTF = band tissue flossing.*

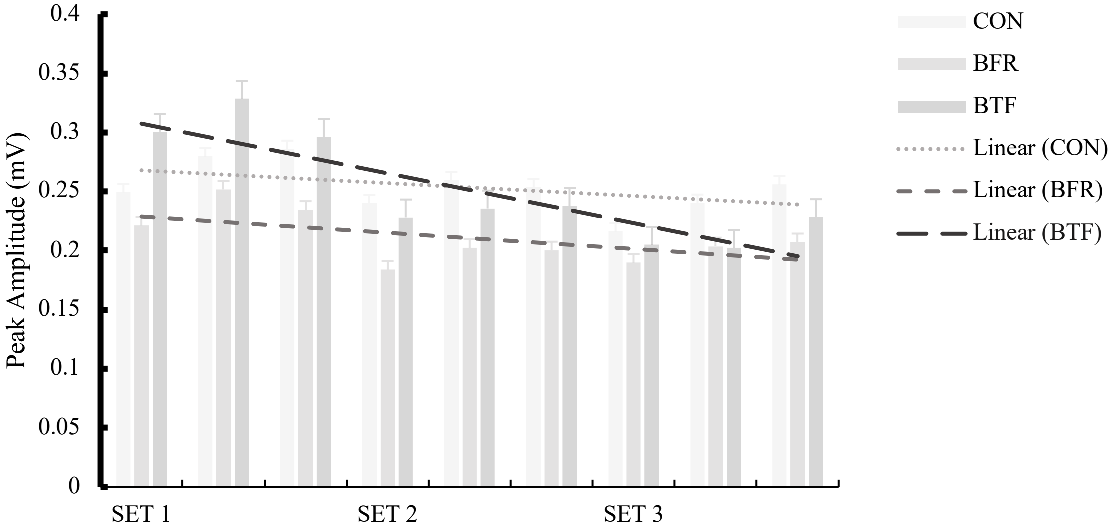

Figure 8b. Mean peak amplitudes and linear trendlines for the first 3 reps, middle 3 reps, and last 3 reps of each set between conditions. SEM displayed as error bars. CON = control; *BFR = blood flow restriction; BTF = band tissue flossing.*

Acute Responses to Conditions Post-Exercise

Heart rate

No significant differences were found for HR immediately post- as well as 1-minute post-exercise between conditions. Further, no significant differences were found between change scores for HR from immediately-post to 1-minute post-exercise within conditions.

In the control condition, HR immediately post- and 1-minute post-exercise was significantly greater than pre-, $t(14) = 7.93$, $p < 0.001$, $d = 2.05$, and $t(14) = 4.72$, $p < 0.001$, $d = 1.22$, respectively. Similarly, in the BFR condition, heart rate immediately post- and 1-minute post-exercise was significantly greater than pre-, $t(13) = 9.75$, $p < 0.001$, $d = 2.61$ and $t(12) = 3.70$, $p = 0.003$, $d = 1.03$, respectively. Again, in the BTF condition, heart rate immediately post- and 1-minute post-exercise was significantly greater than pre-, $t(13) = 8.43$, $p < 0.001$, $d = 2.25$ and $t(13) = 5.09$, $p < 0.001$, $d = 1.36$, respectively. All findings for HR are summarized in Appendix G.

Glucose

Post-exercise glucose measurements were significantly different from pre-exercise measurements within the CON and BTF conditions, but not BFR. In the CON condition, glucose levels immediately post- and 1-minute post-exercise were significantly less than pre-exercise, $p = 0.033$ and $p = 0.027$, respectively. In the BTF condition, glucose levels immediately post- and 1-minute post-exercise were also significantly less than pre-exercise, $p = 0.009$ and $p = 0.017$, respectively. There were no significant differences in glucose pre-exercise nor immediately post-exercise between the conditions. A main effect was found in glucose levels 1-minute post-exercise $F(2, 22) = 2.15$, $\eta 2 = 0.164$. Pairwise testing revealed mean glucose 1-minute post-exercise was significantly less in BFR than BTF, $p < 0.001$ as well as in BFR than CON, $p <$

0.001, but not significantly different between BTF and CON. No significant differences were found in change scores calculated between glucose immediately post- and 1-minute post-exercise for each condition. Findings are displayed in Figure 9 and summarized in appendix H.

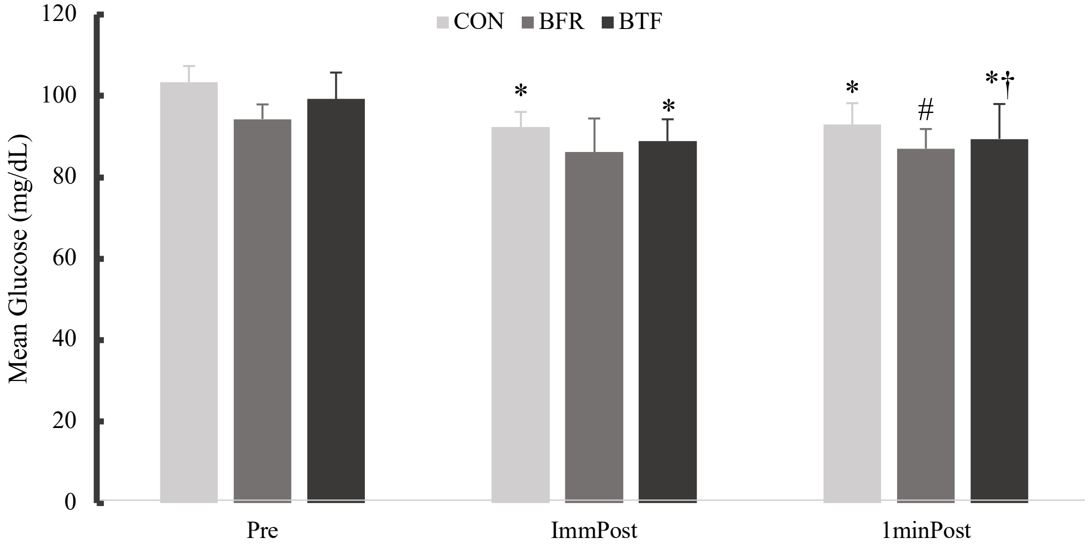

Figure 9. Mean blood glucose across time between conditions. * *= Significantly different from pre-measurement within condition. # = Significantly different from CON. † = Significantly different from BFR. CON = control; BFR = blood flow restriction; BTF = band tissue flossing.*

Lactate

Within all conditions, blood lactate immediately post-exercise was significantly greater than pre-exercise: CON, $p < 0.001$; BFR, $p < 0.001$; BTF, $p < 0.001$. Further, blood lactate 1-minute post-exercise remained significantly greater than pre-exercise in all conditions: CON, $p = 0.002$; BFR, $p < 0.001$; BTF, $p < 0.001$. No significant differences were found in lactate immediately post- as well as 1-minute post-exercise between the conditions, nor were any significant differences found between change scores for the post-exercise measurements between conditions. Findings are displayed in Figure 10 and summarized in Appendix I.

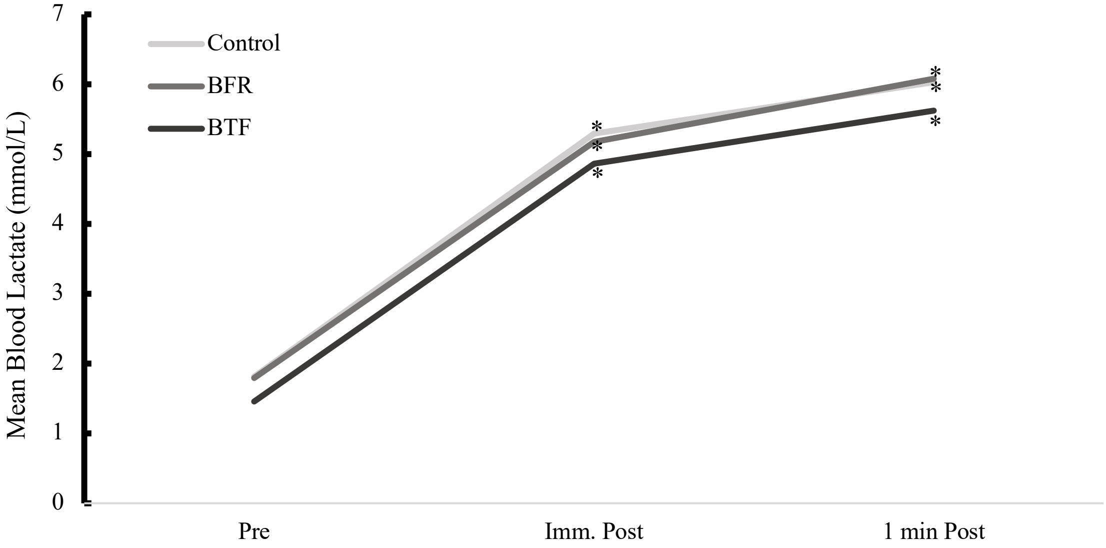

Figure 10. Mean blood lactate (mmol/L) across time between conditions. * = *Significantly different from pre- measurement within condition. CON = control; BFR = blood flow restriction; BTF = band tissue flossing.*

Thigh Circumference Interactions

For exploratory analysis, participants in this study were divided into three groups based on thigh circumference (51-55.9cm, 56-59.9cm, and >60cm) and heart rate, lactate, glucose, and arterial flow outcome measures assessed for interactions. This analysis revealed a main effect in number of revolutions achieved with BTF, F(2, 14) = 7.33, p = 0.008. The number of revolutions achieved with BTF was significantly different between those with the middle level of thigh circumference (M ± SD = 5.40 ± 0.55) and the largest thigh circumference (M ± SD = 4.25 ± 0.61). However, no other outcome measurements were significantly different depending on thigh circumference, suggesting thigh circumference may not have directly influenced response to occlusion. Results of this analysis are provided in Appendix J.

DISCUSSION

The purpose of this study was to compare the efficacy on induction of muscular fatigue of two different methods for occlusion exercise, BFR and BTF with a new, potentially standardizable protocol for consistent BTF application. The primary finding was that BTF causes similar, even exaggerated, decreases in blood flow, accelerations in muscular fatigue, and accumulations in metabolites compared to BFR. While the magnitudes to which both occlusion conditions influenced HR were not significantly different from each other, a mutual difference from CON was not identified in any measures.

This study demonstrated that BTF using this protocol occludes significantly more blood flow than a BFR cuff set to 50% occlusion pressure. BFR at 50% was not significantly different from CON in the magnitude to which arterial blood flow was changed; however, BTF caused significantly greater reductions in flow compared to CON and BFR. While BFR at 50% occlusion pressure caused a 12.36% reduction in volume flow at the tibial artery compared to CON, BTF caused a 32.51% reduction, more than twice as much as BFR. A recent study by Vogrin *et al* (2020) identified “high pressure” using a BTF band as 150-210mmHg, depending on thigh circumference. This “high pressure” was assumed to be comparable to BFR occlusion at 60% (though blood flow was not measured in the Vogrin study) (Vogrin et al., 2020). Based on the Vogrin study and BTF’s demonstration of occluding more blood flow than BFR at 50% in the present study, the use of BTF in this protocol is likely applying “high” pressure, though exact pressure was unable to be measured in the present study.

This high level of occlusion by BTF is further demonstrated by increased rate of fatigue. In this study, BTF was more fatiguing than CON, causing significant reductions in performance compared to CON across all measures. Interestingly, BFR was neither significantly different from BTF or CON. With BFR applying the ‘medium’ pressure here, this finding is consistent with the current literature. According to Gepfert *et al* (2020), BFR at 150% of arterial occlusion pressure during a 3x3 back squat protocol caused significant changes to performance compared to CON, while BFR at 100% arterial occlusion did not (Gepfert et al., 2020). Contradictory to the present study, though, the Gepfert *et al* study found that power increased with application of BFR. This is most likely due to differences between protocols, notably the number of reps and time under occlusion. In the Gepfert *et al*. study, BFR was removed for 3 minutes between each set, allowing time for reperfusion and probable clearance of local metabolic byproducts that was not allowed in this protocol.

Fatigue, as measured by the dynamometer, was not significantly different within conditions for the flexion part of the exercise, though it was for extension. One potential explanation for this could be that less work was done by the flexors than the extensors, for which there could be several reasons. First, the initiation of the exercise on the Humac Norm is the extension, which could be influencing the participant’s perception that the flexion is simply resetting for each extension. Also potentially altering the participant’s perception could be the placement of EMG electrodes on the quads, but not the hamstrings. This could mislead a participant to believing the most important part of the rep should be the extension. Additionally, because of the small sample size, it is possible that the participants all had stronger or better-conditioned extensors than flexors. Regardless, it is not likely that occlusion causes fatigue in the extensor muscles, but not the flexors.

In the present study, no significant differences were found in the EMG data between the conditions. Though pressure was not measured in this study, this finding is consistent with previous studies on high-pressure occlusion and muscle activation. Loenneke *et al* (2015) found that BFR at 50% results in the most robust muscle activation, but then plateaus, suggesting that increasing occlusion pressure does not produce significant increases in muscle activation (Loenneke et al., 2015). This plateau at 50% pressure may be why BTF, which occluded more blood flow than BFR, did not produce EMG amplitudes different from what was seen in BFR. However, it is interesting that EMG amplitudes during the occlusion conditions were not significantly different than during CON. A prior study, using low-pressure BFR (140mmHg), demonstrated that BFR elicits greater muscle activity than CON conditions during supine lying electromagnetic stimulation (Chen et al., 2018). Based on the present study, as well as the Loenneke 2015 study, this trend may not be observed during high-pressure BFR. The lack of difference in muscle activation during the protocols in the present study could also be attributed to the configuration of the electrodes used. There is evidence that a monopolar configuration for surface EMG leads to less signal error by eliminating the need for the two electrodes to remain in line with the muscle fiber direction throughout exercise (Mohr et al., 2018). Further, a monopolar configuration is capable of detecting differences when comparing BFR and CON conditions even when bipolar configuration did not (Hotta & Ito, 2011).

Overall, the conditions were relatively comparable in their impacts on glucose uptake. This is interesting, though, considering total work performed for both extensors and flexors across all of the sets was decreased in the occlusion conditions. The reason for this is hypothesized to be because exercise and hypoxia stimulate glucose transport by the same mechanism, independent of insulin (Cartee et al., 1991). Only the CON and BTF conditions caused glucose uptake that was significant when comparing pre- and post-exercise glucose levels within conditions. Further, none of the pre-exercise glucose levels across conditions were significantly different. However, measures taken 1-minute post-exercise across conditions were significantly different when comparing BFR and CON as well as BFR and BTF. In this measurement, BTF sits in the middle between BFR and CON. However, this does not mean that BFR influences glucose uptake to a greater extent. In fact, percent changes to blood glucose levels showed no differences between the conditions, meaning this difference with BFR in the 1-minute post- data is probably an artifact of having a small sample size.

All of the conditions caused significant increases in lactate post-exercise. However, these changes were not significantly different between the conditions. Exercising with hypoxia caused by BFR significantly increases lactate when compared to non-occlusion exercise of the same volume (Gundermann et al., 2012). Although the present study attempted to control for total volume, there was no plausible way to account for rate of muscular fatigue. Since participants performed less work during the occlusion conditions, this could have resulted in the lack of differences in lactate.

One of the major limitations of this study is that the response to occlusion may be individualized based on a variety of factors, including body composition and response of the vasculature. The Vogrin *et al* study divided participants into three groups based on thigh circumference (51-55.9cm, 56-59.9cm, and >60cm) to assess for differences in response to occlusion between groups (Vogrin et al., 2020). In the present study, the only main effect found existed, not surprisingly, between number of revolutions achieved with the BTF band and thigh circumference. No other outcome measurements were significantly different depending on thigh circumference, suggesting thigh circumference may not have directly influenced the physiological response to occlusion.

The exercise pressor reflex (EPR) may also influence response to occlusion. During intense resistance exercise, blood vessels within the active muscle vasodilate through a process called active hyperemia to accommodate the increased need for oxygen delivery. Concurrently, sympathetic innervation causes vasoconstriction of vessels peripheral to the active muscle in an effort to preserve resources. BFR reduces outflow of this blood in order to accentuate the metabolic environment, upregulating hypertrophic pathways. The EPR is known to be engaged even at mild-intensity exercise and presumed to be exaggerated under BFR conditions (Spranger et al., 2015). The effects of this reflex could be evidenced in the present study's data, in which several participants experienced increases, rather than decreases, in arterial analysis measures following occlusion (Appendix K). EPR is known to be influenced by a variety of factors, including mental stress (Durocher et al., 2011), dietary sodium intake (Babcock et al., 2020), blood pressure (Greaney et al., 2014; Muller et al., 2012), muscle mass and contraction intensity (Iellamo et al., 1999), and training status (Mostoufi-Moab et al., 1998), giving this the potential to be both extremely variable and influential in creating differences between participants.

Other limitations to this study include the inability to measure the exact amount of pressure provided by the BTF bands as well as limited diversity among study participants. Because of this, the results of this study may not be generalizable to children and adults outside of the included age range, nor to adults with different health conditions.

With very limited research on BTF, there are plenty of future studies that could be conducted. An interesting comparison for this study would have been to collect performance measures (MVMC) pre- and post-exercise as well, to elucidate the existence of any acute neuromuscular benefits. Vogrin *et al* reported increases in post-exercise MVMC following low-pressure BTF application during exercise (Vogrin et al., 2020), while Yasuda *et al* (2008) reported depressions in MVMC following 147mmHg BFR (Yasuda et al., 2008). Further, measuring post-exercise lactate for up to an hour might have revealed significant differences. This is based on data from Gundermann *et al* (2012), which showed that lactate 1-hour post-exercise was significantly higher when exercise was performed with BFR than without (Gundermann et al., 2012). Finally, there is a need for more research exploring the pressure exerted by BTF bands across a much wider demographic of individuals.

In conclusion, BTF appears to be comparable to a high-level occlusion method for BFR. Because BTF applies pressure across a greater surface area than BFR, it is probable that BTF requires less pressure to occlude blood flow (Loenneke et al., 2012) and may also result in less discomfort, which has been observed in prior studies (Dankel et al., 2017). BTF causes significantly greater muscular fatigue than non-occlusion resistance exercise, though this fatigue is not significantly different from BFR. Overall, BFR and BTF are similarly efficacious in exaggerating muscular fatigue during resistance exercise.

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APPENDIX

Appendix A. Condition assignments for all participants.

	Condition 1	Condition 2	Condition 3
CON	n = 3	n = 7	n = 5
BFR	n = 9	n = 1	n = 5
BTF	n = 3	n = 7	n = 5

CON = control; BFR = blood flow restriction; BTF = band tissue flossing.

Appendix B. Outcome for statistical assumptions for variables being used in paired-samples t-tests checked before data analysis. Normality was inspected by the Shapiro Wilk test as well as visual observation of Q-Q plots and histograms generated in SPSS. When the normality assumption was violated, nonparametric tests were used, indicated by ‡.

Variable	Mean ± SD	Normality (Shapiro-Wilk)
BMI	21.34 ± 3.62	Met
% Body Fat	26.27 ± 6.37	Met
Thigh Length	42.07 ± 4.23	Met
Thigh Circumference	59.93 ± 6.04	Met
# of Revolutions of BTF	4.83 ± 0.70	Met
LOP (BFR)	192.93 ± 18.05	Met
CONHRPre	76.50 ± 10.83	Met
CONHRImmPost	131.08 ± 31.75	Met
CONHR1minPost	98.00 ± 24.07	Met
CONHRImmPostvs1minPost	33.08 ± 17.00	Met
BFRHRPre	73.79 ± 8.65	Met
BFRHRPostOcc	77.67 ± 12.66	Met
BFRHRImmPost	135.46 ± 23.17	Met
BFRHR1minPost	93.46 ± 18. 36	Met
BFRHRImmPostvs1minPost	40.69 ± 13.85	Met
BTFHRPre	76.00 ± 13.86	Met
BTFHRPostOcc	82.07 ± 12.04	Met
BTFHRImmPost	131.38 ± 29.24	Met
BTFHR1minPost	93.38 ± 19.81	Met
BTFHRImmPostvs1minPost	38.00 ± 14.08	Met
CONLactatePre	1.81 ± 0.86	Met
CONLactateImmPost	5.46 ± 2.50	Met
CONLactate1minPost	6.27 ± 3.20	Met
BFRLactatePre	1.79 ± 0.47	Met
BFRLactateImmPost	5.45 ± 2.03	Met
BFRLactate1minPost	6.24 ± 1.77	Met
BTFLactatePre	1.46 ± 0.53	Met
BTFLactateImmPost	4.86 ± 2.19	Violated‡

BTFLactate1minPost	5.81 ± 2.83	Met
CONGlucosePre	103.36 ± 12.77	Met
CONGlucoseImmPost	92.33 ± 8.05	Met
CONGlucose1minPost	94.08 ± 9.18	Met
BFRGlucosePre	94.33 ± 11.17	Violated[‡]
BFRGlucoseImmPost	86.83 ± 8.09	Met
BFRGlucose1minPost	87.42 ± 9.41	Met
BTFGlucosePre	99.23 ± 9.45	Met
BTFGlucoseImmPost	88.92 ± 5.93	Met
BTFGlucose1minPost	89.50 ± 6.67	Met
CONDistPre	0.22 ± 0.02	Met
CONDistPost	0.22 ± 0.02	Met
CONTAMVPre	5.09 ± 2.62	Met
CONTAMVPost	5.06 ± 2.25	Met
CONVolFlowPre	15.35 ± 11.53	Met
CONVolFlowPost	11.34 ± 4.32	Met
CONAreaPre	0.05 ± 0.02	Violated[‡]
CONAreaPost	0.04 ± 0.01	Met
BFRDistPre	0.25 ± 0.25	Met
BFRDistPost	0.24 ± 0.04	Met
BFRTAMVPre	5.47 ± 3.31	Met
BFRTAMVPost	4.26 ± 1.83	Met
BFRVolFlowPre	15.71 ± 9.78	Violated[‡]
BFRVolFlowPost	11.09 ± 6.61	Met
BFRAreaPre	0.05 ± 0.02	Met
BFRAreaPost	0.04 ± 0.01	Met
BTFDistPre	0.26 ± 0.05	Met
BTFDistPost	0.22 ± 0.03	Violated[‡]
BTFTAMVPre	6.05 ± 3.46	Violated[‡]
BTFTAMVPost	5.21 ± 2.65	Met
BTFVolFlowPre	20.55 ± 10.49	Met
BTFVolFlowPost	13.56 ± 9.50	Met
BTFAreaPre	0.06 ± 0.02	Met
BTFAreaPost	0.04 ± 0.02	Met

Appendix C. Outcome for statistical assumptions for variables being used in repeated measures ANOVAs checked before data analysis. Sphericity was tested using Mauchly's *W*. If sphericity was violated, the non-parametric Kruskal-Wallis independent samples test was used, indicated by ‡. Kruskal-Wallis asymptotic significance provided when applicable.

Variable	**Sphericity**					**Kruskal-Wallis Asymp. Sig.**
		Mauchly's *W*	**χ^2**	***df***	**p-value**	
HRPre	Met	0.81	2.49	2	0.287	
HRImmPost	Met	0.88	1.38	2	0.502	
HR1minPost	Violated‡	0.27	14.24	2	<0.001	0.790
HRImmPostvs1minPost	Violated‡	0.54	6.71	2	0.035	0.641
DistPre	Met	0.93	1.00	2	0.606	
DistPost	Met	0.67	2.37	2	0.306	
TAMVPre	Met	0.76	3.29	2	0.193	
TAMVPost	Met	0.65	2.60	2	0.272	
VolFlowPre	Met	0.73	3.81	2	0.149	
VolFlowPost	Met	0.74	1.83	2	0.400	
AreaPre	Met	0.97	0.37	2	0.830	
AreaPost	Met	0.57	3.43	2	0.180	
MeanPercChangeinDist	Met	0.64	2.67	2	0.263	
MeanPercChangeinTAMV	Met	0.75	1.72	2	0.422	
MeanPercChangeinVolFlow	Met	0.82	1.19	2	0.551	
MeanPercChangeinArea	Met	0.61	3.01	2	0.222	
LactatePre	Met	0.81	2.47	2	0.291	
LactateImmPost	Met	0.91	1.12	2	0.571	
Lactate1minPost	Met	0.90	1.21	2	0.545	
LactateImmPostvs1minPost	Met	0.82	2.41	2	0.299	
GlucosePre	Met	0.92	0.84	2	0.656	
GlucoseImmPost	Met	0.83	1.89	2	0.390	
Glucose1minPost	Violated‡	0.46	7.82	2	0.020	<0.001
GlucoseImmPostvs1minPost	Met	0.99	0.06	2	9.720	
CONGlucose	Violated‡	0.269	14.435	2	<0.001	0.042
BFRGlucose	Violated‡	0.338	14.102	2	<0.001	0.08
BTFGlucose	Violated‡	0.142	21.465	2	<0.001	0.015

CONInPeakTorqExt	Violated[‡]	0.54	7.32	2	0.026	0.674
BFRInPeakTorqExt	Violated[‡]	0.50	8.35	2	0.015	0.525
BTFInPeakTorqExt	Met	0.64	5.35	2	0.069	
CONInPeakTorqFlex	Met	0.67	4.86	2	0.088	
BFRInPeakTorqFlex	Violated[‡]	0.47	8.95	2	0.011	0.662
BTFInPeakTorqFlex	Violated[‡]	0.49	8.60	2	0.014	0.112
MeanPercChangeInPeakExt1to2	Violated[‡]	0.036	39.725	2	<0.001	<0.001
MeanPercChangeInPeakExt2to3	Violated[‡]	0.052	35.429	2	<0.001	0.089
MeanPercChangeInPeakFlx1to2	Violated[‡]	0.212	18.596	2	<0.001	0.348
MeanPercChangeInPeakFlx2to3	Met	0.996	0.042	2	0.979	
CONAvgPowPerRepExt	Violated[‡]	0.54	7.44	2	0.024	0.249
BFRAvgPowPerRepExt	Violated[‡]	0.27	15.81	2	<0.001	0.068
BTFAvgPowPerRepExt	Violated[‡]	0.57	6.77	2	0.034	0.004
CONAvgPowPerRepFlex	Violated[‡]	0.48	8.81	2	0.012	0.343
BFRAvgPowPerRepFlex	Violated[‡]	0.27	15.71	2	<0.001	0.085
BTFAvgPowPerRepFlex	Violated[‡]	0.30	14.34	2	<0.001	0.070
MeanPercChangeAvgPowExt1to3	Met	0.941	0.727	2	0.695	
MeanPercChangeAvgPowExt2to3	Met	0.628	5.581	2	0.061	
MeanPercChangeAvgPowFlx1to2	Met	0.861	1.794	2	0.408	
MeanPercChangeAvgPowFlx2to3	Met	0.931	0.856	2	0.652	
CONTotWorkDoneExt	Violated[‡]	0.46	9.41	2	0.009	0.256
BFRTotWorkDoneExt	Violated[‡]	0.27	15.82	2	<0.001	0.055
BTFTotWorkDoneExt	Violated[‡]	0.53	7.69	2	0.021	0.002
CONTotWorkDoneFlex	Violated[‡]	0.52	7.94	2	0.190	0.445
BFRTotWorkDoneFlex	Violated[‡]	0.32	13.72	2	0.001	0.110
BTFTotWorkDoneFlex	Violated[‡]	0.36	12.22	2	0.002	0.060
MeanPercChangeTotWorkExt1to2	Met	0.885	1.465	2	0.481	
MeanPercChangeTotWorkExt2to3	Met	0.902	1.237	2	0.539	
MeanPercChangeTotWorkFlx1to2	Met	0.922	0.973	2	0.615	
MeanPercChangeTotWorkFlx2to3	Met	0.772	3.100	2	0.212	
InPeakTorqSet1Ext	Met	0.90	1.30	2	0.521	
InPeakTorqSet2Ext	Met	0.95	0.59	2	0.746	
InPeakTorqSet3Ext	Met	0.90	1.25	2	0.534	
InPeakTorqSet1Flex	Met	0.86	1.84	2	0.399	
InPeakTorqSet2Flex	Met	0.99	0.12	2	0.941	
InPeakTorqSet3Flex	Met	0.98	0.24	2	0.887	
TotWorkDoneSet1Ext	Met	0.95	0.66	2	0.719	
TotWorkDoneSet2Ext	Met	0.83	2.23	2	0.328	
TotWorkDoneSet3Ext	Met	0.78	2.99	2	0.224	

TotWorkDoneSet1Flex	Met	0.83	2.31	2	0.316	
TotWorkDoneSet2Flex	Met	0.80	2.66	2	0.265	
TotWorkDoneSet3Flex	Met	0.64	5.38	2	0.072	
AvgPowPerRepSet1Ext	Violated‡	0.59	6.19	2	0.450	0.904
AvgPowPerRepSet2Ext	Met	0.92	0.94	2	0.624	
AvgPowPerRepSet3Ext	Met	0.89	1.46	2	0.482	
AvgPowPerRepSet1Flex	Met	0.97	0.31	2	0.856	
AvgPowPerRepSet2Flex	Met	0.95	0.64	2	0.727	
AvgPowPerRepSet3Flex	Met	0.84	2.11	2	0.349	
EMGSet1Avg	Violated‡	0.21	17.40	2	<0.001	0.574
EMGSet2Avg	Violated‡	0.28	12.75	2	0.002	0.607
EMGSet3Avg	Violated‡	0.28	14.15	2	<0.001	0.604
EMGSet1First3	Violated‡	0.32	12.49	2	0.002	0.624
EMGSet1Middle3	Violated‡	0.18	18.98	2	<0.001	0.563
EMGSet1Last3	Violated‡	0.25	15.22	2	<0.001	0.592
EMGSet2First3	Violated‡	0.51	6.81	2	0.033	0.728
EMGSet2Middle3	Violated‡	0.24	14.33	2	0.001	0.589
EMGSet2Last3	Violated‡	0.27	12.97	2	0.002	0.605
EMGSet3First3	Violated‡	0.30	12.07	2	0.002	0.616
EMGSet3Middle3	Violated‡	0.32	12.63	2	0.002	0.622
EMGSet3Last3	Violated‡	0.27	14.57	2	0.001	0.599
EMGChange1	Met	0.74	3.87	2	0.145	
EMGChange2	Violated‡	0.23	19.30	2	<0.001	0.156
EMGChange3	Violated‡	0.31	15.13	2	<0.001	0.651
EMGChange4	Violated‡	0.48	9.45	2	0.009	0.398
EMGChange5	Met	0.97	0.36	2	0.837	
EMGChange6	Violated‡	0.61	6.53	2	0.038	0.583
EMGChange7	Met	0.86	1.94	2	0.379	
EMGChange8	Met	0.81	2.79	2	0.248	

Appendix D. Means and change values for arterial flow measurement between conditions.

		CON (n=8)	**BFR (n=15)**	**BTF (n=15)**
Dist	Mean Pre	0.25 ± 0.04	0.25 ± 0.04	0.26* ± 0.05
	Mean Post	0.22 ± 0.02	0.24 ± 0.04	0.22* ± 0.03
	Mean ΔPre-Post	0.00 ± 0.01	0.00 ± 0.04	0.04† ± 0.04
	Mean % Δ	0.99 ± 0.00	0.30 ± 14.53	14.58† ± 11.55
TAMV	Mean Pre	5.36 ± 2.73	5.48* ± 3.19	6.05 ± 3.46
	Mean Post	5.06 ± 2.25	4.44* ± 2.66	5.32 ± 2.49
	Mean ΔPre-Post	-0.06 ± 0.85	1.03 ± 1.65	0.73 ± 2.31
	Mean % Δ	0.99 ± 0.00	16.58 ± 21.76	8.85 ± 29.19
VolFlow	Mean Pre	15.91 ± 11.31	15.37 ± 9.52	20.55* ± 10.49
	Mean Post	11.34 ± 4.32	12.18 ± 7.16	12.99* ± 7.63
	Mean ΔPre-Post	-0.01 ± 1.71	3.19 ± 7.79	7.56 ± 6.88
	Mean % Δ	0.99 ± 0.00	15.15 ± 36.50	33.50 ± 28.24
Area	Mean Pre	0.05 ± 0.02	0.05 ± 0.02	0.06* ± 0.02
	Mean Post	0.04 ± 0.01	0.05 ± 0.02	0.04* ± 0.15
	Mean ΔPre-Post	0.00 ± 0.00	0.00 ± 0.02	0.02 ± 0.01
	Mean % Δ	0.99 ± 0.00	1.46 ± 34.82	29.88$^{\#\dagger}$ ± 21.06

*# = Significantly different from CON; † = Significantly different from BFR; * = Significantly different from pre- measurement within condition. CON = control; BFR = blood flow restriction; BTF = band tissue flossing; Dist = distance; TAMV = time-averaged mean velocity; VolFlow = volume flow.*

Appendix E. Descriptive Statistics (M ± SD) on Isokinetic Dynamometry Data

		CON	**BFR**	**BTF**
Extension	InPeakTorqSet1	84.93 ± 36.98	90.79 ± 30.74	88.21 ± 38.53
	InPeakTorqSet2	95.86 ± 35.14	86.71 ± 31.97	80.21 ± 38.63
	InPeakTorqSet3	86.64 ± 31.72	74.00 ± 35.58	57.07 ± 30.82
Flexion	InPeakTorqSet1	53.57 ± 27.04	56.43 ± 23.32	56.71 ± 24.67
	InPeakTorqSet2	57.57 ± 24.61	50.93 ± 20.66	49.79 ± 24.00
	InPeakTorqSet3	51.64 ± 23.04	49.07 ± 18.72	39.36 ± 19.50
Extension	AvgPowPerRepSet1	110.50 ± 45.60	108.64 ± 41.22	105.71 ± 44.74
	AvgPowPerRepSet2	95.79 ± 37.36	82.86 ± 33.49	71.50 ± 40.71
	AvgPowPerRepSet3	83.71 ± 27.57	72.21 ± 34.82	54.43 ± 29.53
Flexion	AvgPowPerRepSet1	72.50 ± 34.65	72.50 ± 31.82	67.79 ± 31.86
	AvgPowPerRepSet2	60.00 ± 27.69	55.29 ± 24.26	47.21 ± 23.13
	AvgPowPerRepSet3	55.86 ± 23.80	50.93 ± 22.48	42.79 ± 19.77
Extension	TotWorkDoneSet1	1335.21 ± 517.72	1298.36 ± 441.59	1243.71 ± 471.66
	TotWorkDoneSet2	1182.00 ± 115.64	1024.86 ± 96.89	865.071 ± 118.23
	TotWorkDoneSet3	1050.71 ± 325.83	896.79 ± 399.62	663.14 ± 333.71
Flexion	TotWorkDoneSet1	880.14 ± 406.02	876.64 ± 383.69	806.29 ± 357.86
	TotWorkDoneSet2	732.14 ± 341.32	679.71 ± 304.23	574.71 ± 287.49
	TotWorkDoneSet3	696.43 ± 308.83	630.14 ± 272.98	524.21 ± 243.65

CON = control; BFR = blood flow restriction; BTF = band tissue flossing; InPeakTorq = initial peak torque; AvgPowPerRep = average power per rep; TotWorkDone = total work done

Appendix F. Root mean square (M ± SD) of peak amplitude of repetitions via surface EMG.

	Set1First3	**Set1Middle3**	**Set1Last3**	**Set1Avg**
CON	0.25 ± 0.14	0.28 ± 0.15	0.28 ± 0.17	0.27 ± 0.14
BFR	0.22 ± 0.12	0.25 ± 0.16	0.23 ± 0.14	0.24 ± 0.13
BTF	0.31 ± 0.17	0.34 ± 0.24	0.31 ± 0.16	0.31 ± 0.18

	Set2First3	**Set2Middle3**	**Set2Last3**	**Set2Avg**
CON	0.24 ± 0.14	0.25 ± 0.15	0.24 ± 0.15	0.25 ± 0.14
BFR	0.18 ± 0.10	0.20 ± 0.13	0.19 ± 0.12	0.20 ± 0.11
BTF	0.25 ± 0.15	0.26 ± 0.19	0.26 ± 0.20	0.23 ± 0.17

	Set3First3	**Set3Middle3**	**Set3Last3**	**Set3Avg**
CON	0.22 ± 0.11	0.24 ± 0.14	0.26 ± 0.15	0.24 ± 0.12
BFR	0.20 ± 0.14	0.20 ± 0.13	0.20 ± 0.13	0.20 ± 0.13
BTF	0.22 ± 0.17	0.21 ± 0.17	0.24 ± 0.20	0.21 ± 0.17

*# = Significantly different from CON; † = Significantly different from BFR; * = Significantly different from pre- measurement within condition. CON = control; BFR = blood flow restriction; BTF = band tissue flossing.*

Appendix G. Means ± SD and change scores of HR (bpm) between conditions.

	CON	**BFR**	**BTF**
Resting HR (Pre-)	76.07 ± 10.57	73.00* ± 9.54	76.00* ± 14.33
PostOcc	N/A	77.67* ± 12.88	82.82* ± 12.83
ImmPost	134.20* ± 32.13	134.00* ± 20.72	139.45* ± 29.67
1minPost	99.20* ± 24.71	92.79* ± 18.39	96.64* ± 22.20
Δ Pre vs. PostOcc	N/A	4.67 ± 8.49	6.07 ± 8.59
Δ Pre vs. ImmPost	58.13 ± 28.38	56.93 ± 20.00	52.79 ± 25.25
Δ ImmPost vs. 1minPost	-35.00 ± 16.54	-41.21 ± 12.93	-38.21 ± 13.25
Δ Pre vs. 1minPost	23.23 ± 19.00	15.71 ± 19.53	12.46$^{\#}$ ± 16.09

*# = Significantly different from CON; † = Significantly different from BFR; * = Significantly different from pre- measurement within condition. CON = control; BFR = blood flow restriction; BTF = band tissue flossing.*

Appendix H. Means of raw values and change scores ± SD of blood glucose (mg/dL) between conditions.

	CON	**BFR**	**BTF**
Pre	103.36 ± 13.34	94.33 ± 11.17	99.23 ± 9.45
ImmPost	92.31* ± 7.86	86.20 ± 7.30	88.92* ± 5.68
1minPost	93.00* ± 9.94	87.07$^{\#}$ ± 8.55	89.46† ± 6.39
Δ Pre-ImmPost	-11.00 ± 13.52	-8.71 ± 14.60	-10.31 ± 10.91
Δ ImmPost-1minPost	1.15 ± 5.76	0.87 ± 5.51	0.54 ± 2.69
Δ Pre-1minPost	-10.36 ± 12.35	-7.27 ± 15.87	-9.77 ± 12.70

*# = Significantly different from CON; † = Significantly different from BFR; * = Significantly different from pre- measurement within condition. CON = control; BFR = blood flow restriction; BTF = band tissue flossing.*

Appendix I. Means of raw values and change scores ± SD of blood lactate (mmol/L) between conditions.

	CON			BFR			BTF		
Pre	1.81	±	0.21	1.79	±	0.58	1.46	±	0.13
ImmPost	5.29*	±	0.66	5.17*	±	1.35	4.86*	±	0.57
1minPost	6.03*	±	0.76	6.08*	±	1.30	5.62*	±	0.73
Δ Pre-ImmPost	3.48	±	0.64	3.38	±	0.47	3.40	±	0.58
Δ ImmPost-1minPost	0.33	±	0.48	0.50	±	1.42	0.76	±	0.41
Δ Pre-1minPost	3.81	±	0.91	3.88	±	2.52	4.16	±	0.77

** = Significantly different from pre- measurement within condition. CON = control; BFR = blood flow restriction; BTF = band tissue flossing.*

Appendix J. Results of One-way ANOVA on outcome measures with participants divided into groups based on thigh circumference. Group 1 = 50-54.9 cm. Group 2 = 55-59.9 cm. Group 3 > 60 cm.

	Sum of Squares	**df**	**Mean Square**	**F**	**Sig.**
# of Revolutions	3.76	2	1.88	7.33	0.008
BFR LOP	412.80	2	206.40	0.60	0.566
BFR HR Δ Pre-PostOcc	271.85	2	135.92	2.34	0.142
BTF HR Δ Pre-PostOcc	11.00	2	5.50	0.06	0.947
BFR Lactate Δ Pre-ImmPost	12.75	2	6.38	1.17	0.344
BTF Lactate Δ Pre-ImmPost	11.06	2	5.53	1.16	0.348
BFR Glucose Δ Pre-ImmPost	52.10	2	26.05	0.11	0.900
BTF Glucose Δ Pre-ImmPost	150.02	2	75.01	0.59	0.574
BFR % Δ Dist	100.92	2	50.46	0.22	0.809
BTF % Δ Dist	82.34	2	41.17	0.28	0.763
BFR % Δ TAMV	2698.70	2	1349.35	4.12	0.043*
BTF % Δ TAMV	1457.65	2	728.83	0.83	0.460
BFR % Δ VolFlow	3073.59	2	1536.79	1.18	0.340
BTF % Δ VolFlow	1331.99	2	665.99	0.81	0.469
BFR % Δ Area	1609.98	2	804.99	0.63	0.550
BTF % Δ Area	1726.99	2	863.50	2.31	0.142

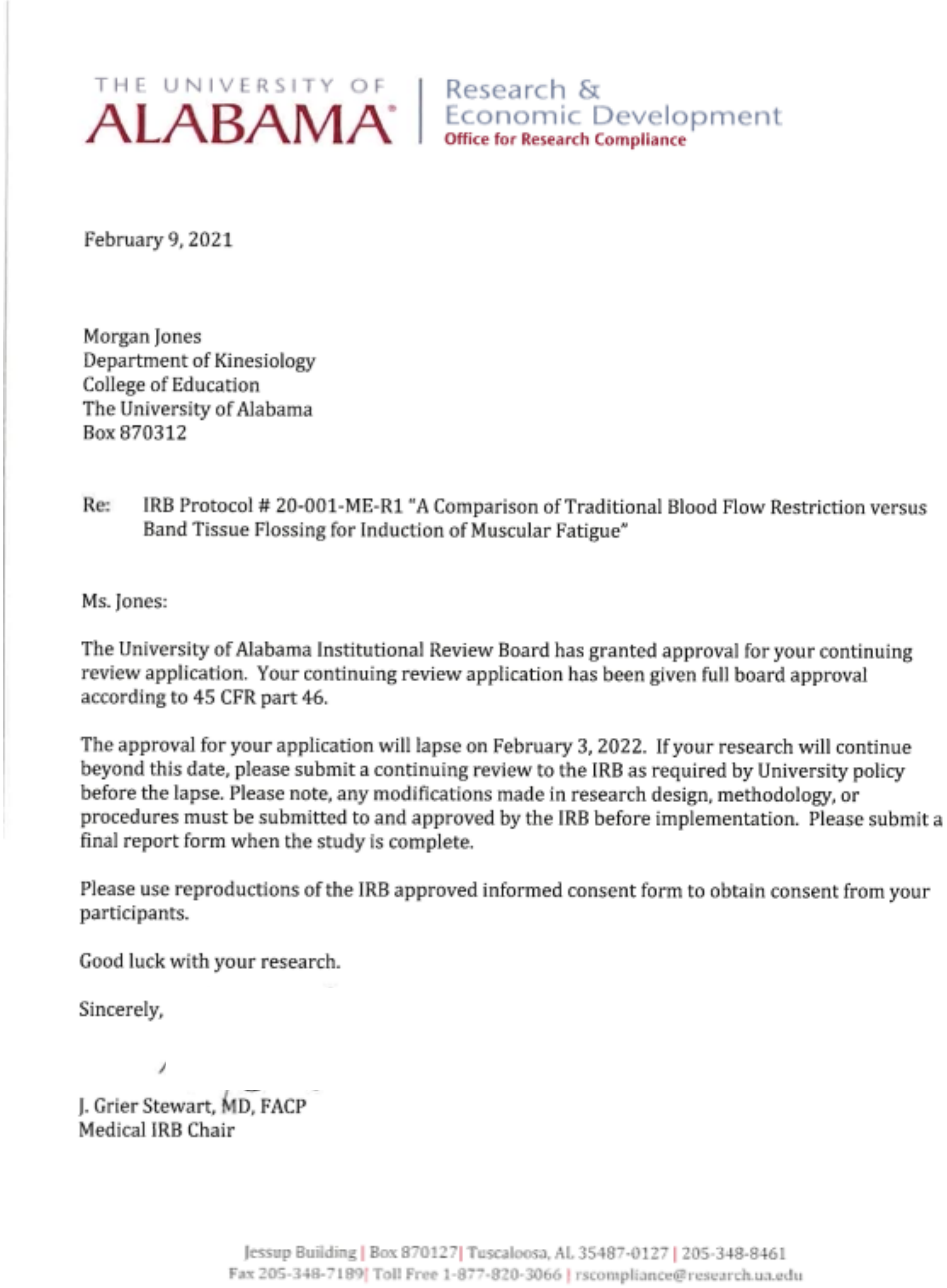
** = Pairwise comparisons revealed no significant differences between groups.*

Appendix K. Increase occurrences in arterial flow during occlusion conditions.

		BFR (N)	BTF (N)
Δ Dist	Increase	4	1
	Decrease	10	13
	No Change	1	1
Δ TAMV	Increase	3	4
	Decrease	12	10
	No Change	0	0
Δ VolFlow	Increase	3	1
	Decrease	12	13
	No Change	0	0
Δ Area	Increase	4	0
	Decrease	9	14
	No Change	2	1
# of Increase Occurrences:		14	6

Dist = distance; TAMV = time-averaged mean velocity; VolFlow = volume flow; BFR = blood flow restriction; BTF = band tissue flossing.

Appendix L. IRB Certificate.



THE UNIVERSITY OF
ALABAMA®
Research &
Economic Development
Office for Research Compliance

February 9, 2021

Morgan Jones
Department of Kinesiology
College of Education
The University of Alabama
Box 870312

Re: IRB Protocol # 20-001-ME-R1 "A Comparison of Traditional Blood Flow Restriction versus Band Tissue Flossing for Induction of Muscular Fatigue"

Ms. Jones:

The University of Alabama Institutional Review Board has granted approval for your continuing review application. Your continuing review application has been given full board approval according to 45 CFR part 46.

The approval for your application will lapse on February 3, 2022. If your research will continue beyond this date, please submit a continuing review to the IRB as required by University policy before the lapse. Please note, any modifications made in research design, methodology, or procedures must be submitted to and approved by the IRB before implementation. Please submit a final report form when the study is complete.

Please use reproductions of the IRB approved informed consent form to obtain consent from your participants.

Good luck with your research.

Sincerely,

J. Grier Stewart, MD, FACP
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