EFFECTS OF EXERCISE WITH AND WITHOUT DIFFERENT DEGREES OF BLOOD FLOW RESTRICTION ON TORQUE AND MUSCLE ACTIVATION

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Accepted 1 September 2014

ABSTRACT: *Introduction:* An unresolved question in resistance training combined with blood flow restriction (BFR) is what percentage of estimated arterial occlusion pressure provides the most robust acute muscular response. *Methods:* Forty participants were assigned to Experiments 1, 2, or 3. Each experiment completed exercise protocols differing by pressure, exercise load, and/or volume. Torque was measured pre- and postexercise, and muscle activation was measured pre- and during each set. *Results:* Pressure and load did not affect torque greatly. Muscle activation increased in all conditions ($P < 0.05$) and was higher with 30% 1RM compared with 20% 1RM. Pressure appeared to increase muscle activation from 40% to 50% arterial occlusion [66% vs. 87% maximal voluntary contraction (30% 1RM)] but was not further increased with higher pressure. *Conclusions:* Different levels of BFR may alter the acute muscular response to a degree, although higher pressures do not appear to augment these changes.

Muscle Nerve **51**: 713–721, 2015

Blood flow restriction (BFR) in combination with low load (~20–30% concentric one repetition maximum (1RM)) resistance exercise has been shown to result in muscle hypertrophy and strength gain in a variety of populations.[1] Research has found that low load resistance exercise in combination with BFR stimulates muscle protein synthesis.[2–5] The increase in muscle protein synthesis may be driven by metabolic accumulation-induced fatigue. Muscle fatigue may result from an increase in intramuscular inorganic phosphate concentration, as this has been observed previously to occur following 4 sets of resistance exercise in combination with BFR.[6] The metabolic accumulation in concert with a reduced oxygen environment (not anoxic) may increase recruitment of higher threshold (Type II) fibers through stimulation of group III and IV afferent fibers.[7] This could be important, as it has been hypothesized that increased muscle fiber recruitment may be related positively to changes in muscle protein synthesis and ultimately muscle adaptation.[8]

The majority of research on BFR has relied on protocols that used an arbitrary pressure for each participant or they have based the restrictive pressure on brachial systolic blood pressure, which is not a large predictor of arterial occlusion in the lower body.[9] An important methodological issue regarding resistance training combined with BFR is to better determine what percentage of estimated arterial occlusion pressure provides the most robust acute muscular response (e.g., torque, muscle activation) and ultimately compare it with the effects observed with higher load resistance training. In conjunction with restrictive pressure, investigating the effect exercise load plays on torque and muscle activation is also important, because it allows one to better determine whether exercise load or applied restrictive pressure is having the greatest impact on the acute response. In addition, comparing responses observed with low load exercise combined with BFR to those observed with low load resistance exercise to failure without BFR are important, as both protocols have been shown to produce favorable skeletal muscle adaptations.[10–12] Understanding the differences in torque and muscle activation between protocols may help with designing more optimal studies in the future. Thus, the purpose of this study was to compare the effects of resistance exercise with and without different degrees of blood flow restriction on torque and muscle activation. To investigate this in several different conditions, we ran 3 experiments with 3 separate groups of physically active men.

Abbreviations: 1RM, one repetition maximum; 20%, 20% 1RM to failure; 30%, 30% 1RM to failure; 20%/40 BFR, 20% 1RM at an estimated 40% arterial occlusion pressure; 30%/40 BFR, 30% 1RM at an estimated 40% arterial occlusion pressure; 20%/50 BFR, 20% 1RM at an estimated 50% arterial occlusion pressure; 30%/50 BFR, 30% 1RM at an estimated 50% arterial occlusion pressure; 20%/60 BFR, 20% 1RM at an estimated 60% arterial occlusion pressure; 30%/60 BFR, 30% 1RM at an estimated 60% arterial occlusion pressure; ANOVA, analysis of variance; BFR, blood flow restriction; BMI, body mass index; bSBP, baseline systolic blood pressure; EMG, electromyography; HL, high load (70% 1RM); MD, minimal differences; MVC, maximal voluntary contraction; VL, vastus lateralis; WBL, whole blood lactate.

Key words: amplitude; KAATSU; muscle hypertrophy; muscle strength; occlusion training

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Published online 3 September 2014 in Wiley Online Library (wileyonlinelibrary.com). DOI 10.1002/mus.24448

MATERIALS AND METHODS

Participants. Forty-five physically active men aged 18–35 years were recruited to participate ($n = 15$ in each experiment). “Physically active” was defined as being active 3 or more days per week with a whole body resistance training component 2 or more days per week for at least the previous 3 months. Physically active participants were used to reflect better the actual acute responses to different exercises. The use of this population decreases the chance of erroneously quantifying acute changes more reflective of muscle damage from an unaccustomed bout of exercise.[13] In addition, different subjects were used in the 3 separate experiments to lessen the chance of producing and quantifying a training effect. Participants who were hypertensive (>140/90 mmHg), used tobacco regularly within the past 6 months, or had more than 1 risk factor for thromboembolism[14] were excluded. Of the initial 45, only 40 completed all testing sessions. Two participants were excluded following the initial visit because they had resting supine blood pressures $\geq$140/90 mmHg. One participant sustained a knee injury before visits 2–5 and was excluded from further participation. One participant sustained a hamstring injury following visit 2 and withdrew from further participation. Both injuries occurred outside of the laboratory and were not related to the study. One participant completed the first 3 visits but was unable to schedule the fourth within the 5–10 day window required. Thus, he was excluded from all further analyses. The study received approval from the University of Oklahoma Institutional Review Board, and each participant gave written informed consent before participation.

Study Design for All 3 Experiments. During the initial screening visit, participants had their height (to the nearest 0.5 cm) and body mass (to the nearest 0.1 kg) measured to calculate body mass index (BMI). Due to potential safety concerns, participants who had a BMI equal to or greater than 30 kg/m^2 along with another risk factor for thromboembolism were excluded.[14] Next, blood pressure and ankle brachial index were measured in the supine position to exclude those who were hypertensive or had indications of peripheral vascular disease. Following this, thigh circumference was measured in the supine position on the nondominant leg to determine the pressure that would be used during the resistance exercise bouts with BFR. Participants were then tested for their bilateral concentric 1 repetition maximum (1RM) on the knee extension machine (NT 1220, Nautilus, Louisville, Colorado). After recording a successful 1RM attempt, participants were familiarized with the cadence of the exercise using a metronome and completed 2 submaximal (30% 1RM, 2 sets of 10) sets under BFR (60% estimated arterial occlusion) to familiarize them with the stimulus. Participants were then scheduled for the first of 4 visits (3 exercise conditions, 1 control, Table 1) with a minimum of 5 and a maximum of 10 days between visits. For the initial screening visit, all participants were tested at least 2 h postprandial and were instructed to avoid caffeine and all exercise (~24 h) before coming in for that visit. For all other visits, participants were only asked to refrain from all exercise prior (i.e., they could exercise after the testing visit each day, but not before) to coming in for testing and to not train legs for at least 48 h before each testing session. The time of day for each session was not standardized, however, most participants visited the laboratory at the same time each week. The individual conditions within each of the experiments will be abbreviated in the results and discussion as follows:

Table 1. Exercise protocols.

	% 1RM	% Arterial occ.	Protocol
Experiment 1			
Condition 1	70	0	4 × 10
Condition 2	20	40	30-15-15-15
Condition 3	30	40	30-15-15-15
Condition 4	0	0	0
Experiment 2			
Condition 1	30	0	4 × Failure
Condition 2	20	50	30-15-15-15
Condition 3	30	50	30-15-15-15
Condition 4	0	0	0
Experiment 3			
Condition 1	20	0	4 × Failure
Condition 2	20	60	30-15-15-15
Condition 3	30	60	30-15-15-15
Condition 4	0	0	0

%1RM, percentage of one repetition maximum; %Arterial occ., percentage of estimated arterial occlusion

Experiment 1 ($n = 14$): HL = 70% 1RM (high load, non-BFR); 20%/40 BFR = 20% 1RM, 40% estimated arterial occlusion pressure; and 30%/40 BFR = 30% 1RM, 40% estimated arterial occlusion pressure.

Experiment 2 ($n = 14$): 30% = 30% 1RM to failure (non-BFR); 20%/50; BFR = 20% 1RM, 50% estimated arterial occlusion pressure; and 30%/50 BFR = 30% 1RM, 50% estimated arterial occlusion pressure.

Experiment 3 ($n = 12$): 20% = 20% 1RM to failure (non-BFR); 20%/60 BFR = 20% 1RM, 60% estimated arterial occlusion pressure; and 30%/60 BFR = 30% 1RM, 60% estimated arterial occlusion pressure.

Resistance Exercise Protocols. Participants were assigned randomly to 1 of 3 experiments. Once assigned, participants completed all protocols in random order within that experiment. The protocols were comparing exercise load, differing degrees of BFR, and exercise volume. The differing degrees of BFR were chosen to determine if a dose response could be observed across restrictive pressures. The maximum was set at 60% of estimated arterial occlusion, as this has been shown previously to produce high levels of fatigue post exercise, with many of the participants unable to complete the goal amount of repetitions.[15] The HL protocol was completed with 1-min rest between sets. All other protocols were separated by 30-s rest periods between sets. A metronome was used to ensure that participants held the cadence of 1 s for the concentric muscle action and 1 s for the eccentric muscle action during the bilateral knee extension exercises. During the control conditions, participants rested in the knee extension device but did not exercise. The protocols within each experiment are found in Table 1. Before each condition, muscle thickness, whole blood lactate (WBL), hematocrit, and torque were measured in that order. In addition, immediately following each exercise bout torque, WBL, hematocrit, and muscle thickness were measured, again in that order. Muscle thickness, hematocrit, and WBL were measured, but those data are to be reported in a separate manuscript. Muscle activation (i.e., amplitude) was measured at pre- (no BFR) and during each set of exercise (with BFR). Both of the pre- and postmeasurements were made in the absence of BFR.

Maximal Voluntary Contraction. The maximal voluntary isometric contraction (MVC) of the dominant knee extensor was performed on an isokinetic dynamometer (Biodex System 3) pre- and postexercise to determine isometric strength. Knee extension was performed with the lever arm of the machine fixed at an angle corresponding to 90 degrees of knee flexion. The pre-exercise MVC began with a warm up of 3 submaximal contractions followed by 2 maximal contractions. The immediately post-MVC involved only 2 maximal contractions. Each contraction was held for 3 s, with 30 s rest between each contraction.[16] The MVC value analyzed was the highest MVC torque (Nm) value observed for a respective time point. Participants were familiarized with the MVC testing during their initial screening visit.

Electromyography. Electromyographic (EMG) signals were recorded from the vastus lateralis (VL) of the dominant leg during exercise. A mark was place on the muscle belly of the VL 66% of the distance between the anterior-superior iliac crest and the lateral patella. At the site, the skin was shaved, abraded, and cleaned with alcohol wipes. Bipolar electrodes were placed over the muscle belly with an inter-electrode distance of 20 mm. The ground electrode was placed on the 7th cervical vertebrae at the neck. The surface electrodes were connected to an amplifier and digitized (Biopac System, Inc., Goleta, California). The signal was filtered (low-pass filter 500 Hz; high-pass filter 10 Hz), amplified (1000×), and sampled at a rate of 1 KHz. Before the exercise bout, the participant performed 2 MVCs with the knee extensors at a joint angle of 90° with 30 s rest between MVCs on an isokinetic dynamometer (Biodex System 3). The EMG was recorded continuously from the vastus lateralis during each exercise bout. The computer software Labview 7.1 (National Instrument Corporation, Austin, Texas) was used to analyze the data. EMG amplitude (root mean square, RMS) was analyzed from the average of the first 3 repetitions and an average of the last 3 repetitions for each set and expressed relative to the highest pre-exercise MVC (%MVC). In addition, the amplitude was further separated by muscle action (Concentric vs. Eccentric). Concentric muscle activation was defined as the first 0.75 s of each contraction, and eccentric muscle activation was defined as the last 0.75 s of each contraction.

Thigh Circumference. The circumference of the nondominant thigh was measured with a tape measure at the 33% site between the top of the patella (knee cap) and the inguinal crease. The 33% site was measured on the initial visit in the supine position to determine the inflation pressure.

One Repetition Maximum. The maximum load that could be lifted through a full range of motion with proper form was assessed and recorded as the concentric 1RM. The bilateral knee extension 1RM was assessed using standard 1RM procedures described previously.[15] All 1RMs were determined within 5 attempts, and approximately 1 min of rest was allotted between attempts.

Blood Flow Restriction. With the participants in a seated position, the blood flow restriction cuffs (5 cm, Hokanson, Inc.) were applied to the most proximal portion of each thigh. The cuff was inflated to 50 mmHg for 30 s and then deflated for 10 s. The cuff was then inflated to 100 mmHg for 30 s and then deflated for 10 s (unless 100 mmHg was the target pressure). The cycle of cuff inflation/deflation was repeated with the cuff pressure increasing in increments of 40 mmHg until the target inflation pressure was reached. The cuff was inflated to the target inflation pressure before the first set of exercise and then deflated and removed immediately following the final set of exercise. The final pressure was set to a percentage

Table 2. Blood flow restriction pressures.

Thigh circ.	Pressure used (60% AO)	Pressure used (50% AO)	Pressure used (40% AO)
<45–50.9 cm	120 mmHg	100 mmHg	80 mmHg
51–55.9 cm	150 mmHg	130 mmHg	100 mmHg
56–59.9 cm	180 mmHg	150 mmHg	120 mmHg
≥60 cm	210 mmHg	180 mmHg	140 mmHg

Circ, circumference; AO, estimated arterial occlusion.

of arterial occlusion estimated from thigh circumference (Table 2). To determine estimated arterial occlusion, we used a previous data set (Loenneke et al.[9]; $n = 116$) and plotted thigh circumference with arterial occlusion. This method is likely imperfect but appears to provide a relative BFR stimulus.[15] Furthermore, the nylon cuffs used in the present study provide a stimulus similar to that observed with 5-cm elastic cuffs inflated to the same target pressure,[17,18] with an initial pressure (pressure applied to limb before inflation) set at 50 mmHg.

Statistical Analyses. All data were analyzed using the SPSS 18.0 statistical software package (SPSS Inc., Chicago, Illinois), with variability represented as standard deviation (SD). A one-way analysis of variance (ANOVA) was completed for exercise volume to determine if differences existed between conditions.

For MVC a 4 (visit) × 2 (time) repeated measures ANOVA was conducted. A significant result from the repeated measures ANOVA was followed up with a paired sample *t*-test to determine where the difference existed across time within each visit. In addition, a one-way ANOVA determined where differences occurred within each time point across visits. A 3 (visit) × 4 (time) repeated measures ANOVA was used for muscle activation. A significant result from the repeated measures ANOVA was followed up with a one-way ANOVA to determine where the difference occurred across time within each visit and within each time point across visits. Statistical significance was set at an alpha level of 0.05. All *post hoc* comparisons maintained the error rate by Bonferroni correcting the P level. Due to lack of statistical power, a between-experiment factor was not included. Experiments were instead compared qualitatively.

Reliability for MVC was determined from the pre- and postdata from the control visit within each experiment. Those measurements were used to determine the intra-class correlations ($ICC_{3,1}$), which were used in the calculation of the standard error of the measurement ($SEM = SD\sqrt{1-ICC}$). The minimal differences (MD) needed to be considered a real change were calculated from the SEM ($MD = SEM \times 1.96 \times \sqrt{2}$). Thus, anything exceeding this MD would be considered a real change that exceeds the error of the measurement.[19] This calculation allowed us to know what effect the exercise condition was having over that which could be expected from repeated testing (pre/post).

RESULTS

Experiment 1. *Group Characteristics.* Participants ($n = 14$) on average were 23 (4) years old, 176 (6) cm tall, 81 (13.6) kg, had a BMI of 25.9 (3.2) kg/m^2, a 1RM of 76.4 kg (13), and a supine measured thigh circumference at the 33% site of 59.4 (6.1) cm.

Maximal Voluntary Contraction. A 4 × 2 repeated measures ANOVA found a significant condition x time interaction with MVC (Fig. 1A; $P < 0.001$). A one-way ANOVA across the pre- values found no statistical difference between conditions ($P = 0.400$). However, a one-way ANOVA did find significant differences across conditions in the post- values ($P < 0.001$). Paired sample *t*-tests found significant differences from pre- to post- in all conditions ($P = 0.004$) except for the control condition ($P = 0.999$). Although the 20%/40 BFR condition decreased statistically from baseline ($P = 0.004$), the value did not exceed the error of the measurement (MD = 50.4 Nm). Thus, only the HL and 30%/40 BFR conditions decreased MVC meaningfully from baseline.

Muscle Activation. A 3 × 4 repeated measures ANOVA did not find a significant interaction with concentric amplitude of the first 3 or last 3 contractions (Table 3; $P \geq 0.078$). However, there were significant main effects for condition ($P < 0.001$) and time ($P \leq 0.008$). For eccentric amplitude, a 3 × 4 repeated measures ANOVA did not find a significant interaction with the first 3 or last 3 contractions (Table 4; $P \geq 0.121$). However, there was a significant main effect for condition ($P < 0.001$) and time ($P \leq 0.007$).

Exercise Volume. A one-way ANOVA found that the total exercise volume differed significantly between conditions ($P < 0.001$). Pairwise comparisons found that exercise volume was highest in the high load condition (2,006 [322] kg) compared with the 20%/40 BFR (1,142 [193] kg; $P = 0.003$) and 30%/40 BFR conditions (1,579 [299] kg; $P = 0.003$). In addition, the 30%/40 BFR condition completed a higher volume of work than the 20%/40 BFR condition ($P = 0.003$). Exercise volume in all experiments is depicted in Figure 1D.

Experiment 2. *Group Characteristics.* Participants ($n = 14$) on average were 23 (4) years old, 175 (7) cm tall, 78.9 (14) kg, had a BMI of 25.7

Table 3. Concentric amplitude of each condition within each experiment*

	Concentric amplitude first 3 reps (%MVC)				Time
Experiment 1	Set 1	Set 2	Set 3	Set 4	2 vs.4
HL[a]	73 (17)	73 (19)	81 (22)	85 (25)	
20%/40 BFR[b]	33 (10)	32 (8)	34 (10)	36 (10)	
30%/40 BFR[c]	43 (12)	50 (16)	51 (15)	53 (17)	
Experiment 2[†]	Set 1	Set 2	Set 3	Set 4	
30%	39 (8)[ab]	53 (12)[ab]	65 (16)[a]	69 (15)[a]	1vs.2,3,4; 2 vs.3,4
20%/50 BFR	33 (10)[b]	37 (16)[b]	41 (16)[b]	45 (16)[b]	1 vs.3,4; 2 vs.3,4
30%/50 BFR	43 (13)[a]	54 (22)[a]	65 (27)[a]	70 (24)[a]	1vs.2,3,4; 2 vs.3,4
Experiment 3[†]	Set 1	Set 2	Set 3	Set 4	
20%	28 (12)	43 (17)[ab]	45 (17)[ab]	48 (17)[a]	1 vs. 2,3,4
20%/60 BFR	28 (11)	32 (13)[b]	37 (14)[b]	40 (16)[a]	1 vs.3,4; 2 vs.3,4
30%/60 BFR	35 (14)	44 (12)[a]	54 (13)[a]	60 (17)[b]	1vs.2,3,4; 2 vs.3,4
	Concentric amplitude last 3 reps (%MVC)				
Experiment 1	Set 1	Set 2	Set 3	Set 4	1 vs.2,3,4
HL[a]	85 (24)	92 (24)	98 (28)	97 (27)	
20%/40 BFR[b]	40 (12)	43 (12)	46 (14)	48 (15)	
30%/40 BFR[c]	56 (14)	62 (19)	65 (22)	66 (21)	
Experiment 2	Set 1	Set 2	Set 3	Set 4	1 vs.2,3,4
30%[a]	67 (13)	77 (15)	82 (23)	82 (27)	
20%/50 BFR[b]	47 (15)	54 (17)	57 (22)	60 (23)	
30%/50 BFR[a]	63 (19)	77 (22)	83 (26)	87 (27)	
Experiment 3[†]	Set 1	Set 2	Set 3	Set 4	
20%	55 (21)[ab]	56 (24)[ab]	60 (21)[ab]	58 (20)[a]	ND
20%/60 BFR	38 (14)[b]	43 (17)[b]	47 (17)[b]	51 (19)[a]	ND
30%/60 BFR	53 (16)[a]	60 (16)[a]	70 (24)[a]	77 (28)[b]	1 vs.2,3,4; 2 vs.3,4; 3 vs.4

*Conditions with different letters represent significant differences between conditions ($P \leq 0.05$). Simple effects of time are noted in the far right column in line with each specific condition. The different numbers represent significant differences between sets ($P \leq 0.05$). No letters within each set across conditions means that the simple effects of condition were not significant following Bonferroni correction. ND means that the simple effects of time were not significant following Bonferroni correction. Main effects of condition are noted by letters within each group (far left column). Conditions with different letters represent significant differences between conditions ($P \leq 0.05$). Main effects of time are noted in the "Set 1, Set 2, etc." row in the far right column. The different numbers represent significant differences between sets ($P \leq 0.05$).

†A significant condition x time interaction ($P \leq 0.05$). Simple effects of condition are noted across each set.

20% 1RM, 20% 1RM; 30% 1RM, 30% 1RM; 40 BFR, 40% arterial occlusion pressure; 50 BFR, 50% arterial occlusion pressure; 60 BFR, 60% arterial occlusion pressure; non-BFR, non blood flow restriction conditions; HL, high load (70% 1RM); 20%, 20% 1RM (no BFR); 30%, 30% 1RM (no BFR). Variability represented as standard deviations.

(3.9) kg/m^2, a 1RM of 77.6 (17.7) kg, and a supine measured thigh circumference at the 33% site of 57.6 (5.5) cm.

Maximal Voluntary Contraction. A 4 × 2 repeated measures ANOVA found a significant condition × time interaction with MVC (Fig. 1B; $P < 0.001$). A one-way ANOVA across the pre- values found no statistical difference between conditions ($P = 0.253$). However, a one-way ANOVA did find significant differences across conditions in the post- values ($P < 0.001$). Paired sample *t*-tests found significant differences from pre- to post- in all conditions ($P = 0.004$) except for the control condition ($P = 0.999$).

Muscle Activation. A 3 × 4 repeated measures ANOVA found a significant interaction with concentric amplitude of the first 3 contractions (Table 3; $P < 0.001$). For concentric amplitude of the last 3 contractions, a 3 × 4 repeated measures ANOVA did not find a significant interaction (Table 4; $P = 0.101$). However, there was a significant main effect for condition ($P < 0.001$) and time ($P < 0.001$). For eccentric amplitude of the first 3 contractions, a 3 × 4 repeated measures ANOVA found a significant interaction (Table 4; $P = 0.039$). For eccentric amplitude of the last 3 contractions, a 3 × 4 repeated measures ANOVA did not find a significant interaction (Table 4; $P = 0.445$). However, there was a significant main effect for condition ($P = 0.001$) and time ($P < 0.001$).

Exercise Volume. A one-way ANOVA found that the total exercise volume differed significantly between conditions ($P = 0.025$). Pairwise comparisons found that exercise volume was highest in the 30% to failure condition (2,113 [562] kg) compared with the 20%/50 BFR (1,162 [286]; $P = 0.003$) and 30%/50 BFR conditions (1,572 [454] kg; $P = 0.003$). In addition, the 30%/50 BFR condition completed a higher volume of work than the 20%/50 BFR condition ($P = 0.003$). Exercise volume across experiments is depicted in Figure 1D.

Experiment 3. ***Group Characteristics.*** Participants ($n = 12$) on average were 21 (3) years old, 179 (6) cm tall, 85.8 (12) kg, had a BMI of 26.5

Table 4. Eccentric amplitude of each condition within each experiment.*					
	Eccentric amplitude first 3 reps (%MVC)				Time
Experiment 1	Set 1	Set 2	Set 3	Set 4	1vs.2; 2 vs.3,4; 3 vs.4
HL[a]	36 (7)	32 (9)	33 (8)	34 (9)	
20%/40 BFR[b]	15 (4)	13 (3)	14 (5)	16 (5)	
30%/40 BFR[c]	20 (4)	17 (3)	19 (3)	20 (4)	
Experiment 2[†]	Set 1	Set 2	Set 3	Set 4	
30%	21 (5)	22 (6)[a]	29 (12)[a]	33 (8)[a]	1 vs.4; 2 vs.4
20%/50 BFR	18 (5)	16 (4)[b]	17 (4)[b]	20 (5)[b]	2 vs.4; 3 vs.4
30%/50 BFR	22 (6)	21 (10)[ab]	28 (18)[ab]	30 (15)[a]	2 vs.4
Experiment 3	Set 1	Set 2	Set 3	Set 4	1 vs.4; 2 vs.4; 3vs.4
20%[ab]	16 (6)	18 (9)	20 (6)	24 (9)	
20%/60 BFR[a]	13 (6)	13 (5)	14 (5)	16 (7)	
30%/60 BFR[b]	19 (6)	18 (5)	20 (7)	23 (6)	
	Eccentric amplitude last 3 reps (%MVC)				
Experiment 1	Set 1	Set 2	Set 3	Set 4	1vs.3,4
HL[a]	38 (11)	37 (13)	41 (9)	44 (12)	
20%/40 BFR[b]	20 (7)	23 (10)	26 (11)	28 (12)	
30%/40 BFR[c]	24 (5)	31 (11)	33 (12)	32 (10)	
Experiment 2	Set 1	Set 2	Set 3	Set 4	1vs.2,3,4; 2vs.4; 3vs.4
30%[a]	31 (8)	40 (9)	43 (14)	50 (15)	
20%/50 BFR[b]	22 (5)	27 (5)	30 (5)	35 (7)	
30%/50 BFR[a]	27 (7)	39 (17)	42 (15)	46 (21)	
Experiment 3	Set 1	Set 2	Set 3	Set 4	1vs.2,3,4; 2 vs.4
20%[a]	34 (19)	35 (13)	40 (15)	39 (12)	
20%/60 BFR[b]	17 (6)	23 (8)	22 (11)	27 (12)	
30%/60 BFR[ab]	23 (7)	32 (12)	34 (14)	37 (16)	

*Conditions with different letters represent significant differences between conditions ($P \leq 0.05$). Simple effects of time are noted in the far right column in line with each specific condition. The different numbers represent significant differences between sets ($P \leq 0.05$). No letters within each set across conditions means that the simple effects of condition were not significant following Bonferroni correction. ND means that the simple effects of time were not significant following Bonferroni correction. Main effects of condition are noted by letters within each group (far left column). Conditions with different letters represent significant differences between conditions ($P \leq 0.05$). Main effects of time are noted in the "Set 1, Set 2, etc." row in the far right column. The different numbers represent significant differences between sets ($P \leq 0.05$).

[†]Significant condition x time interaction ($P \leq 0.05$). Simple effects of condition are noted across each set.

20% 1RM, 20% 1RM; 30% 1RM, 30% 1RM; 40 BFR, 40% arterial occlusion pressure; 50 BFR, 50% arterial occlusion pressure; 60 BFR, 60% arterial occlusion pressure; non-BFR, non blood flow restriction conditions; HL, high load (70% 1RM); 20%, 20% 1RM (no BFR); 30%, 30% 1RM (no BFR). Variability represented as standard deviations.

(3.8) kg/m^2, a 1RM of 81 (17.1) kg, and a supine measured thigh circumference at the 33% site of 60.5 (6.5) cm.

Maximal Voluntary Contraction. A 4 × 2 repeated measures ANOVA found a significant condition × time interaction with MVC (Fig. 1C; $P < 0.001$). A one-way ANOVA across the pre- values found no statistical difference between conditions ($P = 0.562$). However, a one-way ANOVA did find significant differences across conditions in the post- values ($P < 0.001$). Paired sample *t*-tests found significant differences from pre–post in all conditions ($P = 0.004$) except for the control condition ($P = 0.999$).

Muscle Activation. A 3 × 4 repeated measures ANOVA found a significant interaction with concentric amplitude of the first 3 and last 3 contractions (Table 3; $P < 0.001$). For eccentric amplitude, a 3 × 4 repeated measures ANOVA did not find a significant interaction with eccentric amplitude of the first 3 or last 3 contractions (Table 4; $P = 0.166$). However, there were significant main effects for condition ($P \leq 0.02$) and time ($P \leq 0.002$).

Exercise Volume. A one-way ANOVA found that the total exercise volume differed significantly between conditions ($P = 0.008$). Pairwise comparisons found that exercise volume was highest in the 20% to failure condition (2,653 [843] kg) compared with the 20%/60 BFR (1,210 [282]; $P = 0.003$) and 30%/60 BFR conditions (1,624 [355] kg; $P = 0.003$). In addition, the 30%/60 BFR condition completed a higher volume of work than the 20%/60 BFR condition ($P = 0.003$). Exercise volume across experiments is depicted in Figure 1D.

DISCUSSION

When interpreting all 3 experiments together, the results suggest that increasing the exercise load from 20% to 30% 1RM with BFR produced clear changes in torque and muscle activation. In addition, it appears that low to moderate (40–50% estimated arterial occlusion) relative pressures are all that are needed to maximize the acute response

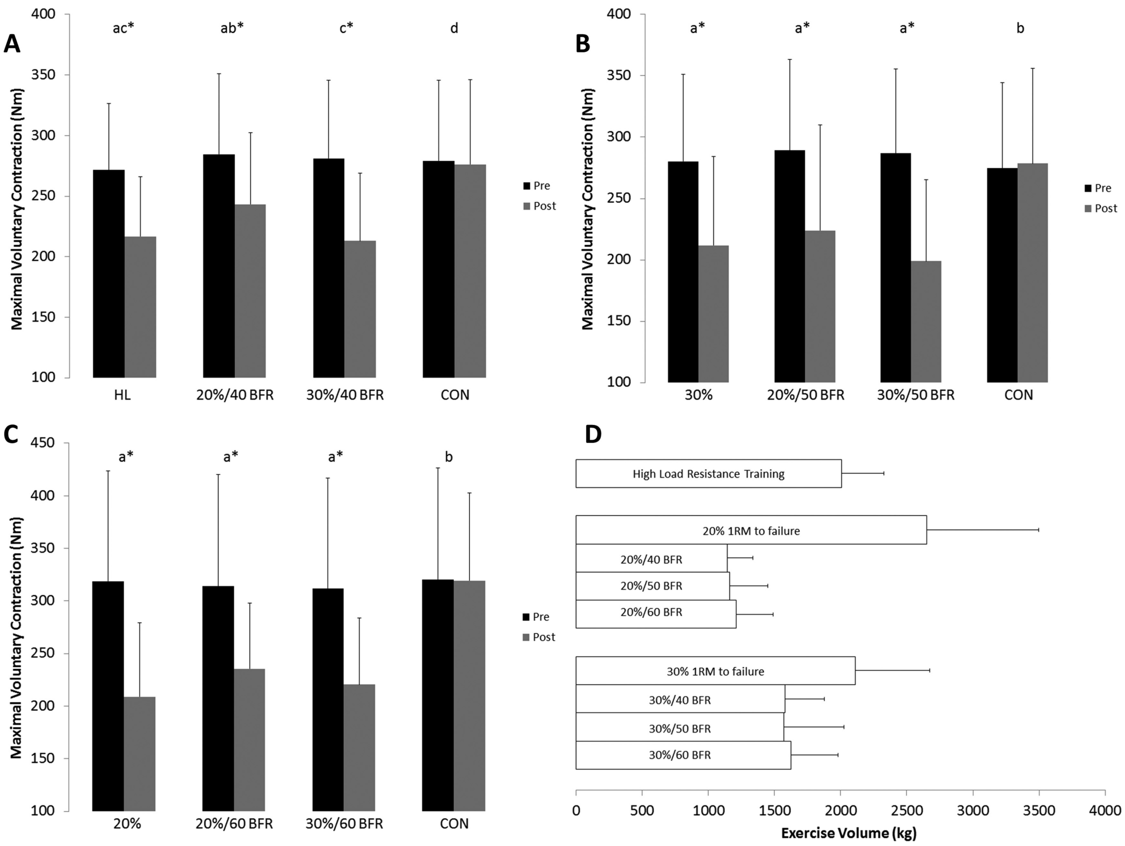

FIGURE 1. Mean changes in maximal voluntary contraction (MVC) in Experiment 1 **(A)**, Experiment 2 **(B)**, and Experiment 3 **(C)**. **D** depicts the mean exercise volume completed within each group. Conditions with different letters represent significant differences between conditions ($P \leq 0.05$). An asterisk denotes a significant difference from pre- to post- ($P \leq 0.05$). Variability represented as standard deviations.

to BFR exercise. The results suggest that 50% estimated arterial occlusion may offer the most robust acute response, with 60% estimated arterial occlusion providing no further augmentation. When the responses from the 30%/50 BFR condition were compared with those observed with non-BFR conditions, the responses appeared similar, albeit at a lower exercise volume. Although speculative until investigated through experiment, these findings suggest that a moderate applied pressure (50% estimated arterial occlusion pressure) would likely produce similar changes in muscle size and strength as a higher applied pressure (60% estimated arterial occlusion pressure). In addition, based on these acute findings we would speculate that applying a moderate pressure with low loads would produce similar changes in muscle size and strength as the non-BFR conditions, albeit with a lower volume of work. However, it is noted that while muscle activation was high with low load resistance exercise with and without BFR, the levels never reached that observed with HL exercise (discussed below).

Torque. Several studies have observed large acute decreases in torque following low load resistance exercise in combination with BFR.[15,16,20–23] This large acute decrease immediately postexercise appears to be evidence of fatigue, not muscle damage.[15,23,24] The increased fatigability is thought to provide at least part of the mechanistic rationale for BFR inducing skeletal muscle hypertrophy when it is combined with resistance exercise.[25] The mechanisms of fatigue were not investigated in our study; however, muscle fatigue may have been due to an increase in intramuscular inorganic phosphate concentration, as this has been observed previously to occur following resistance exercise in combination with BFR.[6,26] Accumulation of inorganic phosphate may lead to a decline in amplitude of the calcium transient and inhibition of the cross-bridge cycle.[27] The results of Experiments 1, 2, and 3 appear to indicate that a higher pressure may not augment the response. To illustrate, increasing the applied pressure from 50 to 60% BFR (particularly with 30% 1RM) does not lead to a further decrease in torque.

The large acute decline in torque from the non-BFR conditions also likely reflects fatigue. There is the possibility for prolonged decrements in torque with the high mechanical loads used in the HL condition, which would be indicative of muscle damage. However, because of the repeated bout effect observed with consistent training, it is unlikely that muscle damage was playing any role in the decrease in torque observed in our resistance trained participants. Cook et al.[21] found similar drops in torque postknee extension exercise in HL (70% peak torque) and LL (20% peak torque) conditions taken to muscular failure. Our experiments showed that the decrease in torque appeared qualitatively greatest for the 20% 1RM to failure condition. The possible difference between conditions may be explained by the higher volume of work completed in the 20% 1RM to failure condition.

Electromyography. Several studies have observed increases in EMG amplitude during low load resistance exercise with and without BFR.[12,21,22,28–30] The increase in EMG amplitude may be due to a metabolic "overload" (i.e., depletion of phosphocreatine stores and decrease in muscle pH) within the muscle.[26] For example, the reduction in oxygen and subsequent metabolic accumulation with muscle contraction and/or BFR may increase fiber recruitment through stimulation of the group III and IV afferents, which may cause inhibition of the alpha motorneuron, resulting in increased fiber recruitment to maintain force and protect against conduction failure.[7] Of studies that have investigated acute increases in EMG amplitude following BFR in combination with resistance exercise, only 1 has investigated those changes across different pressures (80%, 100%, and 120% of bSBP) and it was completed in the upper body.[30] Following cuff inflation, participants performed 4 sets of dumbbell elbow flexion exercise with 30 s rest between each set. The first set consisted of 30 repetitions followed by 3 sets of 15 at 20% 1RM. The authors found that integrated EMG increased progressively during the contraction bout in all groups. However, the amplitude was greater with 120% bSBP than a work-matched non-BFR condition from the end of 30 repetitive contracts to the end of the second set of 15 contractions. Our experiments suggest qualitatively that EMG amplitude is augmented from 40% to 50% BFR, but no further increase was observed when the pressure was increased to 60% BFR. In the aforementioned upper body study,[30] it is possible that large differences in EMG amplitude were not observed between pressures, because the pressure was too low to affect energy supply. It may also be that there are intrinsic differences between the biceps brachii and the vastus lateralis we studied. However, the proposed qualitative differences observed with increasing pressure in experiments should be interpreted with caution until they are compared directly.

The 20% and 30% to failure conditions produced significant increases in muscle activation, but those increases were qualitatively higher in the 30% to failure condition. High levels of EMG amplitude ($\geq\sim$70% MVC) have been observed previously with low load exercise to muscular failure.[21,22,29] Although these low loads increase muscle activation substantially, this investigation and previous work suggests that this level is still less than what is observed with traditional HL resistance exercise.[21] Despite this apparent difference in muscle activation, resistance exercise in combination with BFR[31,32] and low load exercise to failure[10,33] have produced similar changes in muscle mass and strength, which suggests that other factors (e.g., local growth factors, satellite cells, etc.) may be playing important mechanistic roles with low load training.

Limitations. In view of the results presented here, this study has some limitations. First, the amount of BFR was estimated for each participant from previous data collected during supine rest but was not measured directly. This was not done due to the complexities involved with measuring changes in blood flow during exercise of the lower body. Regardless, each participant received graded amounts of BFR, which allowed for the central question of "does applied pressure matter?" to be answered. Second, a comparison across experiments was completed qualitatively. This was due to each experiment being powered to find differences only within each respective experiment. Although it would have been interesting to compare statistically across experiments, qualitative analysis is still useful and is largely the way different studies are compared in the literature. Future experiments using a unilateral exercise model with each leg receiving a different pressure may offer a better statistically powered design for comparing a range of exercise loads and pressures. Lastly, it is noted that these acute load- and pressure-dependent changes should be investigated further with long-term training studies to determine if acute changes predict or correlate to chronic adaptation.

CONCLUSION

In conclusion, these experiments suggest that manipulating the exercise load and/or the BFR pressure applied can produce clear changes in muscle activation. However, the results suggest that high relative pressures ($\geq$60% estimated arterial occlusion) are likely not needed to see benefit from low load exercise in combination with BFR. Furthermore, it is noted that the EMG amplitude of the lower loads never reached that observed with HL exercise. Because similar changes have been observed previously in chronic training studies, this suggests that other mechanisms may be playing a more prominent role with lower loads. We suggest that these findings demonstrate that exercising at different levels of BFR may alter the acute physiologic response. These findings have important implications for designing an optimal protocol for each individual participant who may be: (1) limited to performing low load resistance training due to injury; (2) looking to maximize frequency of training for each body part; or (3) during a deloading period between periodized blocks of training.

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this manuscript. This study was not supported by any external funding. The authors thank Dr. Rosemary Knapp and Dr. Travis W. Beck for their helpful discussion on study design. In addition, the authors would like to thank Xin Ye for his help in EMG analysis. All data was collected in the Neuromuscular Laboratory at the University of Oklahoma. J.P.L., T.A., R.D.L., D.A.B., and M.G.B. designed the study; J.P.L., D.K., C.A.F., and R.S.T. collected the data; J.P.L., D.K., C.F., R.S.T., T.A., R.D.L., D.A., and M.G.B. analyzed and interpreted the data and wrote and edited the manuscript.

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