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ORIGINAL PAPER

Effects of load on the acute response of muscles proximal and distal to blood flow restriction

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Abstract

To determine the effects of load and blood flow restriction (BFR) on muscular responses, we asked 12 participants to perform chest presses under four different conditions [30/0, 30/40, 50/0, and 50/40, presented as percentage one-repetition maximum (1RM)/percentage arterial occlusion pressure (AOP)]. Muscle thickness increased pre- to post-exercise [chest: mean 0.29, 95% confidence interval (CI) 0.21, 0.37 cm; triceps: mean 0.44, 95% CI 0.34, 0.54 cm], remaining elevated for 15 min post-exercise. Electromyography amplitude was greater with 50% 1RM and increased over time for the first three repetitions of each set of chest presses. The last three repetitions differed across time only. AOP increased from pre- to post-exercise, augmented by BFR [30/0: mean 31, 95% CI 18, 44 mmHg; 30/40: mean 39, 95% CI 28, 50 mmHg; 50/0: mean 32, 95% CI 23, 41 mmHg; 50/40: mean 46, 95% CI 32, 59 mmHg). Tranquility decreased and physical exhaustion increased from the pre- to post-condition, with both parameters returning to the baseline 15 min post-exercise level. In conclusion, load and BFR do not elicit meaningful differences in the acute response of chest press exercise taken to failure.

Keywords Muscle hypertrophy · EMG amplitude · Muscle thickness · Occlusion training · Arterial occlusion

Introduction

The American College of Sports Medicine recommends resistance training with a load at least 70% of the one-repetition maximum (1RM) to increase muscle size and strength in healthy adults [1]. However, resistance training with a lower load (e.g., 30% 1RM) may be perceived more favorably [2] and has been shown to induce similar changes in muscle size as high load resistance training [3, 4]. For low load exercise to elicit a hypertrophic response comparable to that of high load exercise it must be taken to, or near, volitional muscular failure, which often requires a larger volume of work [5]. To reduce the workload when exercising with low loads, blood flow restriction (BFR) can be applied to the proximal portion of the exercising limbs to alter oxygen supply, expediting volitional failure [6]. The application of BFR, as it pertains to skeletal muscle adaptation, is meant to reduce arterial flow and occlude venous flow, resulting in a pooling of blood and metabolites (if exercising) distal to the cuff [7]. The resultant lowered volume does not compromise muscle adaptation as BFR training has been shown to elicit increases in muscle size and strength similar to those seen with traditional high load training [8] and low load training to failure [9, 10]. Thus, when the aim is to stimulate muscle hypertrophy, BFR provides a low load alternative to high load training, as well as a lower volume alternative to low load training alone.

Since the application of restriction alters blood flow and the metabolic environment in the appendicular muscles, most investigators studying BFR focus on the response of muscles distal to the cuff [11]. However, a few researchers have considered the effect of BFR on muscles proximal to the applied pressure during compound exercise training in the lower and upper body. Abe et al. [12] found that participants who performed 2 weeks of low load (20% 1RM) squat training under conditions of BFR achieved increased muscle volume of the gluteus maximus whereas those exercised under a free flow condition did not. In another study on upper body muscles, the use of low loads in combination

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with BFR resulted in increased chest muscle thickness following bench press training in young men [13] and following chest press training in postmenopausal women [14]. It has been presumed that BFR expedites fatigue in distal muscles, thus causing an increase in activation of the proximal muscles during a compound movement. Some evidence, however, suggests that low load BFR training results in a slower rate of growth in the muscles proximal to the cuff when compared to traditional high load training [15]. The authors of the latter study proposed that the high load group was training at or near volitional failure while the BFR group may not have been, which could have led to the discrepancies in proximal muscle growth. Further, the authors of a review examining the response of muscles proximal and distal to BFR training hypothesized that an increase in load, pressure and/or exercise repetitions may be necessary when using BFR to induce muscle growth proximal to restriction [11].

The purpose of the study reported here was to test one of these hypotheses by determining whether an increase in load was necessary to augment the acute response of muscles (proximal and distal to the cuff) while performing BFR exercise to volitional failure. Exercise to volitional failure was chosen as it has been argued that to truly determine differences in hypertrophic potential between different exercise modalities, they should be compared only when going to failure [16]. The secondary aims were to assess the cardiovascular and perceptual responses of applying BFR during compound exercises as previous similar investigations have only focused on muscular outcomes.

Methodology

Participants

Sixteen resistance trained young men from the university community volunteered to participate in the study; only 12 completed all visits. Three participants were excluded during the screening process [one was classified as high risk according to the Physical Activity Readiness Questionnaire (Par-Q), one had an orthopedic injury, and one was a regular tobacco user], and one failed to complete all testing visits due to scheduling issues. Therefore, the statistical analysis was completed on the 12 participants who successfully completed all visits. To be included in the study participants had to be resistance trained (regularly performing chest press exercise two or more times per week for the previous 6 months) and within the age range of 18–35 years. Participants were excluded if they regularly used tobacco within the previous 6 months, had any orthopedic injury preventing exercise, or met two or more of the following risk factors for thromboembolism [17]: body mass index ≥ 30; diagnosis of Crohn's Disease; past fracture of hip, pelvis, or femur; major surgery within the last 6 months; varicose veins; family or personal history of deep vein thrombosis; family or personal history of pulmonary embolism. For each visit all participants were instructed to avoid exercise for 24 h, food for 2 h, and caffeine for 8 h prior to testing. This study was approved by the University's Institutional Review Board, and all procedures and potential risks were explained to participants before they provided written informed consent.

Experimental design

The study was conducted over five visits, each at the same time of day ($\pm$ 2 h), with each visit separated by 5–10 days. The first visit consisted of paperwork, measurements of height, body mass, arterial occlusion pressure (AOP), chest press 1RM, and BFR familiarization (1 set of 15 repetitions with 30% 1RM and 40% AOP). For visits two through five participants exercised under four experimental conditions (30% 1RM with 0% AOP; 30% 1RM with 40% AOP; 50% 1RM with 0% AOP; 50% 1RM with 40% AOP). This BFR pressure was used as it has been previously been shown to induce muscle growth following BFR training [18], and it has been used in similar acute protocols to compare stimuli [19]. Each of the latter four visits (two through five) began with a 10-min seated rest period after which exercise affect and AOP were assessed. Next, muscle thickness for the chest and triceps was measured followed by a maximal voluntary contraction (MVC) in the chest press. Participants then exercised using one of the four predetermined conditions (randomized); completing four sets to volitional failure. Electromyography (EMG) data were collected from the chest and triceps during the exercise, while ratings of perceived exertion (RPE) and discomfort were assessed during the rest periods. Once the participant reached failure on the fourth set, arterial occlusion was immediately measured again followed by measurements of muscle thickness and exercise affect. After a 15-min seated rest period muscle thickness and exercise affect were reassessed.

Arterial occlusion pressure

A 5-cm-wide cuff (model SC5; Hokanson, Bellevue, WA) was placed at the proximal portion of each arm. While the participant was seated in the chest press machine with arms relaxed and resting on their thighs, a Doppler probe (model MD6; Hokanson) was placed on the radial artery of the right wrist. The cuffs were then inflated (E20 Rapid Cuff Inflator; Hokanson) and the pressure increased until the loss of an auditory signal from the Doppler probe indicated a cessation of blood flow past the cuff. The lowest inflation pressure needed to occlude blood flow was recorded as the AOP. AOP was measured prior to exercise to determine the level of pressure needed for BFR and used as a baseline with which to compare the post-exercise AOP measurement. The same AOP procedure was performed immediately following the last set of exercises to capture the cardiovascular response to each condition because the participants were already exercising with a 5-cm cuff applied to the arm. Although, it is not a standard measure of blood pressure, it is useful in this case as it allowed for immediate measurement rather than first removing the 5-cm cuff (used for BFR) and replacing it with a standard blood pressure cuff for measurement, which could possibly result in the true response being missed. This protocol has been successfully used in previous studies to obtain insight into the cardiovascular response to BFR exercise [20].

One-repetition maximum

Testing was preceded by a warmup consisting of approximately ten unloaded repetitions on the chest press machine (Hammer Strength Plate Loaded Iso-lateral Bench Press; Life Fitness, Rosemont, IL). Following the warmup, participants attempted one repetition using a load presumed to be relatively low. Next, a load estimated to be around 75–80% of maximum was attempted, which was then followed by an increase or decrease in load depending upon the successful completion of that attempt. If an attempt was successful, the load was increased before the next attempt; if unsuccessful, the load was decreased prior to the next attempt. The process of increasing and decreasing the load (based on fulfilling successful repetition criteria) was continued until the maximum load, as measured to the nearest 2.5 kg, successfully lifted by the participant was found. Each 1RM was determined in approximately five attempts with at least 90 s of rest between each attempt. For an attempt to be considered successful, the participant had to maintain full body contact with the machine padding while moving the weight from the starting position to a position in which the elbows were fully extended. The increments with which the load was increased or decreased were chosen by investigators based on the speed of movement and the effort participants exhibited during each attempt. This testing procedure has been used previously [19, 20]. To standardize grip width, all participants were asked to place their hands one thumb width away from the ends of the machine handles. The 1RM was assessed on visit one to determine the relative training load for subsequent visits.

Exercise-induced feelings

A 12-item questionnaire (Exercise Induced Feelings Inventory) was used to assess the affective response to each exercise condition. These questions are scored on a 5-point scale, with 0 corresponding to "do not feel" and 5 corresponding to "feel very strongly," and are meant to quantify one of four feeling states: positive engagement, revitalization, tranquility, and physical exhaustion [21]. Measurements of exercise-induced feelings were administered before, immediately after, and 15 min after exercise.

Muscle thickness

Muscle thickness measurements were made using B-mode ultrasound (General Electric Co., Fairfield, CT) by coating a probe (8–10 MHz) with transmission gel and holding it lightly against the skin as to not depress the dermal surface. Muscle thickness was determined to be the cross-sectional distance from the muscle–bone interface to the muscle–fat interface. Chest muscle thickness was assessed at half the distance from the anterior axillary crease to the nipple, with the probe oriented along the line of the distance measurement. This measurement was based on pilot testing to determine an area where exercise induced muscle swelling could be assessed. To measure posterior upper arm muscle thickness, a mark was made halfway between the acromion process and the lateral epicondyle of the humerus, then traced to the posterior aspect of the arm. The muscle thickness measurement was made at this site with the probe oriented perpendicular to the humerus. All muscle thickness measurements were taken on the left side of the body (EMG measured on right side) while the participant stood with both arms relaxed. Muscle thickness was assessed at both sites before, immediately after, and 15 min after exercise. Day-to-day measurement variability for this tester, calculated as the minimal difference [22], was 0.29 cm for the chest and 0.25 cm for the posterior upper arm.

Maximal voluntary contraction

Maximal voluntary contraction (MVC) was achieved for the chest press exercise by placing a supramaximal load on the machine and instructing the participant to push as hard and fast as possible from the starting position. Two contractions lasting approximately 3–8 s were completed with 1 min of rest separating each contraction. During the MVC, EMG data were collected from the chest and triceps. The MVC protocol was completed on each testing visit (visits 2–5) prior to exercise for the purpose of normalizing EMG data assessed during the experimental condition to the MVC performed prior to the respective condition.

Exercise

Exercise was performed on a chest press machine (Hammer Strength Plate Loaded Iso-lateral Bench Press; Life Fitness). Participants performed four sets of chest presses to volitional failure, each set separated by a 30-s rest period. All repetitions were to a cadence of 2 s contractions (1 s concentric, 1 s eccentric) using a standardized grip (thumb width from end of handle). To be counted as a repetition the participant had to move the load from the starting position through a full range of motion until the elbows were fully extended. If participants were not able to maintain cadence for two repetitions in a row or could not fully complete a full range of motion as determined by the investigators, the set was ceased. All exercise conditions were performed with 5-cm wide nylon cuffs applied to the proximal portion of each arm; the cuffs were inflated only during exercise for the BFR conditions. During both restriction and non-restriction conditions the cuffs were immediately inflated following exercise to determine post exercise AOP.

Surface electromyography

All EMG electrodes were applied to each participant following recommended guidelines [23]. Briefly, the skin was shaved, abraded, and wiped with an alcohol wipe. Bipolar electrodes (Ag–AgCl) were placed on the skin over the chest and triceps at an interelectrode distance of 2 cm, and the ground electrode was placed on the seventh cervical vertebra at the neck. Chest electrodes were placed at 50% of the distance from the anterior axillary crease to the xiphoid process, along the line of measurement, while the participant stood with arms relaxed. Surface EMG data were collected from the long head of the triceps brachii by placing electrodes two finger widths medially from the 50% site of the distance from the posterior cristae of the acromion to the olecranon process. The distance measurement was taken while the arm was positioned in hand pronation, 90° of elbow flexion, and 90° of shoulder abduction. Electrodes were placed in the orientation of the line of measurement (superior–inferior, when arm is in relaxed position). The surface electrodes were connected to an amplifier and digitized (iWorkx, Dover, NH). The signal was bandpass filtered (low-pass filter 500 Hz; high-pass filter 10 Hz), amplified (1000×), and sampled at a rate of 1 Hz. Data for EMG were collected from the right side of the body during all MVC and exercise sets for each condition on visits two to five.

RPE and discomfort

Ratings of Perceived Exertion (RPE) and discomfort were assessed using Borg's standard 6–20 scale and CR10+ scale, respectively. Both scales were thoroughly explained prior to each exercise condition. and participants were given the opportunity to request further clarification. Participants were asked to rate RPE and discomfort before beginning exercise. RPE were reassessed immediately after each exercise set while discomfort was reassessed 20 s after the exercise set. This was done to better capture the level of discomfort attributed to BFR, as previous studies have noted higher levels of discomfort while the skeletal muscle pump is inactive [18, 24].

Statistical analysis

All data were analyzed using the SPSS version 23.0 software package (IBM, Chicago, Il). A repeated measures analysis of variance (ANOVA) was used to detect any interaction effect of condition and time on muscle thickness, EMG, affect, and repetitions. If there was a significant interaction effect, a one-way repeated measures ANOVA was used to reveal differences across conditions within each time point and across time within each condition. To determine if differences exist in AOP, a repeated measures ANOVA was used. If there was a significant interaction effect, a one-way repeated measures ANOVA was used to reveal differences across conditions within each time point, and a paired samples t test was used across time within each condition. If there were no interactions, main effects were analyzed. For comparisons of RPE and discomfort within each exercise set, we used a Friedman non-parametric test. We did not perform statistical analyses to assess differences across time for RPE and discomfort because neither aspect was a question of interest. Statistical significance was set a priori at an alpha level of 0.05.

Results

Demographics

In total, 12 young men [mean (SD); age 25 (3) years; height 182.4 (12.0) cm; body mass 91.8 (12.0) kg; 1-RM 117 (13) kg; 40% AOP applied pressure for 30% 1RM 72 (7) mmHg; 40% AOP applied pressure for 50% 1RM 69 (7) mmHg] completed all testing conditions.

Muscle thickness

With respect to acute changes in chest muscle thickness, there was no significant interaction ($F_{(6, 66)} = 0.775$, $p = 0.592$) or main effect of condition ($F_{(3, 33)} = 0.420$, $p = 0.740$), but there was a main effect of time (Fig. 1a; $F_{(2, 22)} = 39.549$, $p < 0.001$). Muscle thickness increased [mean change (95% CI)] from pre- to post-exercise 0.29 (0.21, 0.37) cm; $p < 0.001$)] and remained elevated in comparison to the baseline at 15 min post-exercise [0.20 (0.13, 0.27) cm; $p < 0.001$]. Although elevated above the baseline measurement, chest muscle thickness at 15 min post-exercise was significantly reduced relative to that measured at the immediate post-exercise time point [− 0.08 (− 0.16, − 0.007) cm; $p = 0.036$].

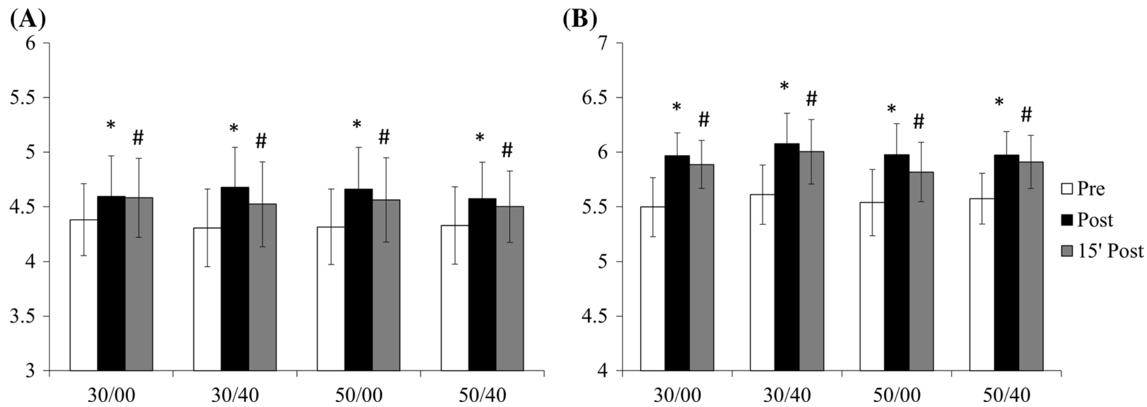

Fig. 1 Muscle thickness measurements (cm) of the chest (**a**) and triceps (**b**) before beginning exercise (Pre), immediately after completion of exercise (Post), and 15 min after exercise completion (15′ Post). Conditions under the figure are given as the percentage of one-repetition maximum (IRM)/percentage of arterial occlusion pressure (AOP). Asterisk above columns indicates statistically significant difference from the Pre condition; hashtag above columns indicates significantly different difference from the Post condition ($p < 0.05$). Data presented as the mean with 95% confidence interval (CI)

Regarding acute changes in thickness of the triceps muscle, there was no significant interaction [$F_{(6, 66)} = 1.179$, $p = 0.329$] or main effect of condition ($F_{(2.102, 23.120)} = 1.754$, $p = 0.194$), but there was a main effect of time [Fig. 1b; $F_{(1.219, 13.406)} = 89.800$, $p < 0.001$]. Muscle thickness increased [mean change (95% CI)] from pre- to post-exercise [0.44 (0.34, 0.54) cm; $p < 0.001$)] and remained elevated relative to the baseline measurement at 15 min post-exercise [0.34 (0.27, 0.42) cm; $p < 0.001$]. Although elevated above the baseline measurement, triceps muscle thickness at 15 min post-exercise was significantly reduced relative to that measured at the immediate post-exercise time point [− 0.09 (− 0.13, − 0.05) cm; $p = 0.001$].

Electromyography

There was no significant interaction for the EMG amplitude of the chest ($F_{(1.87, 20.57)} = 1.230$, $p = 0.311$), but there was a main effect of condition (50% 1RM > 30% 1RM; $F_{(1.688, 18.564)} = 4.532$, $p = 0.03$) and time (Set 1 < Set 2 < Set 3 < Set 4; $F_{(1.207, 13.278)} = 36.837$, $p < 0.001$) for the first 3 repetitions of each set (Table 1). For the EMG amplitude of the last three repetitions (Table 1), there was no significant interaction ($F_{(3.070, 33.768)} = 1.036$, $p = 0.39$) or main effect of condition ($F_{(1.659, 18.253)} = 1.974$, $p = 0.172$), but there was a main effect of time (Set 1 < Set 2, Set 3, Set 4; $F_{(1.295, 14.241)} = 10.009$, $p = 0.004$).

For EMG amplitude of the triceps, there was no significant interaction ($F_{(3.226, 29.034)} = .400$, $p = 0.768$), but there was a main effect of condition (50% 1RM > 30% 1RM; $F_{(3, 27)} = 6.244$, $p = 0.002$) and time (Set 1 < Set 2 < Set 3, Set 4; $F_{(1.191, 10.721)} = 35.141$, $p < 0.001$) for the first three repetitions of each set (Table 1). For EMG amplitude of the last three repetitions (Table 1), there was no significant interaction ($F_{(3.7, 33.296)} = 1.482$, $p = 0.232$) or main effect of condition ($F_{(3, 27)} = 1.739$, $p = 0.183$), but there was a main effect of time (Set 1 < Set 3; $F_{(3, 27)} = 8.624$, $p < 0.001$). Of note, in the case of participants completing fewer than six repetitions, the repetitions were split equally between the first and the last repetition and then EMG amplitude was assessed during those respective repetitions. If there were an odd number of repetitions, for example five, then the middle repetition was not assessed; in this case, only the EMG from the first two and last two repetitions were used for analysis.

Repetitions completed

There was a significant interaction for the number of repetitions completed (Table 2; $F_{(9, 36.487)} = 69.278$, $p < 0.001$). In general, the participants completed fewer repetitions under the 50% 1RM conditions than under the 30%1RM conditions, regardless of whether there was BFR. Further, repetitions tended to decrease across sets.

Arterial occlusion pressure

There was a significant interaction for acute changes in AOP [Fig. 2; $F_{(3, 33)} = 2.923$, $p = 0.048$]. There were no significant differences at the pre-exercise time point ($F_{(3, 33)} = 1.333$, $p = 0.280$) but there were at the post-exercise time point ($F_{(3, 33)} = 4.098$, $p = 0.014$), with pressures generally being higher with the application of BFR, independent of load. All conditions increased [mean change (95% CI)] AOP across time [30/0: 31 (18, 44) mmHg; 30/40: 39 (28, 50) mmHg; 50/0: 32 (23, 41) mmHg; 50/40: 46 (32, 59) mmHg; $p < 0.001$].

Table 1 Electromyography amplitude

Exercise conditions	EMG amplitude (% MVC)			
	Set 1 a	Set 2 b	Set 3 c	Set 4 d
First 3 repetitions of the chest				
30% 1RM a	42 (14)	56 (14)	63 (18)	68 (22)
30% 1RM/40% AOP a	39 (16)	56 (19)	62 (20)	62 (20)
50% 1RM b	60 (21)	89 (50)	92 (49)	94 (46)
50% 1RM/40% AOP b	58 (23)	81 (34)	84 (33)	88 (34)
	Set 1 a	Set 2 b	Set 3 b,c	Set 4 c
Last 3 repetitions of the chest (% MVC)				
30% 1RM	78 (17)	90 (26)	92 (27)	91 (25)
30% 1RM/40% AOP	73 (21)	81 (25)	84 (25)	83 (26)
50% 1RM	100 (45)	114 (64)	118 (71)	119 (71)
50% 1RM/40% AOP	98 (41)	102 (43)	100 (48)	106 (52)
	Set 1 a	Set 2 b	Set 3 c	Set 4 c,d
First 3 repetitions of the triceps (% MVC)				
30% 1RM a	50 (13)	65 (18)	77 (25)	80 (29)
30% 1RM/40% AOP a	54 (26)	75 (36)	84 (42)	89 (44)
50% 1RM b	92 (29)	112 (37)	120 (39)	120 (41)
50% 1RM/40% AOP b	80 (25)	102 (36)	110 (41)	111 (44)
	Set 1 a	Set 2 b	Set 3 b	Set 4 b
Last 3 repetitions of the triceps (% MVC)				
30% 1RM	94 (44)	97 (32)	97 (34)	100 (41)
30% 1RM/40% AOP	106 (68)	118 (67)	119 (68)	123 (60)
50% 1RM	122 (39)	139 (48)	144 (52)	152 (61)
50% 1RM/40% AOP	111 (43)	127 (53)	133 (53)	124 (52)

Data are presented as the mean amplitude, expressed as a percentage of the maximal voluntary contraction (MVC), with the standard deviation (SD) given in parenthesis. Values/conditions followed by different lowercase letters indicate a significant difference across those conditions or across sets. If at least one letter is the same there are no significant differences ($p < 0.05$)

AOP Arterial occlusion pressure, *EMG* electromyography, *1RM* one-repetition maximum

Table 2 Repetitions to failure

Exercise conditions	Set 1	Set 2	Set 3	Set 4	Time
30% 1RM	32 (3) a	11 (2) a	8 (2) a	6 (2)a	Set 1 vs. 2, 3, 4; 2 vs. 3, 4; 3 vs. 4
30% 1RM/40% AOP	32 (4) a	9 (2) b	7 (2) b	6 (1) a	Set 1 vs 2, 3, 4; 2 vs. 3, 4; 3 vs. 4
50% 1RM	18 (2) b	4 (1) c	3 (1) c	2 (1) b	Set 1 vs. 2, 3, 4; 2 vs. 3, 4
50% 1RM/40% AOP	18 (2) b	4 (1) c	3 (1) c	2 (1) b	Set 1 vs. 2, 3, 4; 2 vs. 3, 4

Data are presented as the mean value with the SD given in parenthesis. Values within each set followed by different lowercase letters are significantly different across conditions ($p < 0.05$). Simple effects of time are noted in the far-right column corresponding to each specific condition ($p < 0.05$)

Exercise-induced feelings

Each exercise affect measure was tested for reliability, and all were shown to have good internal consistency (Cronbach's alpha > 0.7). For revitalization (Table 3), there was no significant interaction ($F_{(2.946, 32.403)} = 0.693$, $p = 0.560$), main effect of condition ($F_{(3, 33)} = 0.027$, $p = 0.994$), or main effect of time ($F_{(1.280, 14.081)} = 1.931$, $p = 0.187$).

With respect to tranquility (Table 3), there was no significant interaction ($F_{(6, 66)} = 0.741$, $p = 0.619$) or main effect of condition ($F_{(3, 33)} = 0.365$, $p = 0.779$), but there was a main effect of time ($F_{(2, 22)} = 6.141$, $p = 0.008$). Tranquility decreased [mean change (95% CI)] from the

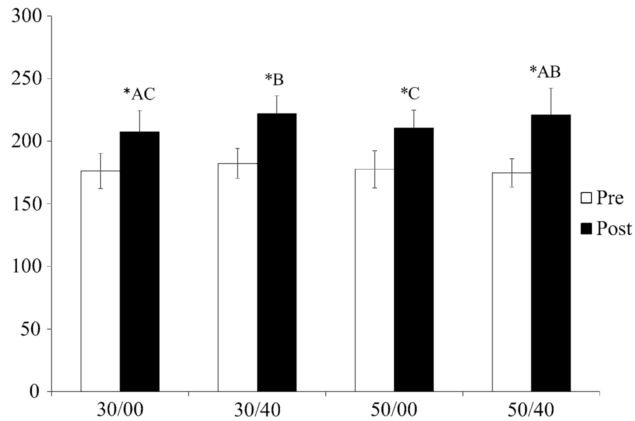

Fig. 2 Arterial occlusion pressure (mmHg) before (Pre) and immediately after (Post) exercise. Conditions are labeled as percentages of 1RMone-repetition maximum/percentage of AOP. Different uppercase letters above columns indicate significant difference across conditions for the post time point; asterisk indicates significant difference between Pre and Post measurements ($p < 0.05$). If at least one letter is the same, the respective conditions are not significantly different. Data are presented as the mean with 95% CI

Table 3 Exercise affect measure

Exercise conditions	Pre-exercise	Post-exercise	15-min post-exercise
Revitalization			
30% 1RM	2.0 (1.0)	2.0 (1.0)	2.1 (1.0)
30% 1RM/40% AOP	1.7 (1.0)	2.1 (1.0)	2.3 (0.8)
50% 1RM	1.8 (0.9)	2.0 (0.6)	2.2 (0.8)
50% 1RM/40% AOP	2.0 (0.7)	1.9 (0.7)	2.3 (0.7)
Tranquility[a]			
30% 1RM	2.3 (0.9)	2.0 (1.1)	2.2 (0.9)
30% 1RM/40% AOP	2.5 (1.1)	2.0 (1.1)	2.4 (1.0)
50% 1RM	2.4 (1.0)	1.8 (1.0)	2.3 (0.8)
50% 1RM/40% AOP	2.4 (0.8)	1.9 (1.0)	2.4 (0.8)
Positive engagement			
30% 1RM	2.3 (0.8)	2.3 (1.1)	2.4 (1.1)
30% 1RM/40% AOP	2.3 (1.1)	2.4 (0.9)	2.6 (0.9)
50% 1RM	2.0 (0.9)	2.3 (0.6)	2.2 (0.9)
50% 1RM/40% AOP	2.2 (0.8)	2.3 (0.9)	2.4 (0.7)
Physical exhaustion[a]			
30% 1RM	1.5 (1.1)	2.1 (0.8)	1.6 (0.7)
30% 1RM/40% AOP	1.4 (0.7)	2.2 (0.6)	1.4 (0.5)
50% 1RM	1.4 (1.2)	2.1 (0.8)	1.5 (0.7)
50% 1RM/40% AOP	1.3 (1.1)	2.0 (0.9)	1.3 (0.5)

Data presented as the mean value with the SD given in parenthesis

[a]Main effect of time ($p < 0.05$)

pre- to post-exercise condition [− 0.47 (− 0.87, − 0.07); $p = 0.025$] but significantly increased from the immediate post-excercise condition back to baseline levels by 15 min post-exercise [0.41 (0.16, 0.65), $p = 0.004$].

For positive engagement (Table 3), there was no significant interaction ($F_{(6, 66)} = 0.385$, $p = 0.886$), main effect of condition ($F_{(3, 33)} = 1.318$, $p = 0.285$), or main effect of time ($F_{(2, 22)} = 0.798$, $p = 0.463$).

For physical exhaustion (Table 3), there was no significant interaction ($F_{(6, 66)} = 0.308$, $p = 0.931$) or main effect of condition ($F_{(3, 33)} = 0.584$, $p = 0.630$), but there was a main effect of time ($F_{(2, 22)} = 8.716$, $p = 0.002$). Physical exhaustion increased [mean change (95% CI)] from pre- to post-exercise [0.74 (0.22, 1.26); $p = 0.009$] but significantly decreased from the immediate post-exercise level back to baseline levels by 15 min post-exercise [− 0.63 (− 0.97, − 0.30), $p = 0.001$].

Ratings of perceived exertion and discomfort

There were no differences in RPE across conditions within any set (Fig. 3a; $p \geq 0.105$), nor were there differences in discomfort within each set (Fig. 3b, $p \geq 0.212$).

Discussion

The aim of the present investigation was to assess the acute muscular, cardiovascular, and perceptual responses of using BFR to stimulate muscles proximal to the restriction during a compound exercise, as well as to determine whether the manipulation of load is necessary to augment the acute muscular response. Overall, the data suggest that there were no meaningful differences in the proximal and distal acute muscular responses across conditions performed to volitional failure, whereas the cardiovascular response to exercise was augmented by applying BFR. For exercise affect, revitalization and positive engagement were unchanged, while changes in tranquility and physical exhaustion were similar across conditions. Assessment of perceptual responses showed RPE and discomfort to be similar across conditions regardless of load and pressure.

Muscular responses

The acute changes in muscle thickness and EMG amplitude of muscles located proximal and distal to the applied pressure were used to gain insight into the potential efficacy of BFR to produce a hypertrophic response using a compound exercise such as the chest press. Previous associations have been made using these outcomes in comparisons of concentric and eccentric exercise, where the exercise modality that resulted in greater acute changes in muscle thickness

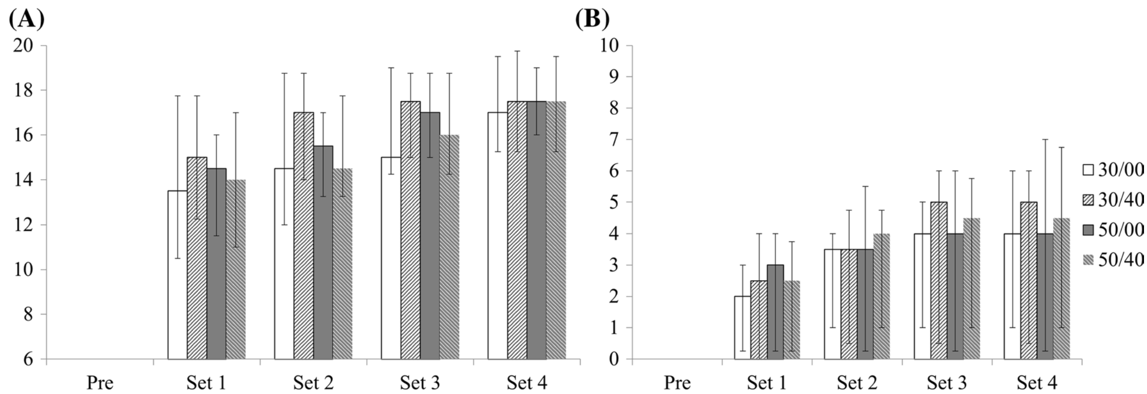

Fig. 3 Ratings of perceived exertion (**a**) assessed before exercise (Pre) and immediately after each set of exercise. Ratings of discomfort (**b**) assessed before exercise (Pre) and 20 s after each set of exercise. Conditions are labeled as the percentage of 1RM/percentage of AOP. Data are presented as the median with the (25th, 75th) percentiles

and EMG amplitude also resulted in greater hypertrophy (albeit not necessarily cause and effect) over a chronic training program [25].

Acute muscle thickness was used in our study as it may be representative of a fluid shift into the muscle cells. This swelling response may have the potential to positively influence protein balance, as has been shown in hepatocytes [26] and skeletal muscle in rodents [27]. Previous investigations have found that resistance exercise while under BFR does result in a muscle swelling response [28, 29]. Similarly, in our study we found changes in the muscle thickness of both muscles measured immediately following exercise. While the swelling response is thought to have some anabolic properties, alone it does not seem sufficient to induce growth [30]. Therefore, in addition to swelling, we also used EMG amplitude as a marker of an exercise protocol's potential to induce muscle growth.

Greater EMG amplitude is indicative to some degree of greater muscle activation, which seems central to stimulating muscle growth [31]. Although there were differences in EMG amplitude at the beginning of each set, the differences were diminished by the end of the sets, further supporting the notion that there will be a lack of meaningful differences in hypertrophy across conditions. The difference in loading is most likely the cause for differences in EMG at the beginning of each exercise set, given that more muscle fibers would need to be active at any given time to overcome the greater load. However, the lack of differences by the end of each set may be driven by each condition being performed to volitional failure, necessitating more of the muscle be activated to overcome the loss of force by fatigued fibers. In the present study, exercise was made relative to the individual's 1RM and was performed to volitional failure to properly compare the effect of load and BFR on the acute muscular response. This protocol helps normalize the stimulus to the individual's maximal strength and muscular endurance level. Previous research has shown that resistance exercise with low loads (e.g., 30% 1RM) will stimulate similar acute [5] and chronic [3, 4] muscular responses as high loads if they are taken to failure. Although BFR normally reduces the repetitions required to reach failure [6] while inducing similar adaptations [9], we found no differences in repetitions due to the application of restriction. This result suggests a lack of effect of BFR to augment the muscular response over the compound exercise alone, which does not align with the results reported by Yasuda et al. [32]. In that study, the authors found that bench press training with restriction increased chest and triceps muscle thickness over traditional training at the same load. Assuming the acute muscular response observed in the present study is indicative to some degree of long-term growth, these results would lead one to believe there would be no difference in hypertrophy across conditions regardless of BFR. If this were the case, the most likely explanation for the discrepancies is that the current study took exercise to failure whereas Yasuda et al. used an arbitrary protocol commonly found in the BFR literature. It should not be ruled out, however, that perhaps other methodological differences, such as restriction pressure, exercise mode, and measurement sites, may also have led to the conflicting results. Even though 40% AOP has been shown to induce distal muscle growth, it may not be enough to augment the response of the proximal muscles. For example, in the current investigation participants utilized the chest press in the upright seated position; in previous studies participants utilized the bench press in the supine position. Coupled with the differences in body position and the pressure applied (approx. 70 vs. approx. 160 mmHg), the level of restriction may have been too low in the current study to influence the response to exercise. This suggests that it may be necessary to investigate higher pressures as they may induce a more fatiguing stimulus in this particular movement [24]. Further, in terms of measurement sites, Yasuda et al. measured chest thickness between the third and fourth costa, and the triceps at 60% from the acromion process to the olecranon process. Since muscle thickness does not change homogeneously, we could have captured different responses. However, this seems unlikely since both investigations detected changes regardless of measurement sites.

Cardiovascular response

Differences in AOP from immediately before to after exercise were used to capture the cardiovascular response elicited by load and BFR. The response was similar between conditions when using 30 and 50% 1RM alone. Adding BFR to the exercise condition, however, augmented this response at both loads. This response is likely driven by a stimulation of afferent fibers caused by restricting blood flow [33]. Previous research has found that BFR does augment the cardiovascular response using low loads during single joint exercise in the upper [24, 34, 35] and lower body [36], with the magnitude of response being load and pressure dependent [37]. In the current study, the average change in AOP ranged from 31 to 46 mmHg, which is commensurate with the mean cardiovascular response observed during a low load BFR bench press (approx. 40 mmHg) compared to the traditional high load bench press (approx. 68 mmHg) [38]. Although direct comparisons between studies may be difficult, given the differences in methodology (we used 5-cm-wide cuffs in the arm while Ozaki et al. [38] used a traditional blood pressure cuff on the thigh), the studies seem to agree that the cardiovascular response is augmented when BFR is applied during compound exercise. However, this response does not seem exaggerated above the changes seen with traditional high load exercise suggesting that there may be no increased risk of a cardiovascular event compared to normal resistance training.

Perceptual responses

Revitalization and positive engagement were unaffected by the exercise conditions, but tranquility decreased immediately following exercise and physical exhaustion increased, with both returning to baseline within 15 min. This result suggests that the changes in affect due to chest press exercise is transient and lasts < 15 min upon exercise cessation. Previous research has shown that intensity [2, 39] and length of rest period [2] may influence positive affect in response to resistance exercise. However, in the current study there were no differences across conditions, suggesting there was no influence of load or blood flow restriction on affect following chest press exercise. The discrepancies between studies may be due to a variety of factors. For example, in the current study only one exercise was performed and it was taken to volitional failure compared to previous studies in which multiple exercises were performed using arbitrary sets and repetitions. When taken to a volitional failure, the differences in affect may be negated even when different intensities are compared. It should also be noted that affect has been measured at various time points surrounding the exercise and not necessarily during the exercise itself. Therefore, for a true comparison it may be necessary to assess affect during exercise rather than after, particularly if the goal is to predict future exercise adherence [40]. However, this approach presents difficulty, especially during resistance training where exercise sets are relatively short.

In our study RPE and discomfort were like affect in that they were not driven by increased load or applied pressure. This finding is in contrast to the results of a previous study showing that BFR increased RPE compared to a non-restricted condition at the same low load [41]. Discomfort and RPE may be driven by the stimulation of afferent fibers via metabolites [33, 42], which are greater during exercise with higher loads and when BFR is applied [7]. Given that a buildup of metabolites is likely the cause of muscular failure, the absence of differences in perceptual response could be due to a similar level of metabolic buildup across conditions. However, this aspect was not directly investigated, and some evidence suggests there may be other mechanisms driving the response since discomfort is not always associated with metabolites, such as whole blood lactate [43].

Limitations

We recognize that the current study is not absent of limitations. First, this investigation was acute in nature. Thus, only inferences can be made about possible long-term adaptations. There was no direct assessment of exercise-induced fatigue following the various exercise conditions due to equipment limitation; however, the comparison of repetitions completed in the latter sets may provide some insight into how fatiguing the various conditions were. Applying a percentage of AOP does not necessarily translate into an equal percentage reduction in blood flow; in other words, applying 40% AOP does not necessarily equal a 40% reduction in blood flow in the upper body [44]. In addition, given the fact that we did not complete an a priori power analysis, we cannot rule out the possibility that the non-significant results in the current study were due to a lack of statistical power. It should be noted that the final sample size ($n = 12$) is similar to that of previous studies ($n = 14$–15) investigating similar measures in muscles distal to restriction [19, 20, 45, 46]. Lastly, due to privacy concerns regarding the location of proximal muscle thickness measurements taken by a male research team, the investigation did not include females. Thus, the results may only be generalized to males.

Conclusion

Overall, the current data suggest there are no meaningful differences in the acute response of the chest and triceps muscles during chest press exercise taken to failure at low and moderate loads with or without BFR. While exercise affect, RPE, and discomfort were similar across conditions, the cardiovascular responses seem to be augmented by the application of BFR. Therefore, applying a moderate BFR pressure seems unnecessary as it does not appear to improve the acute muscular or affective responses to chest press exercise. Future investigations should aim to elucidate the role of higher pressures during compound exercises taken to volitional failure.

Author contributions All authors contributed to this manuscript equally.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed consent Informed consent was obtained from all individual participants included in the study.

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