PODCAST In-Depth VIDEO

Blood Flow Restriction Training for the Shoulder

A Case for Proximal Benefit

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Investigation performed at Houston Methodist Hospital, Houston, Texas, USA

Background: Although blood flow restriction (BFR) is becoming increasingly popular in physical therapy and athletic training settings, little is known about the effects of BFR combined with low-intensity exercise (LIX) on muscles proximal to the site of occlusion.

Hypothesis/Purpose: Determine whether LIX combined with BFR applied distally to the shoulder on the brachial region of the arm (BFR-LIX) promotes greater increases in shoulder lean mass, rotator cuff strength, endurance, and acute increases in shoulder muscle activation compared with LIX alone. We hypothesized that BFR-LIX would elicit greater increases in rotator cuff strength, endurance, and muscle mass. We also hypothesized that the application of BFR would increase EMG amplitude in the shoulder muscles during acute exercise.

Study Design: Controlled laboratory study.

Methods: 32 healthy adults were randomized into 2 groups (BFR group, 13 men, 3 women; No-BFR group, 10 men, 6 women) who performed 8 weeks of shoulder LIX (2 times per week; 4 sets [30/15/15/fatigue]; 20% maximum) using common rotator cuff exercises (cable external rotation [ER], cable internal rotation [IR], dumbbell scaption, and side-lying dumbbell ER). The BFR group also trained with an automated tourniquet placed at the proximal arm (50% occlusion). Regional lean mass (dual-energy x-ray absorptiometry), isometric strength, and muscular endurance (repetitions to fatigue [RTF]; 20% maximum; with and without 50% occlusion) were measured before and after training. Electromyographic amplitude (EMGa) was recorded from target shoulder muscles during endurance testing. A mixed-model analysis of covariance (covaried on baseline measures) was used to detect within-group and between-group differences in primary outcome measures (α = .05).

Results: The BFR group had greater increases in lean mass in the arm (mean ± 95% CI: BFR, 175 ± 54 g; No BFR, –17 ± 77 g; $P <$ .01) and shoulder (mean ± 95% CI: BFR, 278 ± 90 g; No BFR, 96 ± 61 g; $P <$ .01), isometric IR strength (mean ± 95% CI: BFR, 2.9 ± 1.3 kg; No BFR, 0.1 ± 1.3 kg; $P <$ .01), single-set RTF volume (repetitions × resistance) for IR (~1.7- to 2.1-fold higher; $P <$ .01), and weekly training volume (weeks 4, 6-8, ~5%-22%; $P <$ .05). Acute occlusion (independent of group or timepoint) yielded increases in EMGa during RTF (~10%-20%; $P <$ .05).

Conclusion: Combined BFR-LIX may yield greater increases in shoulder and arm lean mass, strength, and muscular endurance compared with fatiguing LIX alone during rotator cuff exercises. These findings may be due, in part, to a greater activation of shoulder muscles while using BFR.

Clinical Relevance: The present study demonstrates that BFR-LIX may be a suitable candidate for augmenting preventive training or rehabilitation outcomes for the shoulder.

Keywords: blood flow restriction; rotator cuff; shoulder; EMG

Muscle atrophy, along with decreases in strength and function, is a common sequela of shoulder injury or surgery.[40,45] However, because shoulders are often immobilized in a sling after injury or surgery, the use of early loading of these limbs to mitigate muscular atrophy is limited. Blood flow restriction (BFR) therapy uses a specialized cuff that is applied proximally around an injured limb and restricts blood flow (40%-80% arterial occlusion) via compression.[40] When combined with low-intensity exercise (<30% of 1 repetition maximum [1RM]), BFR has been shown to produce some of the same favorable effects as high-intensity exercise but at a greatly reduced load that can be performed in the early stages of rehabilitation in injury sites distal to the occlusion cuff (eg, elbow, knee).[12,29,40,56]

Although many of the mechanisms by which BFR may act on skeletal muscle remain under investigation,

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previous reports indicate that performing low-intensity exercise under occluded conditions acutely stimulates muscle anabolism primarily via mitogen-activated protein kinase (MAPK) and mammalian target of rapamycin complex 1 (mTORC1) intramuscular signaling pathways; these pathways regulate skeletal muscle responses to metabolic and mechanical stress as well as signaling via the sensing of effectors released from contracting muscle or systemically that act in an autocrine, paracrine, or systemic fashion.[22,23,25,26,36] When performing low-intensity exercise with BFR, muscles are often exercised to fatigue in a manner that, due to the partial occlusion, temporarily prevents the removal of lactate, calcium, and other metabolites that may reduce intracellular and local blood pH and contribute to stress signaling.[36] This occurrence combined with increased muscle fiber recruitment due to fatigue, structural strain from muscle cell swelling, and release of signaling effectors from muscle (eg, myokines, local insulin-like growth factors [IGFs], microRNA) has been hypothesized to directly and indirectly stimulate muscle anabolism via the aforementioned signaling pathways in concurrence with other mechanisms involved in the regulation of cell growth and degradation.[1,20,25,39,55,60] Because metabolic and mechanical stress is primarily experienced by muscles distal to the site of occlusion, one may speculate that proximal muscles (where blood flow is not occluded) may not experience the same stimulatory effects with regard to changes in strength and muscle mass. However, it has been postulated that BFR can provide benefits to muscle groups directly proximal to the site of occlusion via local paracrine or systemic action as well as elevated muscle fiber recruitment.[19,36]

Although BFR therapy is becoming popular in sports and military rehabilitation, current therapy protocols are based on limited data from short-term investigations, and adequate longitudinal studies are lacking.[36] Importantly, rehabilitation and injury prevention protocols for the upper extremities (particularly the shoulder) are currently underdeveloped, and hard data regarding the efficacy of BFR beyond anecdotal reporting are extremely limited.[36] Although promising results have been reported for the use of BFR for upper body rehabilitation, controlled studies on the effects of BFR for rehabilitation or preventive training on the rotator cuff or shoulder musculature as a whole are insufficient.[36] Previous review literature has proposed that enhanced muscle activation (inferred from electromyography [EMG]) of proximal muscles as a result of occlusion-induced distal fatigue may contribute to enhanced proximal benefit as a result of compensation for fatigued distal muscles.[16,57,61] This was first reported by Yasuda et al[61] to be potentially responsible for greater increases in pectoralis muscle size and strength after 8 weeks of high-volume/low-intensity bench press training in participants who trained with BFR compared with exercise prescription matched controls. Therefore, it is plausible that increased recruitment may not be limited to the regions distal to the BFR cuff. This may be of particular importance for the shoulder as a multiplanar joint that requires dynamic coordination of multiple large and small muscle groups to ensure the effective force-couple and co-contractive nature of the scapulohumeral region.

If determined to be effective for the shoulder, BFR therapy may have significant clinical effect for the prevention of injury in active individuals (particularly those who frequently rely on upper body musculature during sports or occupational performance) and potentially for accelerating rehabilitation from shoulder injuries. In particular, the clinical effect may be most apparent in overhead and throwing athletes, where injuries to the rotator cuff and/or other shoulder muscles can significantly threaten career longevity and have a high rate of recurrence in sports involving repetitive ballistic throwing movements.[8,52] Such findings would also be useful for older adults for the purposes of injury prevention and attenuation of debilitating muscle loss after injury or surgery. In light of previous literature and clinical observations, the purpose of this study was to compare 8 weeks of combined BFR and low-intensity exercise (BFR-LIX) versus low-intensity exercise alone (LIX) with regard to chronic changes in shoulder lean mass, upper extremity lean mass, rotator cuff strength, muscular endurance, and acute EMG amplitude. We hypothesized that BFR-LIX would elicit greater increases in rotator cuff strength, endurance, and muscle mass. Additionally, we hypothesized that the application of BFR would increase EMG amplitude in the shoulder muscles during acute exercise.

METHODS

This investigation was approved by our institutional review board for performing research involving human participants, and all volunteers provided informed consent before participating. Before the investigation began, data were pooled from previous strength training investigations[4,24,35,37,44] as well as from pilot BFR investigations performed in our laboratory and clinic.[34] Based on a power of 0.80 at $\alpha = .05$ with a minimum within-group detectable difference (pre- to posttraining) of 5% in upper extremity

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lean mass and 10% in isometric rotator cuff strength (primary outcome variables), it was determined that a minimum of 15 participants would be required per group. For between-group comparisons, this investigation was powered to detect an average minimum effect size of 0.5. Therefore, a target of 16 to 20 participants per group was set to account for potential dropouts. Participants from the surrounding community were selected who had not been performing upper body resistance exercise >1 day per week. Those exhibiting limited range of motion or dysfunction in the upper extremity or shoulders, vascular dysfunction or disease, class II obesity (body mass index >35), rapid weight change 1 year prior (>10%), or any known limitations to physical exercise were not permitted to participate. In addition, those taking ergogenic aids or medications known to affect muscle metabolism were not included.

A total of 35 untrained healthy adults (age, 18-45 years) were recruited to participate and provided informed consent. Of the 35 adults, 2 people were unable to complete the training due to scheduling conflicts and 1 person withdrew due to range of motion limitations related to a previous shoulder injury, leaving a final sample size of 32 participants who completed the training program. Before the initial assessments, participants were randomly assigned to 1 of 2 training groups (BFR group, 13 men, 3 women; No-BFR group, 10 men, 6 women). An overview of the testing/training schedule and exercises trained is provided in Figure 1.

Pre- and Posttraining Assessments

Before and after training, participants underwent 2 days of assessments separated by 48 to 72 hours.

Lean Mass. During the first day of testing, participants underwent a dual-energy x-ray absorptiometry (DEXA) scan (iDXA; GE) by a licensed radiologist for site-specific measurement of lean mass for the upper extremities and shoulder regions. During each scan, care was taken to ensure that participants maintained the same scan position. For shoulder region analysis, the region of interest (ROI) parameters were templated to individual participants based on skeletal landmarks in their initial scan that were then subsequently used for the posttraining measure. These 2D landmarks included the cervical vertebrae traced to the top of the first rib, down the outer edge of the rib cage to the location at which the scapula visually intersected the ribs, across the humerus (parallel to the bottom of the scan), and then around the upper arm, shoulder, and trapezius muscles, ending at the highest cervical vertebra below the jawbone.

The accuracy of segmented regional soft tissue analysis via DEXA has been previously reported to be within <1% to 6% error with excellent reliability between measurements (intraclass correlation coefficient [ICC] >0.99).[10]

Isometric Rotator Cuff Strength. After DEXA scanning, participants underwent maximal isometric rotator cuff strength assessment of each arm. A standardized procedure was used for shoulder strength testing, and all testing was performed by a sports-specialized (American Board of Physical Therapy Specialties Sports Clinical Specialist) physical therapist (C.H.) who has had extensive training in the evaluation and assessment of the upper extremity in athletic and general population settings. A total of 6 different maximal isometric strength tests were used to measure the strength of the rotator cuff muscles in the following order: (1) seated forward flexion at 90° of shoulder abduction, (2) seated scaption at 90°, (3) seated external rotation (ER) at 0°, (4) seated internal rotation (IR) at 0°, (5) prone ER at 90°, and (6) prone IR at 90°. Peak strength was measured using a microFET2 (Hoggan Scientific) hand-held dynamometer. This measurement technique was used similar to published protocols[13,14] demonstrating good to excellent reliability (ICC 0.85-0.99) for comparable testing procedures. For each isometric test, participants performed a 3-second maximal-exertion contraction against the dynamometer to determine peak strength. For each measure, tests were performed 3 times, and the highest value among the 3 trials was selected as the maximal strength value.

Strength-Endurance. After strength testing, participants were asked to perform the first of 2 endurance tests separated by 48 to 72 hours. On both occasions, a single set of repetitions to fatigue (RTF) were performed for 3 exercises in the following order: standing cable ER at 0° of shoulder abduction, standing cable IR at 0°, and dumbbell scaption with each exercise separated by a 2-minute rest period (Figure 1) and alternating between arms (order randomized). Resistance for the test was set at 20% of maximal strength assessed during the prior isometric testing (20%Iso-max). This test was performed in both groups with and without 50% limb occlusion pressure (LOP) applied by an automated tourniquet system (Delfi Medical Innovations) that provided automatic assessment (similar to an automated blood pressure cuff) and pressure regulation to maintain the same degree of occlusion throughout individual contractions (~10-20 mm Hg adjustment throughout range of motion depending on exercise). Occlusion pressure for the present investigation was selected based on current recommendations from the device manufacturer for the upper extremity supported by current literature.[16,42] For example, Counts et al[16] observed similar chronic and acute responses in the upper extremity using 40% compared with 90% LOP. In addition, Mattocks et al[42] observed 50% LOP to be at the upper end of tolerance, whereas participants were able to achieve comparable workloads to 20% and 30% LOP. For the present study population, 50% LOP ranged from 60 to 80 mm Hg depending on individual participants. A dual-purpose, easy-fit, variable contour nylon cuff (11.5 cm wide) placed around the most proximal portion of the upper extremity (just below the shoulder joint) was used for all testing and training (shown in Figure 1 and the online Video Supplement). The order of testing (occluded and unoccluded) was randomized between the 2 testing days for each participant. During occluded testing, tourniquet pressure was released between exercises.

Electromyography. As a secondary outcome measure, wireless surface electromyography (Trigno; Delsys) was recorded (dominant side only) as an indicator of muscle activation (measured as EMG amplitude [EMGa]). After

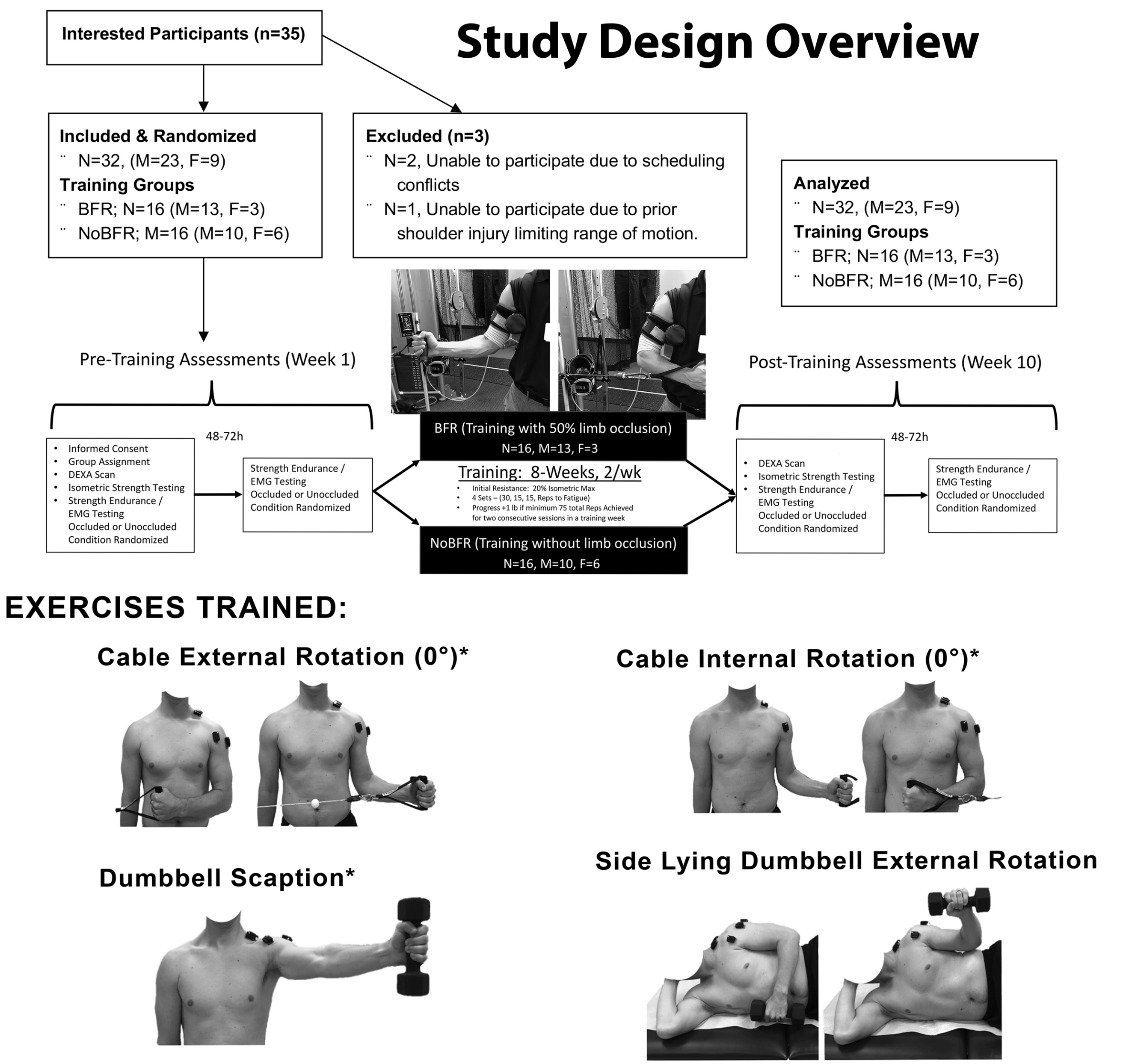


Figure 1. CONSORT (Consolidated Standards of Reporting Trials) recruitment flow diagram and exercises trained. *Exercises also assessed for endurance testing and EMG measures. BFR, blood flow restriction; DEXA, dual-energy x-ray absorptiometry; EMG, electromyographic; F, female; M, male.

appropriate skin preparation using isopropyl alcohol, EMG was conducted during endurance testing via electrodes placed on the anterior, middle, and posterior deltoid muscles as well as the infraspinatus, teres minor, and trapezius muscles (sampling rate, 1926 samples per second; filter range, 20-450 Hz; manufacturer specified).[27] The muscles were selected based on the following criteria: known use during the movements of interest, proximity to the skin surface for EMG recording, and ability to be palpated for targeted electrode placement (Figure 2).

Electrode placement was performed throughout the study by the same experienced research scientist (>15 years, B.L.) with palpation assistance from an experienced physical therapist (experience >10 years, C.H.) with specialization in sports and orthopaedics. Each muscle was palpated individually against resistance to attain optimal positioning parallel to muscle fiber orientation. After the electrodes were secured, adequate connectivity, signal validity, and Bluetooth connectivity were ensured. Before RTF testing trials for each exercise, participants performed a set of 5 calibration contractions at the same resistance (20%Isomax) followed by a 1-minute rest before RTF contractions. All calibration contractions were recorded in the unoccluded state. After collection, EMG data for each contraction were

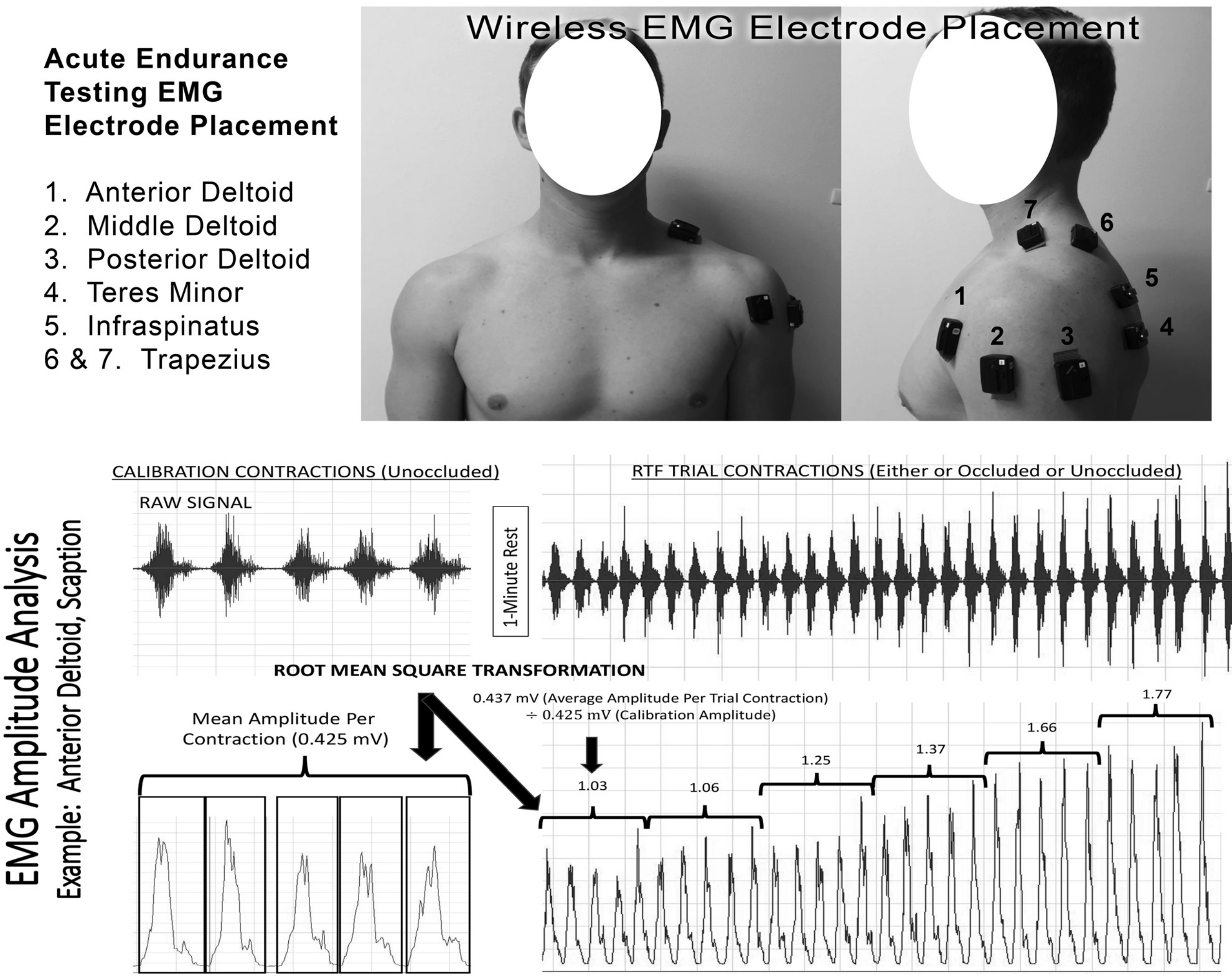


Figure 2. Electromyography (EMG) wireless electrode placement and amplitude analysis. RTF, repetitions to fatigue.

analyzed using EMGworx software (Delsys). After root-mean-square transformation, data were normalized to the average EMG output analyzed from the calibration contractions. Data were then averaged across every 5 contractions during testing before final statistical analysis (Figure 2). The number of repetitions analyzed for each exercise after RTF trials was based on the minimum number of repetitions that could be achieved by all participants for each exercise at 20%Iso-max (cable ER, 20 repetitions; cable IR and scaption, 30 repetitions).

Exercise Training

After initial assessments, participants were randomly assigned to their training groups (BFR, No BFR). Each group then performed 8 weeks of bilateral LIX (2 nonconsecutive days per week) using the following shoulder exercises: cable ER at 0°, cable IR at 0°, dumbbell scaption, and side-lying dumbbell ER at 0° (Figure 1). Initial resistance was set at 20%Iso-max. All bouts were performed in a one-on-one setting guided by trained laboratory staff. For each exercise, participants were asked to perform 1 set of 30 repetitions followed by 2 sets of 15 repetitions and a final set to fatigue. Rest periods were set at 30 seconds between sets and 2 minutes between exercises. For each exercise set, fatigue was determined as the point at which participants were no longer able to maintain proper exercise form. All exercises were performed in a single limb followed by the contralateral limb (order of limb training randomized for each session). Although the final set of each exercise was performed to fatigue, resistance was increased by 1 lb (~0.45 kg) for individual exercises only if a participant could consecutively achieve at least 30/15/15/15 (75 total) repetitions for both exercise sessions within a given training week. As additional training measures, total achievable repetitions, resistance, and exercise volume (sets × repetitions × resistance) for each exercise were recorded for each session. The BFR group performed all training sessions under 50% LOP applied at the proximal arm. When the tourniquet system was used, LOPs were reassessed for every session before exercise, and pressures were continually monitored. Participants were to perform the entirety of each exercise (including intra-set

TABLE 1
Participant Characteristics[a]

Group	Age, y	Height, cm	Body Mass, kg	Body Mass Index
BFR (13 M, 3 F)	27.6 ± 4.3	180.6 ± 4.3	88.6 ± 7.9	27.3 ± 2.8
No BFR (10 M, 6 F)	25.8 ± 4.1	177.6 ± 5.8	82.0 ± 9.6	26.0 ± 2.0

[a]Data are presented as mean ± 95% CI. BFR, blood flow restriction; F, female; M, male.

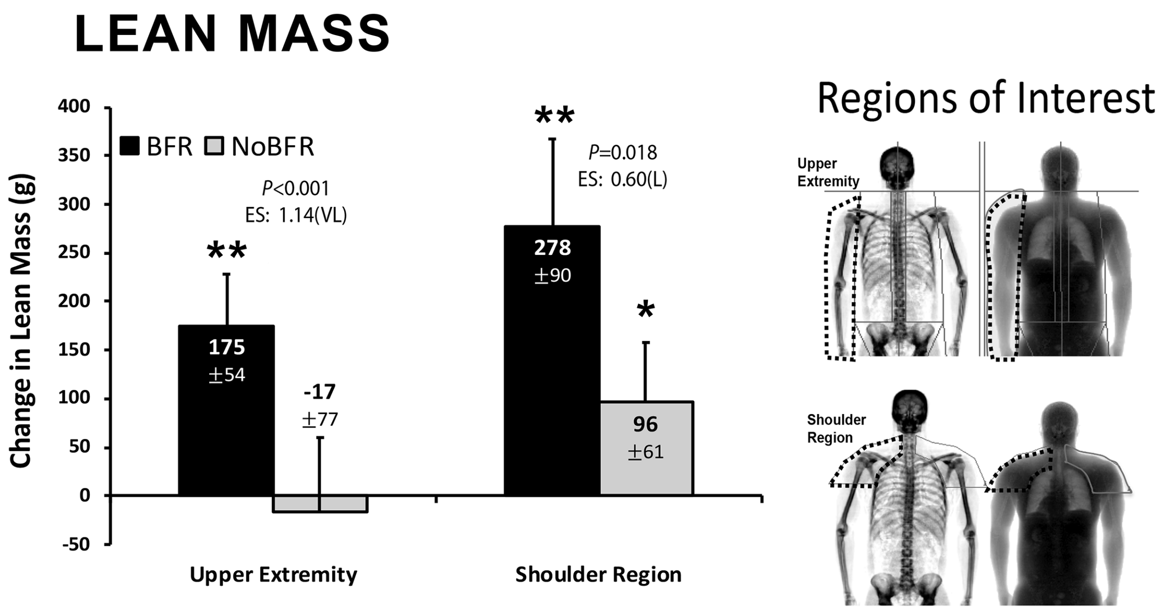


Figure 3. Lean mass. Data are presented as mean ± 95% CI for change in lean mass in the upper extremity and shoulder region (averaged across both limbs). Significant differences between groups for magnitude of change are indicated with *P* values. Effect sizes (ES) for significant between-group responses are reported using the Cohen *d* statistic, whereby values are interpreted as follows: 0-0.1 (negligible); 0.1-0.3 (small); 0.3-0.5 (moderate,); 0.5-0.7 (large; L); >0.7 (very large; VL). *Significant change from pretraining measures within group at $P < .05$. **Significant change from pretraining measures within group at $P < .01$.

rest periods) under 50% LOP with the tourniquets released during the 2-minute rest periods between sets as is commonly applied in our rehabilitation clinics for upper extremity rehabilitation. For completion of the study, participants were required to complete at least 14 of the 16 prescribed sessions (87.5%).

Statistical Analysis

Statistical analyses were performed using SPSS Statistics (Version 23.0; IBM) with bilateral data averaged across limbs. To test for between-group differences in chronic training adaptations (lean mass, isometric strength, strength endurance), a 2 × 2 (group × time) analysis of covariance (ANCOVA) repeated across training was used with pretraining values as covariates. The same model was used for between-group comparisons of change in weekly achievable training volume during the same week of training compared with the first week of training. EMG measures taken during acute endurance testing were compared using a multifactorial mixed-model analysis of variance (ANOVA) that entailed training group (2), time (2), testing condition (2; occluded/unoccluded), and repetition count (2; modeled between groups at the same 5-repetition interval and within groups compared with calibration contraction measures) repeated across training. Significant interactions indicated by type 3 tests of fixed effects were followed by a Bonferroni post hoc test for pairwise comparisons. For significant between-group pairwise comparisons of primary outcome variables, effect size (ES) was calculated using the Cohen *d* statistic [($Mean_1$ – $Mean_2$) ÷ Pooled Standard Deviation] and interpreted as follows: <0.1, negligible; 0.1-0.3, small; 0.3-0.5, moderate; 0.5-0.7, large; and >0.7, very large.[50]

RESULTS

Participant characteristics for each group are presented in Table 1; no differences were detected between groups.

Chronic Training Adaptations

Lean Mass. Training responses for regional lean mass measures are presented in Figure 3. Only the BFR group

TABLE 2
Isometric Strength and Muscular Endurance[a]

Maximal Isometric Strength, kg								
	BFR Group			No-BFR Group				
	Pre	Post	Δ	Pre	Post	Δ	P Value BG	ES, d
Flexion	12.2 ± 0.4	12.8 ± 0.4	0.6 ± 0.8	12.1 ± 0.4	11.9 ± 0.4	–0.2 ± 0.4	NS	NS
Scaption	12.1 ± 0.2	12.4 ± 0.2	0.3 ± 0.4	12 ± 0.2	12.5 ± 0.2	0.5 ± 0.5	NS	NS
ER 0°	13.9 ± 0.4	14.1 ± 0.4	0.2 ± 0.8	13.7 ± 0.4	13.9 ± 0.4	0.2 ± 0.8	NS	NS
IR 0°	20.2 ± 0.7	23.1 ± 0.7	2.9 ± 1.3[b,c]	20.1 ± 0.7	20.2 ± 0.7	0.1 ± 1.3	<.001	0.91 (VL)
ER 90°	16 ± 0.7	16.1 ± 0.7	0 ± 1.4	15.6 ± 0.7	14.7 ± 0.8	–0.9 ± 1.4	NS	NS
IR 90°	17.9 ± 0.8	18.6 ± 0.8	0.7 ± 1.6	17.4 ± 0.8	18.1 ± 0.8	0.7 ± 1.6	NS	NS

Strength-Endurance (Volume), kg								
	Occluded (50% LOP)				Unoccluded			
	Pre	Post	Δ	P Value BG ES, d	Pre	Post	Δ	P Value BG ES, d
Cable ER								
BFR	94.1 ± 10.9	155.1 ± 10.9	61.0 ± 20.7[d]	NS	96.2 ± 10.8	155.9 ± 10.8	59.7 ± 22.6[d]	NS
No BFR	97.3 ± 10.8	155.1 ± 10.8	57.8 ± 20.8[d]		99.5 ± 12.8	157.2 ± 10.7	57.70 ± 20.5[d]	
Cable IR								
BFR	230.9 ± 19.5	389.5 ± 19.6	158.5 ± 37.1[c,d]	<.001	249.3 ± 17.9	407 ± 17.9	157.7 ± 34.0[c,d]	<.001
No BFR	230.7 ± 19.5	305.9 ± 19.5	75.2 ± 37.2[d]	1.04 (VL)	249.1 ± 17.8	342.2 ± 17.8	93.1 ± 33.9[d]	0.89 (VL)
Scaption								
BFR	137 ± 18.9	240.3 ± 18.8	103.3 ± 35.8[d]	NS	140.2 ± 18.4	231.7 ± 18.4	91.5 ± 38.8[d]	NS
No BFR	134.8 ± 18.8	211.2 ± 18.8	76.4 ± 35.7[d]		138.6 ± 18.3	222.7 ± 18.4	84.1 ± 34.8[d]	

[a]Chronic response data for the BFR and No-BFR groups assessed before (pre) and after (post) training are presented as adjusted mean ± 95% CI for maximal isometric strength (assessed using dynamometry) as well as total achievable volume (repetitions × resistance) during single-set repetitions to failure performed at 20% isometric maximum tested with (occluded) and without (unoccluded) 50% LOP applied (averaged across limbs). Effect sizes for significant between-group responses are reported using the Cohen d statistic, whereby values are interpreted as follows: 0-0.1 (negligible); 0.1-0.3 (small); 0.3-0.5 (moderate); 0.5-0.7 (large); >0.7 (very large). BFR, blood flow restriction; BG, between-group; ER, external rotation; ES, effect size; IR, internal rotation; LOP, limb occlusion pressure; NS, not significant; VL, very large.
[b]Significantly different from baseline within group ($P < .05$).
[c]Significantly different training response from the No-BFR group ($P < .01$).
[d]Significantly different from baseline within group ($P < .01$).

had a significant increase in upper extremity lean mass ($P < .001$). Both the BFR ($P < .01$) and No-BFR ($P < .05$) groups had increases in shoulder region lean mass. However, the magnitude of increase (for both regions of interest) was observed to be greater in the BFR group ($P < .05$).

Isometric Strength and Strength Endurance. Pre- and posttraining measures of isometric strength and strength endurance (measured in single-set repetitions to fatigue) are presented in Table 2. Only the BFR group had an increase in strength from the pretraining measurement ($P < .001$); for IR 0°, the magnitude of change from pretraining was greater for the BFR group than the No-BFR group ($P < .001$). No other significant changes in isometric strength were observed for the remaining measures. Although both groups had significant increases across all measures of strength-endurance ($P < .01$), the BFR group had significantly greater increases compared with the No-BFR group for IR 0° under both occluded (~2.1-fold difference between groups) and unoccluded (~1.7-fold difference between groups) conditions ($P < .001$).

Shoulder EMG. No effect of training group or time (pre- or posttraining) was observed, and therefore both were excluded from the model before final analysis, with data collapsed across group and training timepoints. Data for all muscles where differences between conditions (occluded vs unoccluded) were detected are presented in Figure 4. Both testing conditions elicited a gradual increase in EMGa with increasing repetitions per workload ($P < .05$). However, the occluded condition yielded higher EMGa among several muscles within each exercise ($P < .05$).

For cable ER, the occluded condition elicited greater EMGa in the posterior deltoid, infraspinatus, and teres minor across all but one of the repetition intervals ($P < .05$) (Figure 4). For cable IR, greater EMGa was observed in the occluded condition for the anterior deltoid, posterior deltoid, and teres minor for 4 of 6 repetition intervals within each muscle ($P < .05$). Finally, for scaption, the occluded condition resulted in greater EMGa for all muscles analyzed ($P < .05$) with amplitudes across all repetitions for the anterior deltoid, middle deltoid, and trapezius ($P < .05$).

Weekly Achievable Workload. Data for total weekly achievable volume are presented in Figure 5. Although

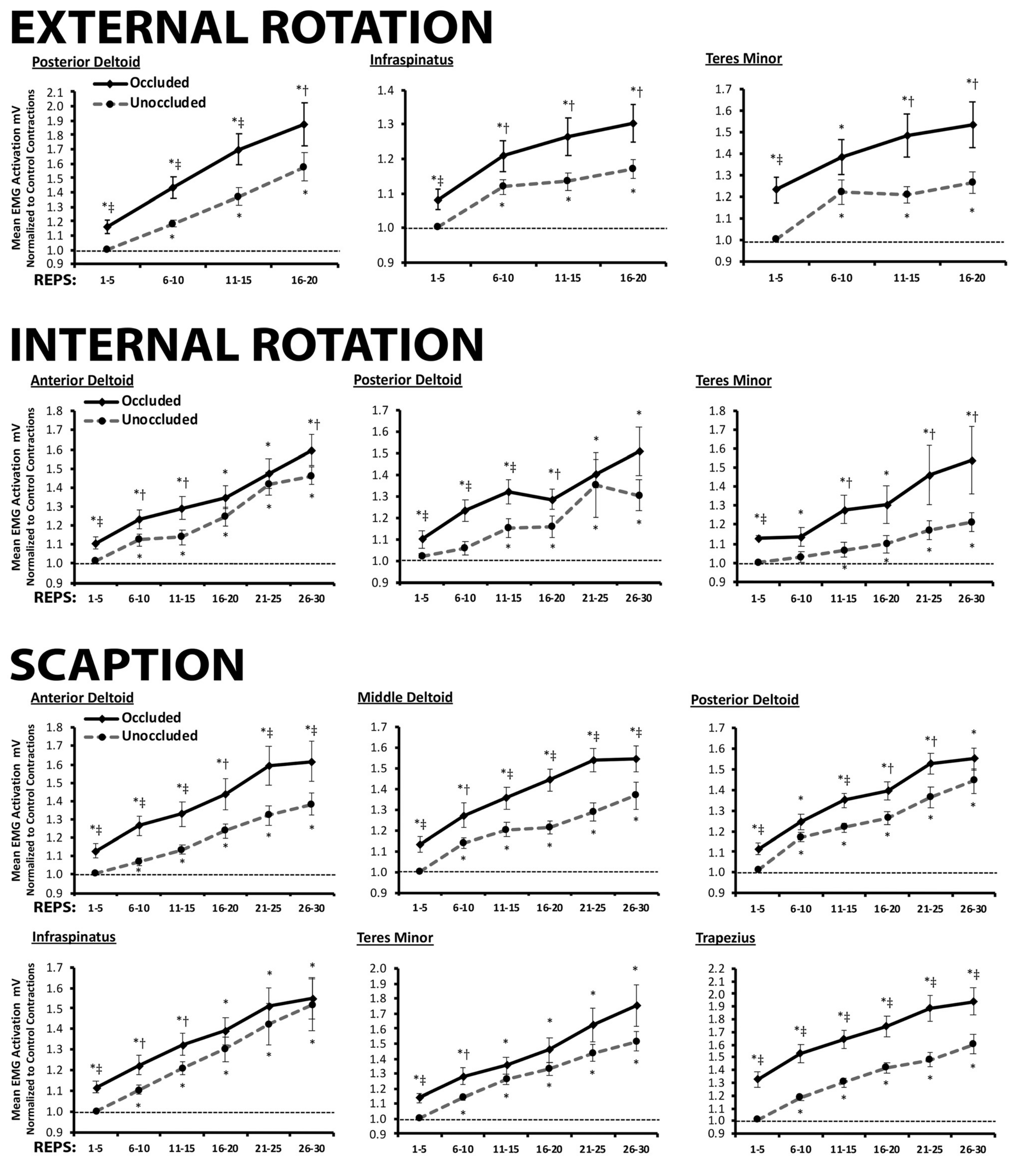
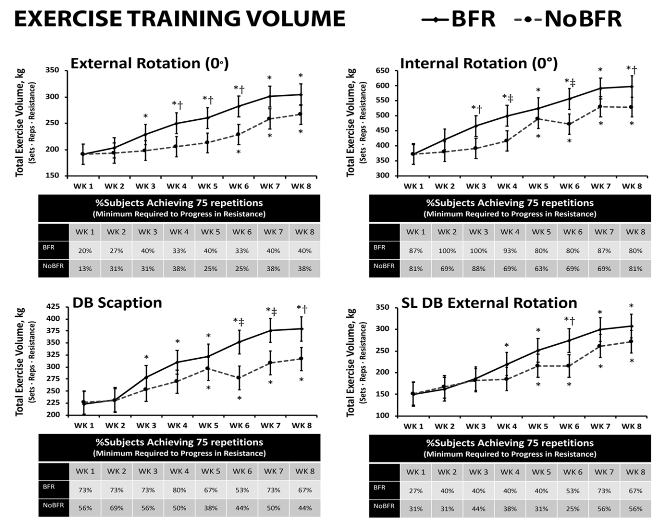


Figure 4. Electromyographic (EMG) findings. Data are presented as acute EMG amplitude (EMGa) recorded from target shoulder muscles during single-set repetitions (averaged across every 5 contractions) to fatigue (RTF) with and without the application of 50% limb occlusion (sample rate, 1926 samples per second; filter, 20-450 Hz). Data are shown are mean ± 95% CI after root mean square transformation and normalization to 5 unoccluded control contractions performed before each trial for each exercise. Because no effects of group or time were observed, data are shown collapsed across both groups and measurement timepoints. *Significant difference from control contractions within condition ($P < .05$). †Significant difference between groups at the same repetition count at $P < .05$. ‡Significant difference between groups at the same repetition count at $P < .01$.

both groups were able to increase their achievable workload throughout the course of training, the BFR group had greater increases in achievable workload for cable ER (weeks 4-6), cable IR (weeks 2-4, 6, 8), dumbbell scaption (weeks 6-8), and side-lying dumbbell ER (week 6) ($P < .05$). Although not statistically compared, these findings corresponded with a greater percentage of participants in the BFR group (on average) who were able to achieve the minimum repetition count (30/15/15/15; total 75) required to progress in resistance each week.



External Rotation (0°) — %Subjects Achieving 75 repetitions (Minimum Required to Progress in Resistance)

	WK 1	WK 2	WK 3	WK 4	WK 5	WK 6	WK 7	WK 8
BFR	20%	27%	40%	33%	40%	33%	40%	40%
NoBFR	13%	31%	31%	38%	25%	25%	38%	38%

Internal Rotation (0°) — %Subjects Achieving 75 repetitions (Minimum Required to Progress in Resistance)

	WK 1	WK 2	WK 3	WK 4	WK 5	WK 6	WK 7	WK 8
BFR	87%	100%	100%	93%	80%	80%	87%	80%
NoBFR	81%	69%	88%	69%	63%	69%	69%	81%

DB Scaption — %Subjects Achieving 75 repetitions (Minimum Required to Progress in Resistance)

	WK 1	WK 2	WK 3	WK 4	WK 5	WK 6	WK 7	WK 8
BFR	73%	73%	73%	80%	67%	53%	73%	67%
NoBFR	56%	69%	56%	50%	38%	44%	50%	44%

SL DB External Rotation — %Subjects Achieving 75 repetitions (Minimum Required to Progress in Resistance)

	WK 1	WK 2	WK 3	WK 4	WK 5	WK 6	WK 7	WK 8
BFR	27%	40%	40%	40%	40%	53%	73%	67%
NoBFR	31%	31%	44%	38%	31%	25%	56%	56%

Figure 5. Achievable exercise volume. Data are presented as mean ± 95% CI for weekly achievable exercise volume (sets × repetitions × resistance) (kg) averaged across bouts (2) for each week of training for cable external rotation 0°, cable internal rotation 0°, dumbbell (DB) scaption, side-lying dumbbell (SL DB) external rotation, and the sum volume for all exercises. *Significant difference from week 1 of training within group ($P < .05$). †Significant difference between groups at the measurement timepoint at $P < .05$. ‡Significant difference between groups at the measurement timepoint $P < .01$. Data are also presented below each chart for the percentage of participants each week who achieved the weekly minimum workload (75 repetitions) to progress in resistance (1 lb) for the following week of training. BFR, blood flow restriction.

DISCUSSION

The purpose of the present study was to determine whether combined BFR-LIX shoulder/rotator cuff training promotes greater increases in shoulder lean mass, rotator cuff strength, muscular endurance, and acute increases in muscle activation compared with LIX alone. The results indicated that the addition of BFR (applied at 50% LOP) to the proximal arm effectively augmented increases in shoulder muscle mass, endurance, and some parameters of isometric strength when combined with the standard rotator cuff training exercises commonly used in clinical and athletic training settings. Although the mechanisms are not completely understood at this time, we hypothesize that these results are attributable, in part, to greater acute activation of deltoid and rotator cuff muscles observed under occluded conditions (Figure 4). Cumulatively, these results suggest that BFR may be a reasonable supplement to low-intensity shoulder and rotator cuff strengthening and may be of interest for rehabilitation, injury prevention, and perhaps performance during overhead activities.

Muscle Mass Development

In the present study, we observed a greater increase in both upper extremity and shoulder region lean mass (Figure 3) in the BFR group. Importantly, exercise training volume (typically quantified in resistance training as sets × repetitions × resistance) rather than intensity of exercise (percentage of maximal strength used during training) has been previously observed to be a prime stimulator of muscle mass development in response to resistance exercise.[9,21] Therefore, it is likely that our present findings are attributable, at least in part, to the greater achievable weekly training volumes observed in the BFR group (Figure 5). Regarding the shoulder region, EMG measures were greater when exercises were performed under the occluded condition compared with the unoccluded condition (Figure 4), indirectly suggesting a greater contribution to the metabolic and mechanical work being performed by the shoulder muscles.[11,51,59] Therefore, we find it reasonable to hypothesize that during training, BFR may have contributed to the present findings via more effective targeting of the muscles of interest during LIX.

As previously mentioned, several mechanisms have been proposed to play a role in acute and chronic muscle responses to BFR-LIX, and BFR-LIX has often been suggested to be comparable to high-intensity exercise (>70% of 1RM) via similarities in intramuscular responses related to intracellular anabolic signaling (mTORC1 and MAPK pathways), protein turnover, hormone signaling, substrate metabolism, and stress response.[1,36,53-55] Although the vast majority of current BFR literature has focused on muscles distal to the site of occlusion (likely explaining some of the present observation regarding the upper extremity), further observations of exercise-induced muscle tissue crosstalk (autocrine, paracrine, and systemic) via myokine, metabolite, and hormonal responses may provide some insight into how BFR may elicit adaptive responses in proximal muscles.[2,15,48] For example, Madarame et al[41] observed greater increases in upper body muscle size and strength in untrained men who performed lower body BFR-LIX compared with those who performed LIX alone. In the same study, a greater acute systemic increase in postexercise growth hormone release was observed. Abe et al[1] and Takano et al[55] observed chronic and acute systemic increases in IGF-1 after BFR-LIX training in the lower limbs. Regarding metabolic stress signaling, BFR-LIX has been observed to increase blood lactate and alter blood pH similarly to high-intensity exercise.[36] Additionally, Oishi et al[43] observed that increased local and systemic concentrations of metabolites such as lactate and calcium through exercise-induced stress or pharmaceutical means increased satellite cell activity and anabolic signaling that may chronically increase satellite cell differentiation and muscle growth via a calcineurin-dependent signaling pathway. With similar findings to the present work, Bowman et al[5] observed increased limb circumference and strength gains after 6 weeks of BFR-LIX training of the rotator cuff and upper extremity when comparing 2 training groups (BFR vs non-BFR). Notably, the BFR group used in that study trained with 1 arm under occluded conditions (60% LOP) and 1 arm without occlusion. Although no direct measures of systemic or intramuscular regulators of acute or chronic anabolism were made, the limb that was trained without occlusion in the BFR group was observed to have a 9% (on average) greater increase in grip strength compared with the non-BFR group that trained entirely without occlusion. Bowman et al concluded that these findings might potentially indicate a systemic effect of BFR-LIX training. On the basis of previous literature and proximity of the shoulder musculature to the distally occluded upper extremity, it is possible that some degree of paracrine or systemic signaling may have similarly contributed to the outcomes observed in the present investigation. However, we caution the reader that (1) the mechanisms discussed were not directly measured during this study; (2) many of the mechanisms postulated to govern local and systemic responses to BFR remain unclear and have yet to be adequately investigated; and (3) generalized inferences about systemic, autocrine, or paracrine musculoskeletal responses to contractile activity in the absence of measurement should be regarded with caution because metabolic, nervous system, and hormonal regulation of exercise adaptation is complex, with a high degree of systemic and intracellular cross-signaling between several physiological systems.[33,38,46,58] Last, the degree to which small muscle group or upper extremity exercise (as performed here) may affect adaptation via systemic responses in comparison to multijoint or large muscle group exercises (eg, squat, leg press, lunge, and dead lift, which are known to elicit large systemic effects) requires further investigation because cumulative contractile activity (exercise volume) and muscle mass involved in a given activity greatly influence hormone and immune responses to activity.[33,40] For example, Brumitt et al[7] observed no difference between training with or without BFR during 8 weeks of twice-weekly side-lying dumbbell ER (30/15/15/15 repetitions; 30% of 1RM) with regard to changes in strength and supraspinatus tendon thickness (measured via ultrasonography). This is in contrast to both the present investigation and the investigation performed by Bowman et al,[5] whereby multiple exercises were used. Additionally, in the present study, participants exercised to fatigue on the final set. Therefore, it is possible that a certain volume threshold and/or cumulative time under occlusion may be required for proximal benefits to BFR training to present.

Strength and Muscular Endurance

Multiplanar isometric shoulder strength is a common clinical measurement taken in athletic training and physical therapy settings to assess rehabilitation progress and potential muscular deficiencies in the extremities. Here we observed greater increases in IR 0° in the BFR group (Table 2). Although the procedures used to assess strength in this fashion have been previously validated and were performed by the same blinded technician, we acknowledge that there may be limitations of the application of hand-held dynamometry in this instance. Importantly, the principle of training specificity states that physiological adaptations to training are specific to the types of training performed.[6] Therefore, the lack of response of some of our measures likely reflects that participants trained using dynamic and nonisometric exercises during the 8-week period. Regardless, the greater improvements in isometric strength in the BFR group at IR 0° compared with other measures is of interest. Although not entirely clear at this time, these results may, in part, be a factor of other large muscle groups, such as the pectoralis, outside of the upper extremities and shoulder region that may also assist during IR at 0°. Notably, we did observe a greater percentage of participants (on average) progressing in resistance from week to week for all exercises, which contributed to greater increases in weekly achievable workload in the BFR group compared with the No-BFR group (Figure 5). Therefore, although maximal isometric strength may have increased only across a single measure, it is likely that dynamic strength was increased at submaximal workloads for the specific activities trained.

With regard to acute muscular endurance, we observed greater improvements in the BFR group for IR 0° (Table 2). Further highlighting the principle of specificity of training and due to the nature of each group's training, the difference in the magnitude of improvement between the BFR and No-BFR groups was greater on average when participants performed endurance testing under the occluded compared with the unoccluded condition (although not statistically compared). Although the improvement in single set repetitions to fatigue was significantly different between groups only for IR 0°, it is notable that the BFR group had a greater increase in achievable training workload for total volume, ER 0°, IR 0°, dumbbell scaption, and side-lying dumbbell ER across several measurement timepoints during training (Figure 5). These results indicate that although isometric strengthening (as a result of this particular intervention) may be limited, the use of BFR-LIX for shoulder and rotator cuff training may be most useful for promoting increases in strength-endurance (in addition to muscle mass, as previously described). Clinically, this type of training may be valuable for injury prevention or shoulder rehabilitation. The rotator cuff and deltoid muscles often function to provide stability and deceleration during large powerful and/or ballistic movements of the upper extremity such as throwing, pushing, and pulling.[31] On the basis of the present data, future investigations should seek to determine whether BFR-LIX training for the shoulders may aid in preventing fatigue-induced shoulder injuries, prolonging occupational or sports performance, and improving recovery from fatiguing overhead activities such as lifting or throwing. Whether such training may be beneficial to individuals or athletes who are already relatively trained remains unknown. For example, Curran et al[17] observed that 8 weeks of BFR-LIX did not contribute to greater increases in quadriceps muscle strength, volume, or activation when performed after 10 weeks of rehabilitation from anterior cruciate ligament reconstruction. Therefore, it is possible that the greatest contribution of BFR may be prevention of muscle loss and function during initial periods of partial unloading (due to injury or surgery) or when an individual is novice to the type of exercises being performed. For example, it has previously been observed that the anabolic responses to acute resistance exercise are blunted in trained compared with untrained, healthy adults.[3,18,32]

BFR and Shoulder Muscle Targeting

As previously discussed, during acute testing we observed greater EMGa under occluded (compared with unoccluded) conditions for each exercise (Figure 4), which indirectly indicates that BFR induced a greater activation of the targeted shoulder muscles. Although we cannot be certain of the entire upper extremity, these findings, with regard to the shoulder region, also align with our observations of greater increases in lean mass and strength-endurance in the BFR group compared with the No-BFR group. However, initially we hypothesized that potential differences in EMGa would be the result of early occlusion-induced fatigue of accessory muscles distal to the cuff site that would result in greater use of shoulder muscles. Although partial support for that hypothesis may be provided by the greater difference in EMGa with increasing repetition counts for some muscles during some exercises (eg, internal rotation of teres minor, as shown in Figure 4), it is notable that the increase appeared to occur right away as occlusion was applied and participants began their repetition test. Because skeletal muscle contraction strength and excitability have been widely shown to be affected by proprioceptive reflex mechanisms that are involved in the detecting of stretch within muscle and tendons (which can affect various chains of movement),[28,47,49] we find it likely that such mechanisms play a role in the acute and chronic proximal responses observed here. For example, tactile pressure cues have been commonly shown in physical therapy settings to increase EMGa via proprioceptive mechanisms.[28,47] Importantly, only 1 standardized occlusion pressure was used during this study (50% LOP), which is commonly used in clinics. Further research will be required to determine how the degree of occlusion may affect EMGa of proximal muscles. Regardless, the present data indicate that the use of BFR may provide improved and more efficient targeting of the rotator cuff and shoulder region as a whole.

Practical Considerations and Limitations

The present study design followed a standardized protocol of repetition, occlusion level, and intensity used in several studies, specified by the manufacturer, and used in rehabilitation settings.[36] However, the protocol used here differed from the majority of previous investigations in that the final set of each exercise was performed to fatigue during each bout. Although automated tourniquet systems may provide safety advantages via dynamic personalized pressure adjustment and monitoring of occlusion pressures,[30] the cost of such tourniquet devices is likely a consideration for coaches, clinicians, and wellness professionals. For example, if training to fatigue yielded similar training outcomes, it is unlikely that BFR would be a practical training aid for noninjured populations for preventive use. However, the present findings indicate that BFR-LIX training acutely and chronically yielded greater adaptations when performed to fatigue. Therefore, BFR-LIX training for the shoulder may be beneficial for those who are at a greater occupational and/or sports-related risk for shoulder injuries.

Because of improved targeting, BFR-LIX may also be a suitable clinical therapy for minimizing injury- or disuse-related muscle and strength loss after injury or surgery. In patients with shoulder injuries (nonoperative or operative), the goals of performing rotator cuff exercises are to prevent muscle atrophy, regain range of motion, and restore strength and endurance to the level of the uninjured contralateral limb. On the basis of the findings in this study, we hypothesize that such treatment with BFR may improve recovery trajectories and overall clinical outcomes in patients recovering from shoulder injury or surgery. However, future research is needed in patient populations to determine the efficacy of BFR for shoulder rehabilitation.

In this investigation, participants started at 20% of their isometric maximal strength for each exercise, as is common protocol in our rehabilitation clinics. Although not statistically compared, a greater percentage (on average) of participants (in both groups) were able to complete the minimal workload needed to progress in resistance more frequently during IR and scaption compared with both of the ER exercises. In the absence of electronic isokinetic testing devices, future studies may consider using a repetition maximum protocol for the exercises performed or adjusting the starting percentages depending on the exercise.

This study is not without limitations. Due to the nature of testing, technicians and participants were not blinded to condition during acute EMG testing and data recording. Therefore, we are unable to confirm that participants, knowingly having occlusion applied, did not alter performance in some way during maximal repetition testing. To minimize the effect of test acclimation, the order of testing (occluded/unoccluded) was randomized. Because surface EMG was used, we can only generalize to regions of the shoulder where electrodes were placed over muscle that could be palpated (as opposed to needle-based EMG, where electrodes are inserted directly into muscle). Although participants trained to fatigue, we also cannot dismiss that a placebo effect may have affected those in the BFR group during training. Another limitation of the present work is that these exercises were performed by previously untrained adults in isolation rather than being incorporated into a broader upper body or total body resistance training. For those interested in the use of BFR-LIX shoulder training for improving performance or preventing sports injuries (eg, throwing athletes), further investigations will be required regarding how to best incorporate BFR-LIX into a progressive or maintenance-based strength training program. Because the rotator cuff and deltoid muscles often function to provide stability to the shoulder during contraction and deceleration after rapid rotational movements, BFR-LIX may be best and most safely performed toward the end of an upper body training bout so that rotator cuff fatigue is not present during exercises that require larger muscle groups and greater resistance loads. Further, although a non-BFR intervention group (the No-BFR group) was used in this investigation for comparison of responses, a nonexercise control group was not used; using such a control group might have assisted in determining the reliability of some of the acute testing over time for assessing outcomes. Last, we did not examine systemic, local, or intramuscular effectors known to influence skeletal muscle metabolism in response to acute or chronic training. As such, further study will be required to better characterize potential acute and chronic effects of BFR-LIX training that may affect muscles directly proximal to the site of occlusion or elsewhere.

CONCLUSION

The use of BFR applied around the proximal arm augments adaptation to LIX via greater increases in whole arm and shoulder region muscle mass, strength-endurance, and some clinical measures of isometric strength (although seemingly limited) compared with LIX alone. Although several mechanisms have been proposed to be responsible for BFR-induced training adaptations in skeletal muscle distal to the site of occlusion, we conclude that responses observed in the shoulder muscles as a whole were due in part to increased EMGa, which may indicate increased muscle activation proximally. Overall, the present results provide considerable support for using BFR for preventive rotator cuff and deltoid training. These findings also provide support for future research on the utility of BFR for rehabilitation after both operative and nonoperative treatment of rotator cuff injuries. Last, further research is needed to determine how BFR-LIX rotator cuff strengthening may be best incorporated into a comprehensive training program for injury prevention, rehabilitation, and improved performance as well as which populations may benefit the most.

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A Video Supplement for this article is available online.

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