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ONLINE ARTICLES

Rotator cuff training with upper extremity blood flow restriction produces favorable adaptations in division IA collegiate pitchers: a randomized trial

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Background: Recent evidence indicates that combined upper extremity blood flow restriction (BFR, applied distally to the shoulder) and low-load resistance exercise (LIX) augments clinically meaningful responses in shoulder region tissues proximal to the occlusion site. The purpose of this investigation was to determine the efficacy of BFR-LIX for the shoulder when added to standard offseason training in Division IA collegiate baseball pitchers. We hypothesized that BFR-LIX would augment training-induced increases in shoulder-region lean mass, rotator cuff strength, and endurance. As secondary outcomes, we sought to explore the impact of BFR-LIX rotator cuff training on pitching mechanics.
Methods: Twenty-eight collegiate baseball pitchers were randomized into 2 groups (BFR$^{N = 15}$ and non-BFR [NOBFR]$^{N = 13}$) that, in conjunction with offseason training, performed 8 weeks of shoulder LIX (Throwing arm only; 2/week, 4 sets [30/15/15/fatigue], 20% isometric max) using 4 exercises (cable external and internal rotation [ER/IR], dumbbell scaption, and side-lying dumbbell ER). The BFR group also trained with an automated tourniquet on the proximal arm (50% occlusion). Regional lean mass (dual-energy x-ray absorptiometry), rotator cuff strength (dynamometry: IR 0 & 90, ° ER 0 & 90, ° Scaption, Flexion), and fastball biomechanics were assessed pre and post-training. Achievable workload (sets × reps × resistance) was also recorded. An ANCOVA (covaried on baseline measures) repeated on training timepoint was used to detect within-group and between-group differences in outcome measures ($\alpha = 0.05$). For significant pairwise comparisons, effect size (ES) was calculated using a Cohen's d statistic and interpreted as: 0-0.1, negligible; 0.1-0.3, small; 0.3-0.5, moderate; 0.5-0.7, large; >0.7, and very large (VL).
Results: Following training, the BFR group experienced greater increases in shoulder-region lean mass (BFR: ↑ 227 ± 60g, NOBFR: ↑ 75 ± 37g, P = .018, ES = 1.0 VL) and isometric strength for IR 90 ° (↑ 2.4 ± 2.3 kg, P = .041, ES = 0.9VL). The NOBFR group experienced decreased shoulder flexion ↓ 1.6 ± 0.8 kg, P = .007, ES = 1.4VL) and IR at 0 ° ↓ 2.9 ± 1.5 kg, P = .004, ES = 1.1VL). The BFR group had a greater increase in achievable workload for the scaption exercise (BFR: ↑ 190 ± 3.2 kg, NOBFR: ↑ 90 ± 3.3 kg,

Houston Methodist Research Institute approved this study (approval no. PRO00017362).

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$P = .005$, ES = 0.8VL). Only the NOBFR group was observed to experience changes in pitching mechanics following training with increased shoulder external rotation at lead foot contact (↑ 9.0° ± 7.9, $P = .028$, ES = 0.8VL) as well as reduced forward ↓ 3.6° ± 2.1, $P = .001$, ES = 1.2VL) and lateral ↓ 4.6° ± 3.4, $P = .007$, ES = 1.0VL) trunk tilt at ball release.

Conclusion: BFR-LIX rotator cuff training performed in conjunction with a collegiate offseason program augments increases in shoulder lean mass as well as muscular endurance while maintaining rotator cuff strength and possibly pitching mechanics in a manner that may contribute to favorable outcomes and injury prevention in baseball pitching athletes.

Level of Evidence: Level I; Randomized Controlled Trial; Treatment Study

Keywords: Shoulder; rehabilitation; velocity; exercise; thrower; endurance

Throwing athletes such as baseball pitchers require advanced coordination and strength around the scapulohumeral region where acute or overuse injuries can threaten career longevity and have a high-recurrence rate.[10,51] Therefore offseason and inseason programs designed to strengthen the rotator cuff and surrounding musculature are common for maintenance and injury prevention.[2,60] However, the addition of high-intensity, high-load training exercise (HIX) of the rotator cuff muscles may be inadvisable due to a corresponding increased risk of overtraining and/or injury.[36]

Blood flow restriction (BFR) therapy utilizes a specialized cuff applied around the proximal upper and lower extremities for the purpose of partially-occluding blood flow (typically 40%-80% arterial limb occlusion pressure, LOP) via compression.[39] When combined with low-load resistance exercise (LIX; <30% 1-repetition maximum), BFR-LIX has been shown to produce adaptations similar HIX.[15,39,41,54] Chronic responses to BFR-LIX include increased muscle hypertrophy,[29,30] reductions in postoperative atrophy of muscle and bone,[14,38,52,54] and improved muscle function.[39] Although less studied, the application of BFR in sport training has recently been a topic of heightened interest.[3,21,57]

Because occlusion-mediated metabolic and mechanical stress is primarily experienced by musculature distal from the site of compression, much of the focus of previous BFR interventions has been on structures distal to the occlusion site. However, recent findings indicate that BFR may also enhance adaptations to tissues directly proximal to the site of occlusion.[8,19,37,59] In recent observations, BFR-LIX (50% LOP around the proximal upper extremity) yielded greater increases in whole limb and shoulder region muscle mass, greater improvements in muscular work capacity, increased muscle activation, and some increases in isometric strength compared with LIX alone in healthy, untrained adults following 8 weeks of rotator cuff training.[37] These observations align with previous findings of greater proximal increases in muscle size and strength following upper extremity BFR-LIX training.[8,59]

Based on current literature, BFR-LIX may be suitable for shoulder training in throwing athletes.[35] However, preliminary reports have involved primarily nonathlete populations. Further, relative responsiveness to a given training stimulus diminishes the more trained an individual is.[46] In other words, the impact of BFR-LIX for athletes who are already subjected to progressive HIX training and sport-specific practice remains to be determined. As an important clinical concern, it is also unknown as to whether BFR could have a beneficial or deleterious impact on throwing mechanics.

In light of recent findings and a paucity of throwing athlete-specific data in the literature, the purpose of this investigation was to determine the efficacy of BFR-LIX for the shoulder when added to offseason training in Division IA collegiate baseball pitchers. Based on previous reports,[8,37,59] we hypothesized that BFR-LIX would augment training-induced increases in shoulder-region muscle mass, rotator cuff strength, and endurance. As secondary outcomes, we sought to explore the impact of BFR-LIX rotator cuff training on fast ball pitching mechanics.

Materials and methods

This investigation was approved by the Houston Methodist Research Institute institutional review board and all athletes provided informed consent before participating (clinicaltrials.gov registration: NCT04540367). The study intervention took place during offseason training (Fall 2019 & Fall 2020) within a single division IA collegiate baseball program and lasted for a duration of 8 weeks. An overview of the study design and participant inclusion/exclusion is shown in the CONSORT[4] diagram presented in Fig. 1. To be eligible for inclusion, all athletes had to be healthy collegiate division IA pitchers (no contraindications to exercise) and actively participating in team-directed offseason training involving weekly sport-specific practice paired with a progressive strength and conditioning program. Inactive athletes with previous upper or lower extremity injures undergoing rehabilitation as well as any further contraindications to their standard offseason sport training were excluded. Prior to participation, athletes were randomized into two groups (BFR or non-BFR [NOBFR]) by the research team's clinical trials manager using block randomization within each scholastic classification and an Excel-based (Microsoft, Redmond, WA, USA) randomization function.

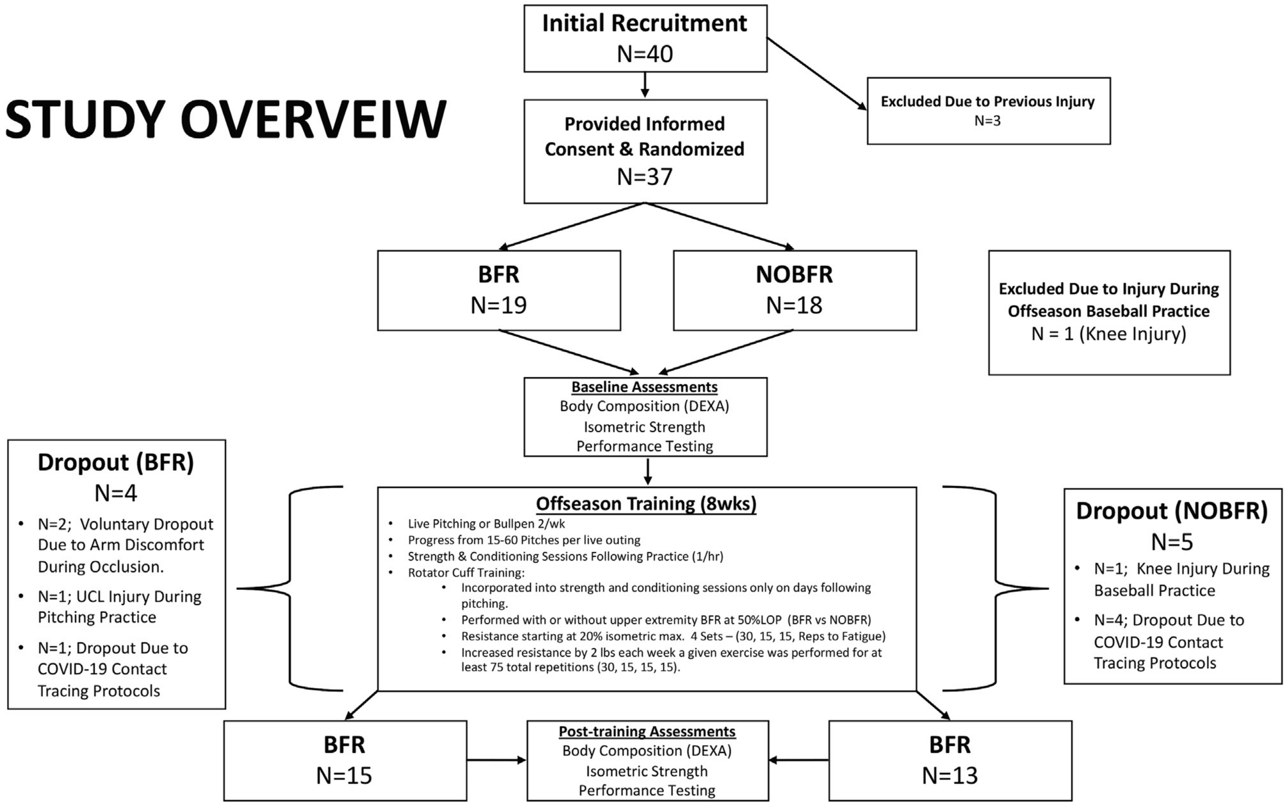

Figure 1 CONSORT recruitment flow diagram. *BFR*, blood flow restriction; *DEXA*, dual-energy x-ray absorptiometry; *CONSORT*, Consolidated Standards of Reporting Trials.

Pre and post-training assessments

The week before and after the experimental 8-week training period, all pitchers underwent a series of standardized assessments on two separate days.

Lean mass

The following methods for quantifying changes in lean mass were matched to previous investigations.[13,37,38] During the first day of testing, pitchers underwent a dual-energy x-ray absorptiometry (DEXA) scan (iDXA; GE, Boston, MA, USA) by a licensed radiologist (blinded to group assignment) for site-specific measurements of total body composition and lean mass for the upper extremities and shoulder regions. Each scan was performed the week before and after the 8-week training period with a minimum of 72 hours of rest prior to assessment with time of day matched as closely as possible. For shoulder region analysis, the regions of interest were templated to individual participants based on skeletal landmarks in their initial scan that were then subsequently used for the post-training measure as previously specified by Lambert et al.[37] The accuracy of segmented regional soft tissue analysis via DEXA has been previously reported to be within 1%-6% error with excellent reliability between measurements (intraclass correlation coefficient, 0.99).[12]

Isometric rotator cuff strength

During the same weeks of testing (pre & post) and on a separate day, pitchers underwent isometric rotator cuff strength assessment of each shoulder performed by a sports-specialized physical therapist (C.H., blinded to group assignment) in the rested state with a minimum of 72 hours of rest prior to assessment. Six different maximal isometric strength tests were used to measure rotator cuff strength: 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 via a "make test" using a microFET2 (Hoggan Scientific, Salt Lake City, UT, USA) hand-held dynamometer (ICC 0.85-0.99).[16,17] During testing, participants performed 3 maximal-exertion contractions against the dynamometer to assess the average strength value.

Pitching biomechanics/3D motion capture

As a secondary outcome measure, 22 athletes (BFR = 12, NoBFR = 10) underwent biomechanical assessments of fast ball pitching during the weeks of pre and post-training measurements (Fig. 2).[23,26,27] Notably, only pitchers who's academic and athletic schedules allowed for biomechanical assessment were able to perform this portion of the investigation. All motion capture measurements took place in a controlled indoor pitching lane off of a standard pitching mound. Kinematics were assessed using a Vicon Motion Capture System with 11 Vantage-V16 optical cameras (240-250 Hz) and 2 Bonita (60-62.5 Hz) video cameras (Vicon, Oxford, UK) paired with Vicon's Nexus software. Prior to motion capture, participants performed a standardized warmup. Next, 44 retro-reflective markers were adhered to anatomical landmarks. Following a standard calibration, pitchers were

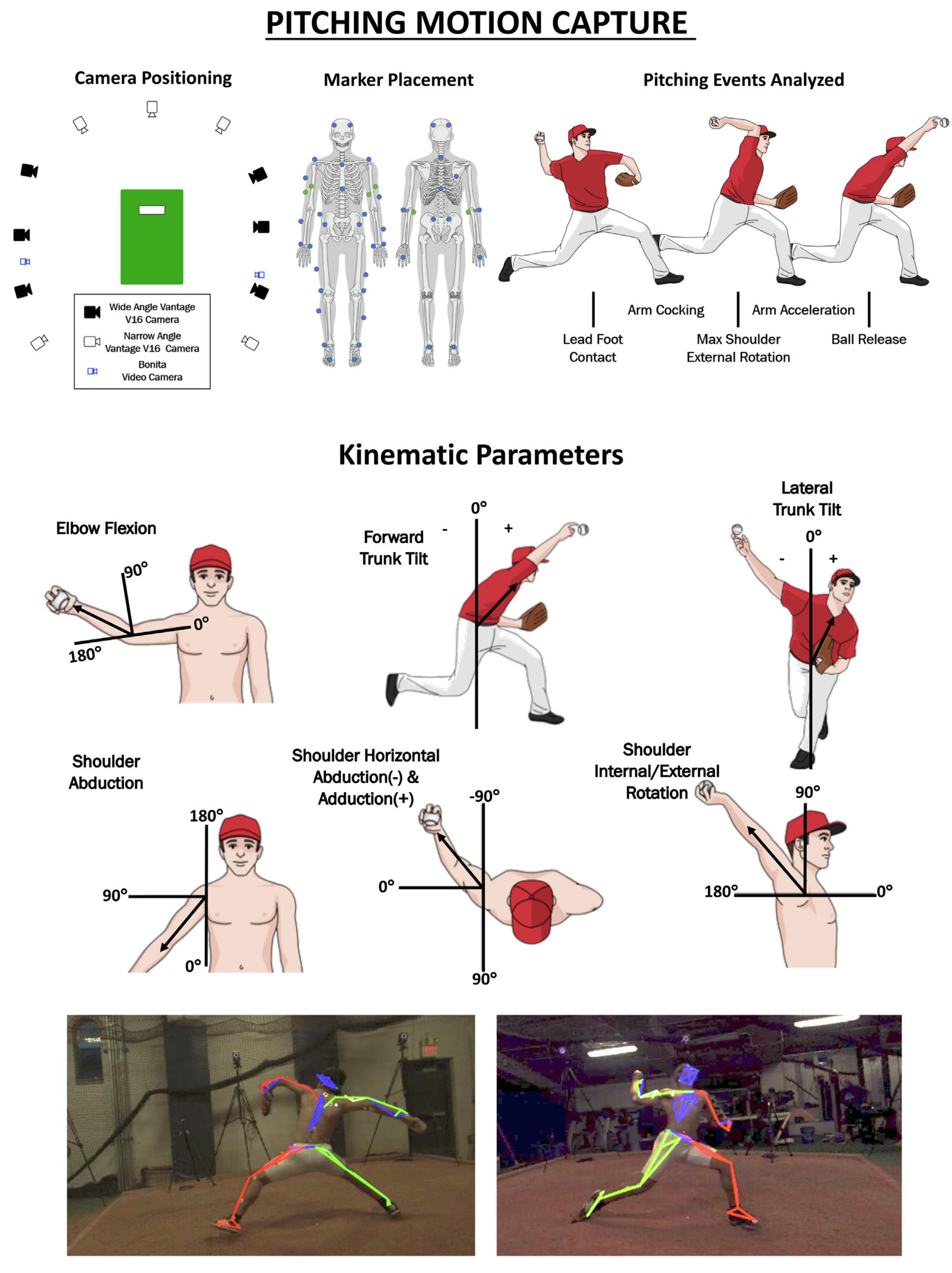

Figure 2 Biomechanical assessment of pitching. Images reflect optical and video camera placement, marker placement, pitching events analyzed, kinematic parameters of interest, and an example 3D motion capture video overlay.

Table I Strength and conditioning program overview

Pitcher strength training block			
Week	Objective	Volume	Intensity
1	Strength Endurance	3 × 10	60%
2	Strength Endurance	3 × 8	65%
3	General Strength	3 × 5	70%
4	General Strength	3 × 5	75%
5	General Strength	3 × 5	80%
6	General Strength	1 × 5	60%
7	Max Strength	3 × 3	80%
8	Max Strength	3 × 3	85%

Day 1 (Lower Body Emphasis) - Squat Movement, Romanian Deadlift Variation, Single Leg Squat Variation, Back Extension Variation, **Rotator Cuff Training (BFR or NOBFR).
Day 2 (Upper Body Emphasis) - Dumbbell Bench Press, Dumbbell Row Variation, Pushup Variation, Suspension Trainer Row Variation.
Day 3 (Total Body Emphasis) - Dead Lift Variation, Lunge Variation, Overhead Press Variation, Pullup Variation, Nordic Leg Curl Variation, **Rotator Cuff Training (BFR or NOBFR).

BFR, Blood flow restriction; *NOBFR*, non-BFR.

permitted to throw warmup pitches until they indicated they were ready to perform at maximal effort. Kinematics were then recorded during 10 fastball pitches. Motion capture data were then filtered via a low-pass Butterworth Filter using a cutoff frequency of 13.4 Hz.[25] The remaining analysis was performed using custom Python scripts (The Python Software Foundation, Wilmingon, DE, USA) where kinematic parameters of interest were calculated using methods described previously.[20,23-25] Measures of interest were selected by clinical research staff based on literature investigating shoulder and elbow kinematics during pitching and potential mechanisms related to fatigue and injury.[20,22,24,28]

Exercise training

Sport training/strength and conditioning

During the 8-week off-season training period, all athletes participated in regularly scheduled baseball practice 4 times per week. All pitchers were assigned to pitch twice per week in either bullpen or live scrimmage settings separated by at least 72 hours. In accordance with their training, pitchers progressed from a maximum allowable pitch count of 15 pitches per outing during week 1 of the study to between 40 and 70 pitches per outing by week 8 (depending on game scenario and individual performance). In addition to sport-specific training, all pitchers participated in the same HIX strength and conditioning program 3 times per week following practice (summarized in Table I) with progressing training intensity.

Rotator cuff training

After initial assessments and in addition to their standardized HIX strength and conditioning program, all athletes performed 8 weeks of supplemental unilateral shoulder training (pitching arm only) twice weekly immediately following HIX strength and conditioning sessions on days 1 and 3 (performed following pitching outings). Exercise implementation, order, and progression was matched with the training regimen previously implemented in healthy adults.[37] During each session, both the BFR and NOBFR groups performed the following exercises: cable ER0°, cable IR0°, dumbbell scaption, and side-lying dumbbell ER0°. All sessions were supervised by trained staff who monitored exercise form and recorded repetition counts for each exercise. Initial resistance was set at 20% iso-max in accordance with standard BFR training protocols.[36] 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. Fatigue was determined as the point at which participants were no longer able to maintain proper exercise form. Although the final set of each exercise was performed to fatigue, resistance was increased by 2 lb (∼0.91 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 an additional training measure of strength endurance, total achievable workload (sets × repetitions × resistance) for each exercise was recorded for each session.[37]

Although all pitchers performed the same training regimen, the BFR group performed all rotator cuff training under 50% LOP applied at the proximal arm by an automated tourniquet system (Delfi Medical Innovations, Vancouver, BC, Canada) that provided automatic assessment and pressure regulation to maintain the same degree of occlusion throughout individual contractions (∼10-20 mmHg adjustment throughout range of motion depending on exercise). LOP for the present investigation was matched to that used by Lambert et al[37] during rotator cuff training in healthy untrained adults as well as current evidence supported[18,43] recommendations from the device manufacturer for the upper extremity exercise.[18,43] LOPs were reassessed for every training session before exercise. Participants in the BFR group performed the entirety of each supplemental shoulder exercise (including intra-exercise rest periods) under 50% LOP with the tourniquets released during the 2-minute rest periods between exercises. For completion, participants were required to complete at least 13 of the 16 prescribed sessions.

Statistical analysis

Before the investigation began, a power analysis was performed using data from a previous strength training investigation that utilized the same shoulder training protocol performed in this study.[37] Sample sizes for other similar training investigations over an 8-12 week period were also considered for reference.[6,31,38,40] Based on a power of 0.80 at $\propto = 0.05$ with a minimum within-group detectable difference (pre to post-training) of 5% in upper extremity lean mass and 10% in rotator cuff strength (primary outcome variables), it was determined that a minimum of 12 athletes would be required per group. For between-group comparisons, this investigation was powered to detect an average minimum effect size of 0.7 for pairwise comparisons. Therefore, a target of 12-20 athletes per group was set to account for potential dropouts. An overview of the testing/training schedule and rotator cuff exercises trained is provided in Fig. 1. Statistical analyses were performed using SPSS Statistics (version 23.0; IBM, Armonk, NY, USA).[37] To test for within-group change from pre to post-training and between-group differences in chronic changes in lean mass and isometric strength in both the throwing (treatment) and nonthrowing (control) arms, a (2) group × (2)arm ANCOVA (repeated on measurement timepoint) was used with pretraining values as covariates. In the pitching arm only, a (2) group ANCOVA repeated on measurement timepoint and covaried on pretraining values was then used to compare within and between group changes in strength endurance (achievable workload) for each shoulder exercise between weeks 1 and 8 of training. The same model was then used to analyze biomechanical measures of interest in the athletes who were able to undergo motion capture analysis. Next, a Bonferroni post hoc test was used to adjust for multiple pair-wise comparisons. Type I error was set at $\propto = 0.05$ for all analyses. For significant pair-wise comparisons of primary outcome variables indicated by post hoc analysis, effect size (ES) was calculated using the Cohen's d statistic[49] 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 (VL).[37]

Results

As shown in Figure 1, 28 athletes completed the investigation. Athlete characteristics within each group were as follows,

BFR: N = 15; 19.7 ± 1.2 years of age; 188.6 ± 1.8 cm; 91.6 ± 2.1 kg; Starters = 4, Relievers = 11; Right-Handed = 12, Left-Handed = 3; 2.1 ± 1.0 years in collegiate baseball.

NOBFR: N = 13, 19.8 ± 1.5 years of age, 186.0 ± 2.4 cm, 92.1 ± 4.3 kg, Starters = 3, Relievers = 10; Right-Handed = 11, Left-Handed = 2; 2.2± 1.1 years in collegiate baseball.

Lean mass

Both groups were observed to have similar increases in total body lean mass following training (BFR: ↑ 1.33 ± 0.31 kg, $P = .001$ | NOBFR: ↑ 1.29 ± 0.51 kg, $P = .027$). Training responses for regional lean mass measures are presented in Fig. 3. Only the BFR group was observed to have an increase in upper extremity (↑ 131 ± 37 g, $P < .001$, ES = 1.28VL, Fig. 3, *A*) and shoulder region lean mass (↑ 227 ± 60 g, $P < .001$, ES = 1.59VL, Fig. 3, *B*) for the throwing arm following the training period. This resulted in greater post-training lean mass values that were greater in the BFR group compared to the NOBFR group for the upper extremity (BFR = 4410 ± 52 g | NOBFR = 4307 ± 56 g; $P = .024$; ES = 0.97VL, Fig. 3, *A*) and shoulder region (BFR = 2771 ± 72 g | NOBFR = 2623 ± 78 g; $P = .018$; ES = 1.00VL, Fig. 3, *B*) of the throwing arm. Additionally, the BFR group was observed to have a within group increase in shoulder region lean mass for the nonthrowing arm (↑ 139 ± 63g, $P = .021$, ES = 0.97VL, Fig. 3, *B*).

Isometric strength

Pre and post-training measures of isometric strength are presented in Table II. Only the BFR group was observed to have an increase in any of the strength measures following training which was observed for IR at 90° in the throwing arm only (↑ 2.4 ± 2.3 kg, $P = .041$, ES = 0.92VL). The NOBFR group experienced decreases in throwing arm isometric strength for flexion ↓ 1.6 ± 0.8 kg, $P = .007$, ES = 1.41VL) and IR at 0° ↓ 2.9 ± 1.5 kg, $P = .004$, ES = 1.09VL) where a difference in training response was also observed compared to the BFR group (IR0°; BFR = ↑ 1.0 ± 2.2 kg | NOBFR = ↓ 2.9 ± 1.5 kg; $P = .003$, ES = 1.40VL). The NOBFR group was observed to have lower strength measures in the throwing arm compared to the nonthrowing arm for flexion ($P = .015$, ES = 0.88VL) and ER at 90° ($P = .044$, ES = 0.73VL) following training (Table II).

Strength endurance/achievable workload

Training responses for total achievable workload are presented in Fig. 4. Both groups experienced increases in achievable workload for all exercises between training weeks 1 and 8 ($P < .001$) with the BFR group having a greater increase for the dumbbell scaption exercise (BFR: ↑ 190 ± 3.2 kg, NOBFR: ↑ 90 ± 3.3 kg, $P = .005$, ES = 0.81VL).

Pitching performance and biomechanics

Data for fastball pitching biomechanical variables of interest are presented in Table III. Only the NOBFR group was observed to experience changes in pitching mechanics following the training period with increased shoulder external rotation at lead foot contact (↑ 9.0° ± 7.9, $P = .028$, ES = 0.79VL) as well as reduced forward ↓ 3.6° ± 2.1, $P = .001$, ES = 1.19VL) and lateral ↓ 4.6° ± 3.4, $P = .007$, ES = 0.97VL) trunk tilt at ball release. These changes resulted in post-training measures that differed from the BFR group where no changes were observed from pre to post-training (shoulder ER at lead foot contact:

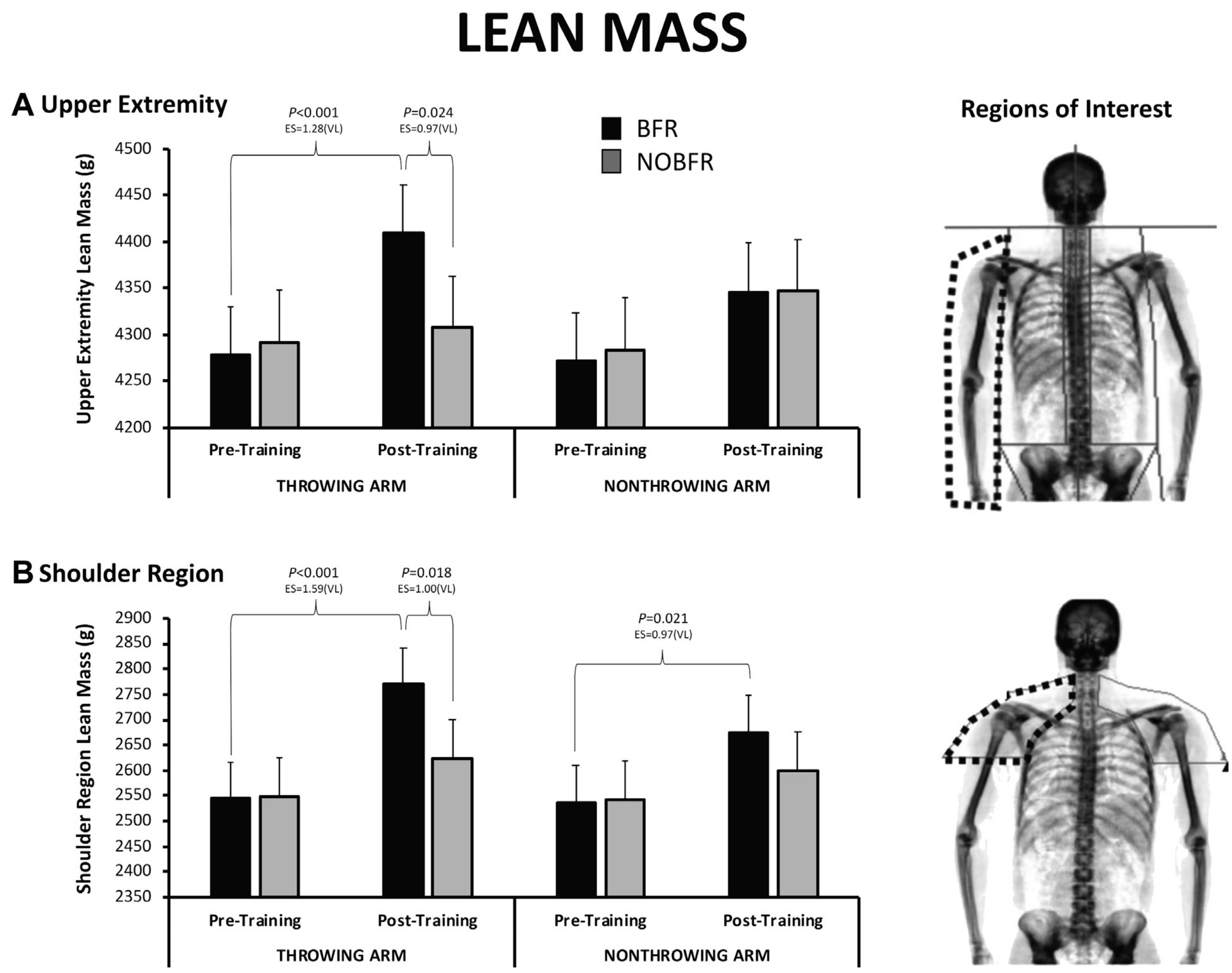

Figure 3 Lean mass. Data are presented as means ± 95% CI for change in lean mass in the upper extremity (**A**) and shoulder regions (**B**). Limbs within group were compared at the same post-training measurement timepoint (throwing vs. nonthrowing), from pre to post-training within limb, and with the same limb between groups at the same post-training measurement timepoint. Significant differences between groups for magnitude of change are indicated with *P* values. ES for significant between-group or between-limb responses are reported using the Cohen's d statistic whereby values are interpreted as follows: 0-0.1 (N); 0.1-0.3 (S); 0.3-0.5 (M); 0.5-0.7 (L); >0.7 (VL). *Significant change from pretraining measures within group at $P < .05$. **Significant change from pretraining measures within group at $P < .01$. *ES*, effect sizes; *N*, negligible; *S*, small; *M*, moderate; *L*, large; *VL*, very large.

$P = .002$, ES = 1.11VL; ball release [forward trunk tilt: $P < .001$, ES = 1.16VL; lateral trunk tilt: $P = .006$, ES = 1.00VL]).

Discussion

The purpose of this investigation was to evaluate the efficacy of supplementing a standardized collegiate baseball offseason program with BFR-LIX shoulder training in division IA pitchers. Similar to previous findings and in line with our hypotheses, the present results indicate that BFR-LIX rotator cuff training augmented increases in shoulder/upper extremity lean mass as well as some measures of work capacity and isometric strength compared to rotator cuff training alone. Unlike prior investigations, these results were observed in trained athletes undergoing HIX offseason training indicating that although supplemental shoulder training was performed at low loads, the addition of BFR provided enough of a novel stimulus to elicit further adaptations beyond standard training. Additionally, the decreases in isometric strength observed in the NOBFR group but not the BFR group may indicate a clinically meaningful preservation of function/strength in the midst of cumulative fatigue associated with increasing pitch volumes throughout the offseason period. These adaptations may have also contributed to a preservation of pitching mechanics in the BFR group. While further study should be performed on larger groups and populations to confirm the observed results within this investigation, the findings presented here are encouraging for this unique population of throwing athletes.

Table II Maximal isometric strength

Maximal isometric strength (kg)	BFR group		NOBFR group	
	Pre	Post	Pre	Post
Flexion				
Throwing Arm	14.7 ± 0.5	14.0 ± 0.5	14.8 ± 0.6	13.2 ± 0.6[**,#]
Nonthrowing Arm	14.6 ± 0.5	14.0 ± 0.5	14.7 ± 0.6	14.2 ± 0.6
Scaption				
Throwing Arm	14.7 ± 0.5	14.5 ± 0.5	14.7 ± 0.6	14.5 ± 0.6
Nonthrowing Arm	14.7 ± 0.5	14.3 ± 0.5	14.7 ± 0.6	14.1 ± 0.6
ER 0°				
Throwing Arm	15.9 ± 0.8	15.8 ± 0.8	16.2 ± 0.9	16.4 ± 0.9
Nonthrowing Arm	16.0 ± 0.8	15.9 ± 0.8	16.0 ± 0.9	16.0 ± 0.9
IR 0°				
Throwing Arm	24.3 ± 1.2	25.4 ± 1.2	24.8 ± 1.4	21.8 ± 1.4[**,‡]
Nonthrowing Arm	24.1 ± 1.2	24.4 ± 1.2	24.2 ± 1.3	22.5 ± 1.3
ER 90°				
Throwing Arm	19.7 ± 1.3	17.3 ± 1.3	19.7 ± 1.4	18.9 ± 1.4[#]
Nonthrowing Arm	20.0 ± 1.3	17.8 ± 1.3	20.1 ± 1.4	21.1 ± 1.4
IR 90°				
Throwing Arm	19.7 ± 1.3	22.1 ± 1.3[*]	20.0 ± 1.5	20.9 ± 1.5
Nonthrowing Arm	19.9 ± 1.4	20.4 ± 1.4	19.5 ± 1.5	21.4 ± 1.5

ER, external rotation; *IR*, internal rotation; *BFR*, blood flow restriction; *NOBFR*, non-BFR.
Maximal isometric strength. Chronic response data for the BFR and NOBFR groups assessed before (pre) and after (post) training are presented as adjusted means 95% ± CI for maximal isometric strength (kilograms, kg, assessed using dynamometry).
[*,**] Significantly different from baseline within-group at $P < .05$ and < 0.01, respectively.
[‡] Significantly different training response compared to the BFR group ($P < .01$).
[#] Significantly different from the nonthrowing arm at the same measurement timepoint within-group.

Muscle mass development and work capacity

Similar to previous reporting,[37] those in the BFR group experienced greater increases in upper extremity and shoulder region lean mass compared to the NOBFR group (Fig. 3). In this instance, the rotator cuff training program for all participants was paired with a standardized HIX strength and conditioning program involving progressive overload using large muscle group exercises. As it has previously been observed that training responses diminish the more trained an individual is,[46] the present results indicate that the addition of BFR elicited further adaptive responses compared to standard rotator cuff training alone. Regarding the potential novel anabolic stimulus of BFR, partial occlusion of the exercising limb has been observed to result in acute hypoxic conditions, reduced local blood pH, metabolite accumulation, and acute muscle cell swelling, thus providing an environment prone to metabolic and mechanical stress sensing/signaling through regulatory pathways of cell growth, degradation, and proliferation (locally and potentially, systemically).[35,39,42] The augmented anabolic response observed in the BFR group may have also resulted, in part, from increased work capacity (achievable workload) for the scaption exercise compared to the NOBFR group (similar to previous findings,[37] Fig. 4). Notably, resistance training volume and total muscle mass utilized during exercise are key factors in hypertrophic responses to strength training.[1,11]

Within the present study, improvements in achievable workload were greater in the BFR group for the scaption exercise only (Fig. 4). Relative to the other exercises performed, scaption involves both the longest lever arm and the greatest amount of muscle mass recruitment. It has also been previously shown that occlusion applied during the scaption exercise at 50% LOP yields an elevated increase in activation of the deltoids, infraspinatus, teres minor, and trapezius muscles (assessed via electromyography [EMG]).[37] Therefore, whether or not BFR may only need to be applied to larger shoulder movements such as the scaption exercise to gain benefit remains a topic of further study. However, recent reports may provide some initial guidance.[8,9] For example, Brumitt et al[9] 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 1-repetition maximum) with regard to changes in strength and supraspinatus tendon thickness. In contrast, the present study is in line with findings from prior investigations involving multiple exercises with regards to hypertrophic responses to BFR-LIX.[6,37] Similar contrasting findings have also been

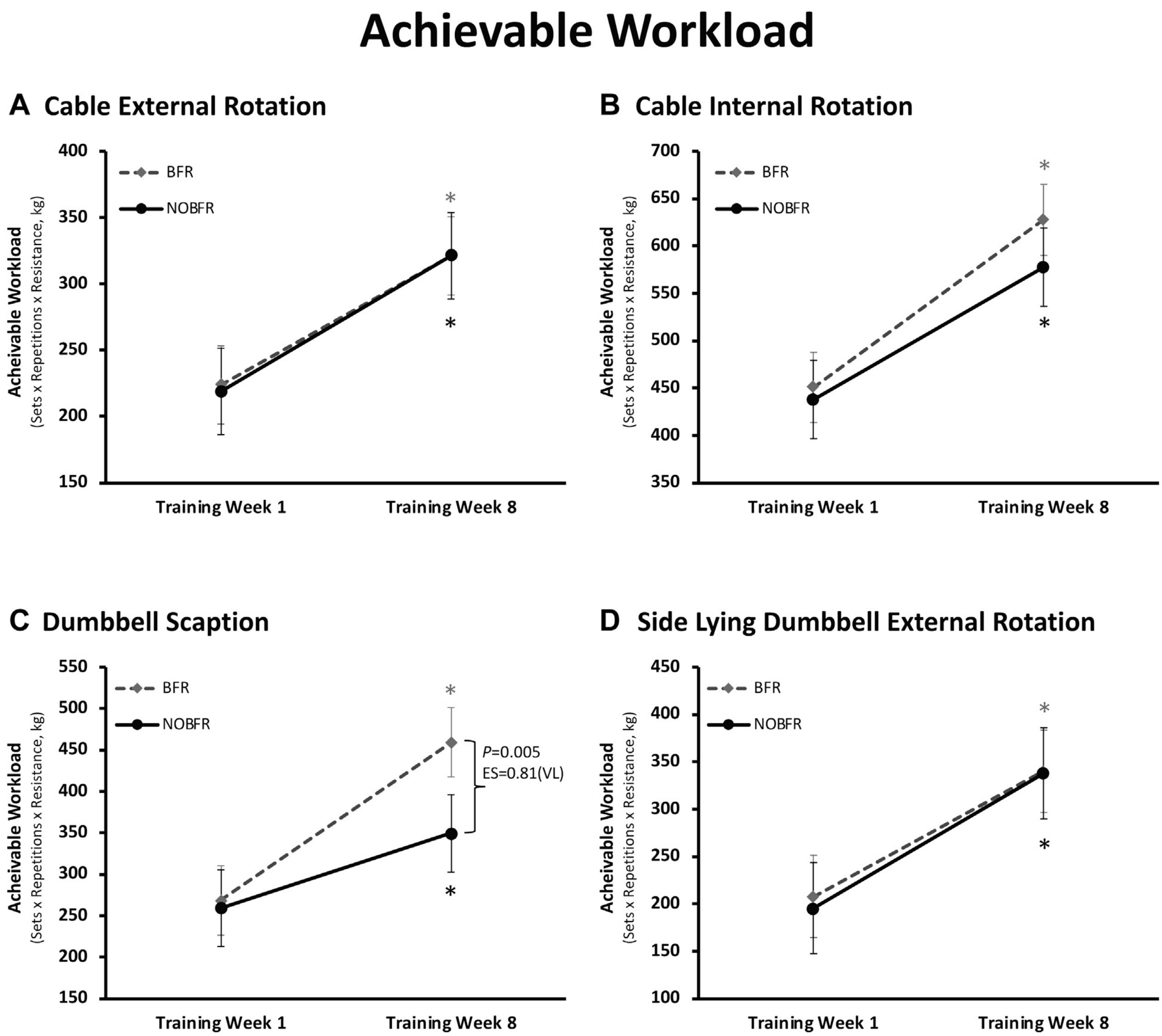

Figure 4 Total achievable workload (**A-D**) Data are presented as means ± 95% CI for change in weekly achievable exercise workload (sets × repetitions × resistance) (kg) averaged across bouts (2) from training week 1 to training week 8. Comparisons were performed within group (comparison of pre to post-training) and between groups at the post-training timepoint. Significant differences between groups for magnitude of change are indicated with *P* values. ES for significant between-group responses are reported using the Cohen's d statistic whereby values are interpreted as follows: 0-0.1 (N); 0.1-0.3 (S); 0.3-0.5 (M); 0.5-0.7 (L);>0.7 (VL). * *Significant change from pre-training measures within group at $P < .01$. *CI*, confidence interval; *ES*, effect sizes; *N*, negligible; *S*, small; *M*, moderate; *L*, large; *VL*, very large.

reported for lower extremity exercise as well.[7,48] Therefore, although increases in achievable workload were only observed for the scaption exercise, there may be an exercise volume or time under occlusion threshold for eliciting adaptations to musculature directly proximal to the site of occlusion which may require multiple exercises.[35]

Preservation of shoulder strength

Adequate shoulder strength has been long established to be a major factor in injury prevention and performance in throwing populations[55] with declines commonly observed over the course of a season due to cumulative fatigue.[33,34,44,56,58] Stone and Schilling also postulated that neuromuscular fatigue may play a major role in both strength and performance changes.[53] A key finding of the present investigation was that strength measures were preserved in the BFR group compared to the NOBFR group (Table II). Therefore, while BFR may not significantly increase maximal strength outside of IR as was also observed in general population adults,[37] the addition of BFR to rotator cuff training may prevent clinically concerning decreases in rotator cuff strength across an offseason period in the midst of increasing pitch volumes. Such findings have

Table III Fastball pitching biomechanics

Lead foot contact				
Position (degrees)	BFR		NOBFR	
	Pre	Post	Pre	Post
Elbow flexion	97.1 ± 3.1	97.0 ± 3.1	96.8 ± 3.4	96.6 ± 3.4
Shoulder ER	41.1 ± 5.2	38.2 ± 5.2	41.3 ± 5.6	50.2 ± 5.6*,#
Shoulder horizontal abduction	27.7 ± 1.9	27.6 ± 1.9	27.7 ± 2.0	29.0 ± 2.0
Shoulder abduction	91.1 ± 2.4	91.8 ± 2.4	91.2 ± 2.6	89.5 ± 2.6
Forward trunk tilt	−2.1 ± 1.3	−1.5 ± 1.3	−2.0 ± 1.4	−2.8 ± 1.4
Arm Cocking Phase				
Position (degrees)	BFR		NOBFR	
	Pre	Post	Pre	Post
Elbow flexion	111.3 ± 3.0	113.5 ± 3.0	110.8 ± 3.3	111.4 ± 3.3
Shoulder ER	161.8 ± 4.7	161.5 ± 4.7	160.1 ± 5.2	157.1 ± 5.2
Shoulder horizontal adduction	11.6 ± 1.5	12.3 ± 1.5	11.8 ± 1.7	11.5 ± 1.7
Arm Acceleration Phase				
Velocity (degrees/second)	BFR		NOBFR	
	Pre	Post	Pre	Post
Max shoulder ER velocity	5241.6 ± 511.8	5696.6 ± 511.8	5259.2 ± 560.7	5791.5 ± 560.7
Max elbow extension velocity	2356.4 ± 338.7	2561.9 ± 338.7	2310.5 ± 371.1	2547.6 ± 371.1
Ball Release				
Position (degrees)	BFR		NOBFR	
	Pre	Post	Pre	Post
Elbow flexion	31.1 ± 1.0	30.6 ± 1.0	30.8 ± 1.1	31.0 ± 1.1
Shoulder horizontal adduction	3.4 ± 1.9	3.0 ± 1.9	3.4 ± 2.1	3.1 ± 2.1
Shoulder abduction	83.5 ± 1.1	82.5 ± 1.1	83.4 ± 1.2	83.1 ± 1.2
Forward trunk tilt	39.7 ± 1.4	40.6 ± 1.4	39.7 ± 1.5	36.1 ± 1.5**,##
Lateral trunk tilt	31.4 ± 2.2	31.4 ± 2.2	31.4 ± 2.4	26.8 ± 2.4**,##

ER, external rotation; *BFR*, blood flow restriction; *NOBFR*, non-BFR.
Fastball pitching biomechanics. Data are presented as adjusted means ± 95% CI for fastball pitching mechanics with a focus on the pitching shoulder and elbow as well as trunk movement during an isolated bullpen before and after training in our volunteer subgroup (BFR, n = 12; NOBFR, n = 10).
*,** Significantly different from baseline within-group at $P < .05$ and < 0.01, respectively.
#,## Significantly different from the BFR group at the same measurement timepoint within-group at $P < .05$ and < 0.01 respectively.

implications for maintenance of performance, injury prevention, and rehabilitation. Further research is needed to determine the extent to which a preseason or in-season shoulder exercise regimen augmented with BFR may mitigate rotator cuff strength loss during inseason play.[47]

Pitching mechanics and performance

Pitching mechanics remain topic of considerable interest whereby even subtle variability in throwing mechanics may significantly affect performance as well as injury risk.[24,50] Additionally, at increasing elite levels of play (collegiate & professional), reduction in pitching mechanics variance in an individual is expected with even subtle changes being indicative of injury risk.[8,20,28] Aside from injury, fatigue has been shown to negatively impact pitching mechanics in the midst of increasing pitch counts during both offseason and inseason play.[32,52,55]

Similar to observations regarding isometric strength, only the NOBFR group was observed to have changes in pitching mechanics following training (Table III). These changes are similar to those found by previous authors examining the role of fatigue and how mechanics may degrade over the period of a sport season.[5,22,32] However, the BFR group in this investigation did not demonstrate any significant changes in mechanics. Therefore, the present results may indicate that the addition of BFR to standard rotator cuff training did not negatively affect pitching mechanics and may assist in preservation across an offseason with possible contributions from increased muscle mass, increased work capacity, and preserved strength in the shoulder region. Importantly, we caution the reader that several factors known to influence pitching mechanics were not accounted for in the present study and while the present data remain promising, further research remains needed to examine the effects of BFR training on pitching mechanics and performance across both offseason and inseason play.

Practical considerations and limitations

The current study design followed a standardized protocol used in several prior BFR investigations, specified by the manufacturer, and used in rehabilitation settings.[39] The shoulder training protocol was also matched to a previous investigation performed in healthy general population adults.[37] Importantly, this training protocol did differ from some previous investigations as the final set of each exercise was performed to fatigue rather than being terminated at 15 repetitions. While automated tourniquet systems whereby occlusion pressures can be constantly monitored are often clinically preferred for safety, cost of such devices is often an important consideration. Therefore, if simply performing low-load repetitions to fatigue yielded similar training outcomes, it is likely that the addition of BFR may be cost prohibitive. In this instance, the use of BFR was able to elicit additional benefits compared to performing standard training alone which may be of benefit for preserving pitching athlete shoulder health.

The present study is not without limitations. While the investigation was powered to detect the findings presented, the authors acknowledge the relatively small sample size from a single institution. Notably, the sample size calculations were based off of a previous investigation whereby both limbs were trained and averaged.[37] Therefore, although detectable differences between groups were present, analyses involving ‘‘arm’’ in the model (lean mass, isometric strength) may be underpowered and will require further study to confirm the present findings. However, given the rarity of interventional trials on collegiate athletes in this manner, the authors feel that these data add considerably to the understanding of BFR sport training settings. Furthermore, pitchers performed their shoulder training protocol only following their standard HIX strength and conditioning sessions on days following pitching outings. It is currently unknown how changing the timing and/or frequency of rotator cuff training may have impacted the current results. Next, participants were not blinded to group assignment and we cannot dismiss that a placebo effect may have affected those in the BFR group. Although a NOBFR intervention group was used in this investigation for comparison of training responses, a complete nonexercised control group was not used as it was neither feasible nor permitted. Assessment of body composition was performed using DEXA which has been shown to be a reliable and repeatable tool for determining total and regional changes in body composition.[12] Although measures can be influenced by rapid changes in fluid shifts as seen in the early period following exercise,[45] care was taken to assess all athletes in the rested state. We also acknowledge a limitation of DEXA for quantifying regional lean mass but not mass of individual muscles (rotator cuff or deltoid) which should be considered. Future studies may benefit from incorporation of both DEXA and other imaging techniques to further outline the impact of BFR training on individual muscles. Next, pitching mechanics were only assessed in a controlled setting during consecutive fastball pitching for a portion of the participating athletes due to other conflicts with scholastic and team scheduling. We acknowledge that maximal athletic performance can be variable and that multiple measurement timepoints, while not achievable in this study, may have provided greater insight as to the impacts of each training intervention on pitching performance. Because pitching outings performed during offseason training were highly variable in nature due to prescripted game situations with pitch types designed to mimic various game scenarios, the impact of either intervention (BFR, NOBFR) on ingame pitching statistics was not able to be examined. Notably, the timeframe of study participation and data collection encompassed the Fall of 2020. Although training protocols and practice schedules were maintained, we rule out that COVID related disruptions to academic scheduling and daily living habits may have impacted, at least to some degree, training outcomes that were not statistically controlled for. Lastly, no blood or tissue sampling was permitted for this investigation which may have allowed for examination of physiologic factors that could have influenced training adaptations.

Conclusion

When performed after offseason pitching outings in conjunction with a standard high-intensity collegiate offseason strength and conditioning program, BFR-LIX rotator cuff training augments increases in shoulder lean mass as well as muscular endurance (achievable workload), while maintaining rotator strength in a manner that may contribute to favorable outcomes in baseball pitching athletes over time. These findings provide support for future research investigating the efficacy of BFR for preventative inseason shoulder training. The present results also provide rationale for future research on the efficacy of BFR augmented rehabilitation after operative and nonoperative injuries in throwing/overhead athletes. Lastly, because the current and prior training protocols have been largely based off of the clinical and laboratory applications of BFR, future investigations should seek to determine the optimal combination of exercise selection, training frequency, BFR occlusion duration, and timing within a sport training program that may provide the greatest benefit for different types of throwing or overhead athletes.

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