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Effects of Blood Flow Restriction During Acute Multi-Joint Eccentric Exercise on Muscle Recovery

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EFFECTS OF BLOOD FLOW RESTRICTION DURING ACUTE MULTI-JOINT

ECCENTRIC EXERCISE ON MUSCLE RECOVERY

by

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Abstract

Blood flow restriction (BFR) exercise has become an increasingly common modality due to evidence that it may yield positive muscle-related effects from low-intensity exercise. However, eccentric-only exercise in a multi-joint format has not yet been investigated in regard to the BFR influence on muscle recovery characteristics. The purpose of this study was to assess muscle recovery responses via isometric peak force (PF), soreness (i.e., VAS, PPT, PPD), and functional power (i.e., SLHD) following a 5-minute low-load multi-joint eccentric exercise bout with or without blood flow restriction. Thirty participants were randomly assigned into either an eccentric-only (CON) or an eccentric BFR (ECC-BFR) group. The CON group performed a single 5-minute bout of eccentric exercise while the ECC-BFR group performed the same exercise bout but with a tourniquet applied to the dominant limb (upper thigh). Muscle function was assessed in both groups at baseline (Pre) and again at 5-minutes after the exercise (Post) and again at 24, 48, and 72 h following the exercise session. There was no interaction effect for PF (p = 0.490). A main effect for time for PF and SLHD was shown such that these measures decreased at up to 48 h post exercise, in both groups. There was a significant group × time interaction for VAS ($p = 0.017$) and PPT ($p = 0.015$) that favored the ECC-BFR group. Low-load eccentric exercise with BFR may improve recovery, without any impact on PF responses. Such a result could help with adherence factors to eccentric exercise, due to a decrease in perceived soreness while maintaining a higher pain threshold.

Introduction

Eccentric exercises may be better for facilitating improvements in strength adaptations than concentric exercises due to their ability to produce 20-60% greater improvements in maximal force production (Gordon et al., 2019; Mike et al., 2015; Weeks et al., 2023), with a 4-fold lower energy requirement than a concentric contraction at the same workload (Hoppeler, 2016). Due to these findings, eccentric exercise has been found to be ideal for improving muscle strength, particularly in individuals with limited performance capabilities (Cognetti et al., 2022).

However, one prominent limitation of eccentric overload exercise is the increase in muscle damage peaking 24-72 h post exercise (Cheung et al., 2003; Harper et al., 2021). Thus, researchers have sought to develop techniques to reduce this muscle damage while preserving the positive effects of low-load eccentric exercise (Lauver et al., 2020). One of these potential methods is the use of blood flow restriction (BFR) (Lauver et al., 2017). BFR is performed using a pneumatic system which applies an external pressure, typically through a tourniquet cuff, to the most proximal region of the upper or lower limb (Lorenz et al., 2021). When the cuff is inflated, there is gradual compression of the vasculature underneath the cuff, resulting in partial restriction of arterial blood flow to structures distal to the cuff. Consequently, this partial restriction reduces arterial outflow and impedes venous return which leads to an overall increase in muscular remodeling (Patterson et al., 2019).

BFR has been found to have a wide variety of positive effects when exercising at low-loads, and it has been found that there is an increase in muscle recovery when compared to low-load exercise alone (C. E. Proppe et al., 2022). Other studies have found that low-load BFR may also promote muscle growth and satellite cell activity that is equivalent to traditional high intensity resistance exercise while decreasing perceived soreness (Davids et al., 2021; Lorenz et al., 2021; C. E. Proppe et al., 2022). The effects of low-load eccentric BFR on maximal voluntary contractions (MVCs) are well-established and subjects are shown to maintain a higher maximal strength compared to both low-load eccentric exercise without BFR and concentric exercise with BFR (Lauver et al., 2017, 2020; Thiebaud et al., 2013). The incorporation of BFR has not been directly associated with a decrease in muscle damage, however previous findings provide preliminary evidence suggesting low-load eccentric exercise with BFR could potentially have beneficial effects while also minimizing muscle damage compared to other training modalities (Cognetti et al., 2022; Early et al., 2020; Hoppeler, 2016; Lauver et al., 2017).

BFR is becoming a common rehabilitative modality due to its ability to yield strength results equivalent to, or greater than, other approaches while exercising at a lower intensity, volume, and load, which may help reduce stress on healing tissues (Cognetti et al., 2022; Harper et al., 2019; Lorenz et al., 2021). Exercising with low-load BFR has been shown to elicit equivalent muscular activation and adaptations compared to traditional high intensity resistance exercise, likely due to its ability to recruit higher threshold motor units (Cognetti et al., 2022; Yasuda et al., 2006), while decreasing perceived soreness (Davids et al., 2021; Kataoka et al., 2022; Yamanaka et al., 2012). Due to these findings, coupling low-load eccentric exercise with BFR has the implication to retain a higher strength output and pain threshold while reducing the magnitude of muscle damage 48 h post exercise compared to low-load concentric exercise with BFR (Lauver et al., 2017; C. E. Proppe et al., 2022; Thiebaud et al., 2013). Eccentric training with BFR has been proven beneficial to rehabilitating populations due to its ability to maintain strength output with a lower level of soreness compared to traditional rehabilitation protocols (Early et al., 2020).

The purpose of this study was to assess muscle damage via perceived soreness, pain threshold, and pain detection as well as isometric strength recovery in the dominant leg of recreationally active young adults immediately and three days following a 5-minute low-load eccentric exercise bout on a multi-joint dynamometer (Eccentron, BTE Technologies, Hanover, MD, USA). Based on previous literature, we hypothesized performing a low-load multi-joint eccentric exercise bout with BFR (ECC-BFR) would decrease muscle damage defined in the current study as a lower perceived soreness score and higher perceived pain detection (PPD) and tolerance (PPT), while also maintaining peak strength and power, following the exercise bout compared to low-load multi-joint eccentric exercise alone (Cognetti et al., 2022; Gray et al., 2022; Lauver et al., 2017; Lorenz et al., 2021; Thiebaud et al., 2013). The findings of this study may demonstrate the effectiveness and benefits of incorporating BFR during early rehabilitation as it has the potential to increase program adherence, decrease muscle damage, and promote muscular growth (Cognetti et al., 2022; Fisher et al., 1988).

Methodology

Participants

College-aged men and women (N = 30) volunteered to participate in this study. All demographic data may be found in table 1. An a-priori power analysis was conducted using G*Power 3.1.9.7 (power = 0.8, $\alpha = 0.5$). A similar study that evaluated eccentric training (Gordon et al., 2019) found a sample size of n = 16 with a Cohen's d for effect size of 0.79 was needed to achieve the predetermined power level. Eligibility criteria required *p*articipants to be between the ages of 18 and 30 years old and recreationally active, which was defined as participating in recreational activities or moderate dose physical activity more than 3 times per month. Participants were excluded if they regularly engaged in lower body exercise (resistance training > 2 times per week, aerobic exercise more than 5 days a week for > 30 min/session), had chronic cardiovascular conditions (heart dysfunction/disease, diabetes/blood sugar abnormalities, or anemia), or lower limb neuromuscular conditions. Participants were not allowed to ingest non-steroidal anti-inflammatory drugs 14 days prior to the exercise session and throughout the course of the study. Participants refrained from performing any lower limb exercise three days before their initial visit until the end of the study, due to its direct impact on the post-test measures. This study was approved by the Utah State University Institutional Review Board, and all participants read and completed an informed consent form prior to study participation.

Table 1: Demographic data of the BFR and Control groups.

Variable	ECC-BFR (n = 15)	CON (n = 15)	Total
Age (yrs)	20.27 (1.83)	21.27 (2.37)	20.77(2)
Height (cm)	169.89(23.79)	173.20(7.5)	171.55(17)
Weight (kg)	87.13 (29.45)	78.38 (12.25)	82.76(22)
Left Leg Dominant	13.33%	0%	6.67%
Female (%)	53.30%	53.30%	53.30%

Research Design

This study involved a between-group, experimental design where participants visited the Dennis Dolny Movement Research Clinic at Utah State University 7 times throughout the study (3 h of total time). During the initial visit participants signed an informed consent form, documented their medical history to determine eligibility, and performed a maximum eccentric force test on the Eccentron. During the next 2 familiarization visits, participants performed 72 cumulative maximal repetitions on the Eccentron, either 48 or 24 repetitions per visit, which was randomly determined. Following the last familiarization (visit 3), participants returned to the lab 3-7 days later for a fourth visit. At that time, participants were randomly assigned to be in the experimental (ECC-BFR) or eccentric only control group (CON). This visit consisted of different muscle damage assessments before and after a 5-minute eccentric exercise bout with or without BRF, as was previously determined. Muscle damage was assessed using isometric peak force on the Eccentron (Weeks et al., 2023), PPD, and PPT (Fleckenstein et al., 2017; Harper et al., 2021; Lauver et al., 2017). A Visual Analog Scale (VAS) was also used to assess perceived soreness (Crane et al., 2022; C. E. Proppe et al., 2022; Weeks et al., 2023). Participants in both groups returned to the laboratory for additional follow-up testing (see below) at 24, 48, and 72 h after the single exercise bout completed in visit 4.

Familiarization Sessions

Questionnaires & Informed Consent

Participants completed a health history questionnaire to determine their eligibility for the study and reviewed and completed an informed consent. Dominant limb was assessed via the Waterloo Footedness Questionnaire-Revised (Elias et al., 1998). This ten-question assessment is the preferred reporting method to assess participants' self-reported limb dominance and foot preference for bilateral and unilateral stabilizing tasks (van Melick et al., 2017).

Familiarization Testing

Participants performed a 5-min warm-up on a cycle ergometer at 50 watts while maintaining a pace of 50-60 rpm (Spencer et al., 2023), followed by ten unweighted squats to 90 degrees of hip flexion. After the warmup, participants performed three trials of alternating eccentric contractions (six reps per limb) on the Eccentron (Eccentron, BTE Technologies, Inc., Hanover, MD) with the lower limbs moving the knee joint from 30° to 90° at a speed of 18 repetitions per minute. The first two trials consisted of a warm-up, in which participants were instructed to resist the eccentric load of the machine at sub-maximal efforts of 50% and 70%, respectively. The last trial consisted of maximally resisting the alternating eccentric load for all 12 contractions (Crane et al., 2022).

Participants returned to the lab two more times within 3-7 days prior to the exercise session for additional familiarization consisting of maximal eccentric contractions on the Eccentron device to become accustomed to resisting the eccentric load. On the last day of the familiarization protocol, participants practiced two different tests at the end of the visit. The first test consisted of two single-leg hops for distance (SLHD) on the dominant leg, at maximum effort (Sullivan et al., 2021). The second assessment was two maximal voluntary isometric contractions (MVIC) on the Eccentron. They were instructed to place their dominant foot on the pedal with their heel positioned at the bottom of the pedal. The seat position was adjusted such that their knee angle was set between 30-45 degrees. Pedals were locked in place and the participants were instructed to push into their dominant foot pedal as fast and as hard as they could and to hold that for approximately 5 seconds until the researcher told them to stop. A 1-minute rest was provided between each MVIC (Weeks et al., 2023; Yasuda et al., 2012).

Experimental Intervention Visit

Participants were randomly assigned to either the experimental (ECC-BFR) or eccentric only control group (CON). The ECC-BFR group rested in the supine position for 10-min before blood pressure measurements were taken. Systolic and diastolic blood pressure were measured from the brachial artery while lying in the supine position using an appropriately sized automatic blood pressure cuff (OMRON Corp., Model HEM-773, Kyoto, Japan). Thigh circumference (i.e., cm) of the dominant limb was measured at 33% of the distance from the inguinal crease to the top of the patella using a tape measure and a mark was made on the same leg 33% distal to the inguinal crease. Circumference was measured at these marks per BFR protocol for appropriate cuff placement (Loenneke et al., 2015).

Pre-test

Both groups performed the following baseline measures on the dominant limb. There were no differences in protocol between groups other than CON did not have blood flow occluded during the exercise bout. Participants were instructed to perform three unloaded squats to parallel and record their perceived soreness of the posterior hip and anterior thigh utilizing the Visual Analog Scale (VAS) (Haefeli & Elfering, 2006). This scale consists of participants marking their perceived soreness on a 100-mm line with the left and right ends of the line corresponding to “no soreness” and “most soreness ever experienced” (Crane et al., 2022). Next, participants had pressure applied to the belly of the rectus femoris at the previously marked site via a pressure algometer with a 1 cm^2 flat rubber tip (Wagner FPX, Wagner Instruments, Greenwich, USA) to measure the PPD and PPT (Harper et al., 2021; C. E. Proppe et al., 2022).

Participants then completed a 2-min cycle ergometer warm-up at 50W of resistance followed by a series of strength and power tests. The first of these tests was 3 SLHD, recorded in inches, as a direct assessment of functional power. Each trial was recorded to the nearest fourth of an inch, and the final score was calculated as the highest of the three trials, which was then converted to centimeters. Next, participants completed 2 MVICs on the Eccentron with the dominant limb. After the baseline assessments were obtained, participants were given a 3-min rest before a 5-min eccentric exercise bout (Weeks et al., 2023).

Exercise Bout

The exercise bout consisted of a 1-min warm-up at 25%, 3-min at 50%, and a 1-min cool-down at 25% of their maximal eccentric strength as was recorded immediately prior to the exercise session. The ECC-BFR group had a 12 cm cuff (SC10 Cuff, D. E. Hokanson, Inc., Bellevue, WA, USA) placed on the dominant lower limb, centered on the previously marked area, and used a calculating cuff inflator (TD312, D. E. Hokanson, Inc., Bellevue, WA, USA) to inflate 40% (Gray et al., 2022) of their thigh arterial occlusion pressure using the following equation (Loenneke et al., 2015):

$$40\%\ \text{Arterial occlusion (mmHg)} = 0.4 \times (5.893\ (\text{Thigh circumference (cm)}) + 0.734\ (DBP) + 0.912\ (SBP) - 220.046)$$

The cuff pressure remained inflated throughout the full 5-min bout and was released following the exercise.

Immediate post exercise test

The same pre-test measures of soreness, power, and strength on the dominant limb were performed immediately after the 5-minute exercise bout as a post exercise assessment.

Recovery Sessions

Along with the immediate post-exercise assessments, all groups reported back to the laboratory 24 h, 48 h, and 72 h, within ± 2 h of the low-load eccentric exercise bout to perform additional testing to observe muscle impairment (Cheung et al., 2003; Lauver et al., 2017). The same cycle ergometer warm-up and post-test assessments (i.e., VAS, PPD, PPT, SLHD, and MVICs) that were performed during the experimental intervention were performed during the recovery sessions.

Data analysis

All raw force data for the MVICs were obtained from the Eccentron using a Biopac data acquisition system (MP150WSW; Biopac Systems, Inc., Santa Barbara, CA, USA). Data were sampled at 2000 Hz and processed offline with custom-written LabVIEW software (LabVIEW 8.5; National Instruments, Austin, TX, USA). The raw analog signals (V) were converted to Newtons (N) using the following calculation as per the manufacture's equation:

$$Newtons = ((Vsignal – Vzero\_offset) * 4903.3) / 1.9937.$$

MVIC peak force (PF) values are reported in absolute units. The PF was calculated as the highest 500 ms epoch for the MVICs and the highest value was used for all subsequent analyses.

Statistical Analysis

All statistics were performed using Statistical Package for Social Sciences software version 28 (IBM Corp, Armonk, NY: IBM Corp). Descriptive statistics are reported as mean ± standard deviation. An analysis for each variable was completed using a mixed factor analysis of variance (ANOVA) with the between factor being the group (ECC-BFR × CON) and the within factor being time (pre-test (Pre) × post-test (Post) × 24 h (P24) × 48 h (P48) × 72 h (P72) followups). When appropriate, follow-up analyses included Bonferroni-adjusted post hoc comparisons. An alpha value was set *at* $p \leq 0.05$ to be considered statistically significant.

Results

The means ± SD for all variables are presented in Table 2. For PF, there was no group × time interaction ($p = 0.490$), but there was a main effect for time ($p = 0.003$). Follow-up analyses revealed that for the group-specific pairwise comparisons, Pre was greater than all other time points ($p < 0.02$) except for P72 ($p = 0.380$), when collapsed across groups. No other differences existed between time trials ($p > 0.380$).

For VAS soreness, there was a significant group × time interaction ($p = 0.017$; Figure 1). Follow-up analyses revealed the ECC-BFR group had significantly lower VAS at Pre compared to all other time points ($p < 0.01$) and that P24 and P48 were higher than P72 ($p < 0.001$), whereas for the CON Pre was lower than Post ($p = 0.012$), P24 ($p < 0.01$), and P48, ($p < 0.001$) but not P72 ($p = 1.00$) and P48 was higher than P72 ($p < 0.01$). Also, there were no differences between groups when examining independent t-tests between each time point, although P approached significance ($p = 0.065$) for P48.

For PPD, there was no group × time interaction ($p = 0.379$), nor main effect for time ($p = 0.207$). For PPT, there was a significant group × time interaction ($p = 0.015$; Figure 1). Follow-up analyses revealed that for the group-specific pairwise comparisons there were no differences for any time points for either ECC-BFR ($p > 0.108$) or CON ($p > 0.074$). However, independent t-tests comparing between group time points showed that ECC-BFR was higher than CON for P72 ($p = 0.007$) and approached being higher for P48 ($p = 0.060$), but was not different for Pre ($p = 0.585$), Post ($p = 0.069$) or P24 ($p = 0.170$).

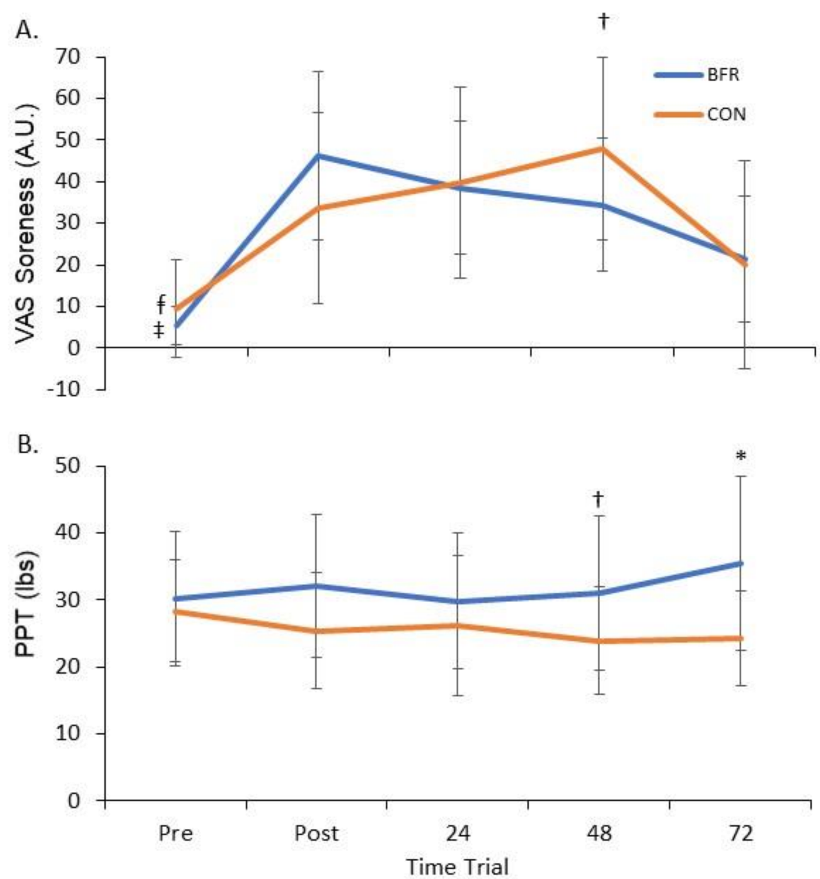
For SLHD, there was no group × time interaction ($p = 0.593$), but there was a main effect for time ($p = 0.002$). Follow up analyses revealed that Pre and Post were higher than P24 ($p = 0.035$ and 0.018, respectively; collapsed across group).

Table 2. Mean (SD) for all variables for the ECC-BFR and CON groups across all the assessment time points.

Variable	Pre	Post	24	48	72
			ECC-BFR (n=15)		
VAS†	5.40 (4.48)	46.20 (20.37)	38.53 (16.04)	34.40 (16.04)	21.46 (15.12)
PPD	15.32 (6.45)	15.55 (6.53)	13.94 (6.40)	13.74 (6.67)	15.14 (6.53)
PPT†	30.17 (10.03)	32.09 (10.64)	29.79 (10.17)	30.97 (11.51)	35.52 (12.98)
SLHD*	138.02 (28.97)	133.90 (30.96)	127.59 (35.42)ƒ	130.76 (31.33)	132.71 (27.72)
MVIC-PF*	2134.66 (589.07)	1947.31 (532.32)*	1907.83 (776.84)*	1774.67 (610.98)*	1854.75 (608.14)
			CON (n=15)		
VAS†	9.46 (11.63)	33.66 (22.99)	39.73 (22.96)	47.93 (22.09)	19.93 (25.01)
PPD	15.93 (4.41)	13.39 (3.57)	13.94 (4.60)	13.74 (4.24)	13.45 (3.27)
PPT†	28.38 (7.60)	25.37 (8.66)	26.14 (10.40)	23.89 (8.00)	24.32 (7.05)
SLHD*	124.87 (21.37)	125.52 (22.11)	118.88 (26.08)ƒ	117.33 (20.98)	122.55 (23.79)
MVIC-PF*	2261.01 (467.52)	1981.39 (431.45)*	2052.41 (444.37)*	1972.38 (358.35)*	2144.30 (598.25)

Note: VAS = Visual Analog Scale; PPD = Perceived Pain Detect; PPT = Perceived Pain Tolerance; SLHD = Single Leg Hop for Distance; MVIC-PF = Maximum Voluntary Isometric Contraction Peak Force; * indicates a significant effect for time, collapsed across groups, and the time column * indicates different from Pre when collapsed across groups. † indicates a significant group × time interaction (see text for details). ƒ indicates different from both Pre and Post (collapsed across group).

Figure 1. Soreness-related measures of the dominant leg depicting (A) visual analog scale (VAS), and B) perceived pain tolerance (PPT) variables for the blood flow restriction (ECC-BFR) and control (CON) groups. There was a significant group × time interaction (p = .017) for VAS (plot A) where ‡ indicates Pre was lower than all other time points for BFR whereas ƒ indicates lower than Post, 24, and 48 but not 72 h time points for CON. † indicates p = .065 for between group differences at the 48 h time point. There was a significant group × time interaction (p = 0.015) for PPT (plot B) although pairwise comparisons showed no statistically significant differences between any of the time points for either group (within group time point comparisons). * indicates BFR was higher than CON for the 72 h time point and † indicates p = .060 for between group differences at the 48 h time point.



Discussion

The primary results of this study indicated that eccentric exercise with BFR did not have any effects on muscle strength (PF) recovery, but that it had an effect on decreasing perceived soreness and increasing perceived pain threshold in the days that followed a low-load eccentric workout.

A principal finding herein was that PF was not found to show any group differences, indicating that the BFR did not have any impact on the recovery profile of isometric muscle strength. The results did show that there was a main effect for time, collapsed across groups. This indicated that the eccentric exercise bout did indeed elicit a muscle damage response such that muscle strength declined at Post, 24 h, and 48 h post exercise, although recovery was achieved by 72 h post exercise for this variable. Although it was beyond the scope of this investigation to explore the mechanisms responsible for these outcomes, it is possible that the reason for a lack of BFR effect on muscle strength recovery could be due to an increased activation of higher threshold motor unit recruitment caused by the eccentric loading (Lauver et al., 2017; Tesch et al., 1990). A previous study showed a significantly higher EMG activity of the quadriceps during concentric BFR exercise compared to concentric exercise alone (Lauver et al., 2020). However, there was no significant difference in muscle activation when using BFR during eccentric exercise compared to doing eccentric only (Lauver et al., 2020). This is similar to the results by Yasuda et al. (2012) that analyzed biceps brachii MVIC muscle activation following a 6-week training study utilizing either concentric exercise with BFR or eccentric exercise with BFR. The authors found significantly higher muscle activation following the concentric BFR training than eccentric BFR training. It was theorized that the increase muscle activation was perhaps caused by the hypoxic state distal to the tourniquet that increases the mechanical tension on the muscle fibers during low-load concentric exercise that is equivalent to traditional high intensity resistance exercise (Cognetti et al., 2022; Davids et al., 2021). However, this appears to not be the case with eccentric exercise with BFR which is more likely to yield a minimal effect on larger motor unit recruitment compared to eccentric exercise alone (Lauver et al., 2017, 2020). It has been shown that eccentric exercise, even at relatively low intensities (i.e., 50% of maximum), creates a considerable enough mechanical load that elicits strength loss during recovery for which BFR cannot over compensate (Hill et al., 2021; Lauver et al., 2017; Paschalis et al., 2005).

The findings of this study were consistent with other studies that have analyzed the effects of BFR and eccentric exercise on MVIC-PF of the knee extensors (Lauver et al., 2017; C. Proppe et al., 2022) and elbow flexors (C. E. Proppe et al., 2022; Yasuda et al., 2012). Proppe et al. (2022) found that during a fatiguing low-intensity exercise bout of concentric knee extension with and without BFR there was no difference in PF and muscle activation following the exercise bout. An additional study by Proppe et al. (2022) explored the effect of BFR on a low-load reciprocal elbow flexion and extension training program, and the results showed that BFR did not affect peak power changes on each training day, but that it did yield a higher pain threshold than the low-load alone. Similar results were reported by Lauver et al. (2017) which showed that after 4 sets of maximal eccentric exercise of the knee extensors with or without BFR, MVIC-PF decreased in both groups over time and the only differences were found during sets 2 and 3 in which BFR maintained a higher PF than eccentric exercise alone. A follow-up study compared BFR during concentric and eccentric muscle contractions and found that MVIC was significantly higher in both BFR groups compared to groups without BFR, however, the concentric BFR groups may have had a higher muscle activation than the eccentric BFR group

(Lauver et al., 2020). This common finding may be due to the fact that during eccentric exercise, BFR has no effect on the mechanical loading of the muscle fibers compared to concentric exercise, however, BFR is shown to decrease the inflammatory response caused by type 1 muscle fiber metabolism (Cognetti et al., 2022). Thus, it appears that BFR is not effective at preserving or restoring muscle strength (isometric PF) in the post eccentric exercise period.

Another key finding in the present study was that VAS ($p = 0.017$) and PPT ($p = 0.015$) both showed a significant group × time interaction, indicating that the BFR group trended toward lower perceived soreness (VAS) and higher perceived pain threshold (PPT), particularly at the later time periods (48 and 72 h, respectively). Also, the changes in pain tolerance (PPT) were shown to be a better indicator of muscle soreness/damage than pain detection (PPD) given that the PPD variable did not change across both groups ($p = 0.379$).

This ‘soreness’ phenomenon was consistent with other studies utilizing single-joint low intensity exercise with BFR (Korakakis et al., 2018; C. E. Proppe et al., 2022). This may be due to the decrease in localized and systemic inflammatory responses after using BFR which may have led to a lower perceived soreness, via the VAS measure, in the days following the exercise bout (Behringer et al., 2018; Eslamdoust et al., 2020; Karabulut et al., 2013) and a higher PPT. With regard to the sensitivity of measurements, the results of this study support the use of PPT and VAS as opposed to the PPD variable. This suggests that the pressure at which pain is detected is not a relative indicator of eccentric-induced muscle damage compared to pain tolerance or perceived pain (Fleckenstein et al., 2017; Harper et al., 2021). In a study assessing the effects of resistance training on the knee extensors of osteoarthritis patients with and without BFR, it was found that pain measures significantly improved following the BFR training protocol. However, pain was measured according to the WOMAC pain subscale which may explain the inconsistency (Harper et al., 2019). Early et al. (2020) also recorded a lower VAS measure following an 8-week (20 visit) training study comparing traditional resistance training with and without BFR. Additionally, another previous study suggested that BFR caused a decrease in perceived pain following resistance and aerobic exercise (Cognetti et al., 2022). It appears that BFR may have a positive effect on mitigating soreness responses from eccentric-induced muscle damage. Further research is warranted to substantiate these findings, in a multi-joint eccentric exercise context, and to explore the specific mechanisms that may be responsible for such an effect.

The current study has some limitations that are worth addressing. The physiological mechanism for the decrease in pain following a BFR exercise bout was unable to be identified. The changes in pain measures may be due to a decreased inflammatory response, an increase in anabolic hormones to better facilitate recovery, or even to proprioception factors that the present study was unable to measure due to the invasive nature of the measures (Davids et al., 2021; Eslamdoust et al., 2020; Lauver et al., 2017; Pignanelli et al., 2020). Future work could examine the degree to which BFR may contribute to a lesser degree of muscle fiber damage (Behringer et al., 2018; Davids et al., 2021; Eslamdoust et al., 2020; Hughes et al., 2021). As such, future investigations may consider administering blood sampling and muscle biopsies during the pre and post testing sessions to identify the cellular and metabolic responses following a BFR session (Behringer et al., 2018; Davids et al., 2021; Eslamdoust et al., 2020). Along with these analyses, a multitude of contraction types should be performed for comparative purposes (i.e., concentric and eccentric) to further assess the functional and exercise type implications of BFR on recovery responses (Gordon et al., 2019; Weeks et al., 2023). We only allocated one assessment of unilateral functional power (SLHD) which only measures power in one plane.

SLHD requires participants to move their center of mass in a horizontal direction, rather than other measurements like the single leg vertical jump that measure vertical displacement (Swearingen et al., 2011). We suggest using SLVJ in conjunction with SLHD for a more comprehensive assessment of the lower limb (Sullivan et al., 2021; Swearingen et al., 2011). Furthermore, research that leads to the eventual development, creation, and implementation of a low-load eccentric training protocol with BFR would be advantageous for use in clinical or sports settings.

In conclusion, these findings add to the literature in regard to the manner in which BFR may influence muscle recovery from multi-joint eccentric exercise. The results showing that muscle strength is not impacted, but muscle soreness may have a favorable response from BFR may be beneficial when utilizing BFR to aid in clinical populations or rehabilitation programming. Given that a major issue in both clinical and rehabilitation is adherence to the exercise program, a clinical population may be more likely to adhere to a rehabilitation program if their pain tolerance is higher and perceived pain is lower (Fisher et al., 1988). The findings of this study may indicate that BFR can decrease perceived pain and increase pain tolerance which may be a beneficial modality to implement into an eccentric exercise program for individuals that are more sensitive to pain and/or soreness. Finally, the finding that BFR did not have any impact on the recovery profile of muscle strength indicates that BFR is not useful when a more rapid or effective muscle strength restoration is the principally desired outcome.

References

Behringer, M., Heinke, L., Leyendecker, J., & Mester, J. (2018). Effects of blood flow restriction during moderate-intensity eccentric knee extensions. *The Journal of Physiological Sciences*, *68*(5), 589–599. https://doi.org/10.1007/s12576-017-0568-2

Cheung, K., Hume, P. A., & Maxwell, L. (2003). Delayed onset muscle soreness: treatment strategies and performance factors. *Sports Medicine*, *33*(2), 145–164. https://doi.org/10.2165/00007256-200333020-00005

Cognetti, D. J., Sheean, A. J., & Owens, J. G. (2022). Blood flow restriction therapy and its use for rehabilitation and return to sport: physiology, application, and guidelines for implementation. *Arthroscopy, Sports Medicine, and Rehabilitation*, *4*(1), e71–e76. https://doi.org/10.1016/j.asmr.2021.09.025

Crane, J. S., Thompson, B. J., Harrell, D. C., Bressel, E., & Heath, E. M. (2022). Comparison of high versus low eccentric-based resistance training frequencies on short-term muscle function adaptations. *Journal of Strength and Conditioning Research*, *36*(2), 332–339. https://doi.org/10.1519/JSC.0000000000003482

Davids, C. J., Næss, T. C., Moen, M., Cumming, K. T., Horwath, O., Psilander, N., Ekblom, B., Coombes, J. S., Peake, J., Raastad, T., & Roberts, L. A. (2021). Acute cellular and molecular responses and chronic adaptations to low-load blood flow restriction and high-load resistance exercise in trained individuals. *Journal of Applied Physiology*, *131*(6), 1731–1749. https://doi.org/10.1152/japplphysiol.00464.2021

Early, K. S., Rockhill, M., Bryan, A., Tyo, B., Buuck, D., & McGinty, J. (2020). Effect of blood flow restriction training on muscular performance, pain, and vascular function.

International Journal of Sports Physical Therapy, *15*(6), 892–900. https://doi.org/10.26603/ijspt20200892

Elias, L. J., Bryden, M. P., & Bulman-Fleming, M. B. (1998). Footedness is a better predictor than is handedness of emotional lateralization. *Neuropsychologia*, *36*(1), 37–43. https://doi.org/10.1016/S0028-3932(97)00107-3

Eslamdoust, M., Ghazalian, F., Gholami, M., Ebrahim, K., & Bazgir, B. (2020). The effect of eccentric resistance training with and without blood flow restriction on serum IL6 and MMP9 levels in young active men. *Journal of Archives in Military Medicine*, *7*(4). https://doi.org/10.5812/jamm.106779

Fisher, A. C., Domm, M. A., & Wuest, D. A. (1988). Adherence to sports-injury rehabilitation programs. *The Physician and Sportsmedicine*, *16*(7), 47–52. https://doi.org/10.1080/00913847.1988.11709551

Fleckenstein, J., Simon, P., König, M., Vogt, L., & Banzer, W. (2017). The pain threshold of high-threshold mechanosensitive receptors subsequent to maximal eccentric exercise is a potential marker in the prediction of DOMS associated impairment. *PLoS ONE*, *12*(10), e0185463. https://doi.org/10.1371/journal.pone.0185463

Gordon, J. P., Thompson, B. J., Crane, J. S., Bressel, E., & Wagner, D. R. (2019). Effects of isokinetic eccentric versus traditional lower body resistance training on muscle function: Examining a multiple-joint short-term training model. *Applied Physiology, Nutrition, and Metabolism*, *44*(2), 118–126. https://doi.org/10.1139/apnm-2018-0333

Gray, S., Cuomo, A., Proppe, C. E., Traylor, M. K., Hill, E. C., & Keller, J. L. (2022). Effects of sex and cuff pressure on physiological responses during blood flow restriction resistance exercise in young adults. *Medicine & Science in Sports & Exercise*, *Publish Ahead of Print*. https://doi.org/10.1249/MSS.0000000000003103

Haefeli, M., & Elfering, A. (2006). Pain assessment. *European Spine Journal*, *15*(Suppl 1), S17–S24. https://doi.org/10.1007/s00586-005-1044-x

Harper, S., Peters, F. J., Brandon S. Pollock, Keith Burns, John McDaniel, & Angela L. Ridgel. (2021). Design of an eccentric recumbent ergometer to elicit delayed onset muscle soreness. *Research Directs in Health Sciences*, *1*(1). https://doi.org/10.53520/rdhs2021.1045

Harper, S., Roberts, L., Layne, A., Jaeger, B., Gardner, A., Sibille, K., Wu, S., Vincent, K., Fillingim, R., Manini, T., & Buford, T. (2019). Blood-flow restriction resistance exercise for older adults with knee osteoarthritis: a pilot randomized clinical trial. *Journal of Clinical Medicine*, *8*(2), 265. https://doi.org/10.1249/MSS.0000000000003103

Hill, E. C., Housh, T. J., Smith, C. M., Keller, J. L., Schmidt, R. J., & Johnson, G. O. (2021). High- vs. low-intensity fatiguing eccentric exercise on muscle thickness, strength, and blood flow. *The Journal of Strength & Conditioning Research*, *35*(1), 33. https://doi.org/10.1519/JSC.0000000000002632

Hoppeler, H. (2016). Moderate load eccentric exercise; a distinct novel training modality. *Frontiers in Physiology*, *7*. https://doi.org/10.3389/fphys.2016.00483

Hughes, L., Grant, I., & Patterson, S. D. (2021). Aerobic exercise with blood flow restriction causes local and systemic hypoalgesia and increases circulating opioid and endocannabinoid levels. *Journal of Applied Physiology*, *131*(5), 1460–1468. https://doi.org/10.1152/japplphysiol.00543.2021

Karabulut, M., Sherk, V. D., Bemben, D. A., & Bemben, M. G. (2013). Inflammation marker, damage marker and anabolic hormone responses to resistance training with vascular restriction in older males. *Clinical Physiology and Functional Imaging*, *33*(5), 393–399. https://doi.org/10.1111/cpf.12044

Kataoka, R., Vasenina, E., Hammert, W. B., Ibrahim, A. H., Dankel, S. J., & Buckner, S. L. (2022). Muscle growth adaptations to high-load training and low-load training with blood flow restriction in calf muscles. *European Journal of Applied Physiology*, *122*(3), 623–634. https://doi.org/10.1007/s00421-021-04862-7

Korakakis, V., Whiteley, R., & Giakas, G. (2018). Low load resistance training with blood flow restriction decreases anterior knee pain more than resistance training alone. A pilot randomised controlled trial. *Physical Therapy in Sport*, *34*, 121–128. https://doi.org/10.1016/j.ptsp.2018.09.007

Lauver, J. D., Cayot, T. E., Rotarius, T. R., & Scheuermann, B. W. (2020). Acute neuromuscular and microvascular responses to concentric and eccentric exercises with blood flow restriction. *Journal of Strength and Conditioning Research*, *34*(10), 2725–2733. https://doi.org/10.1519/JSC.0000000000003372

Lauver, J. D., Cayot, T. E., Rotarius, T., & Scheuermann, B. W. (2017). The effect of eccentric exercise with blood flow restriction on neuromuscular activation, microvascular oxygenation, and the repeated bout effect. *European Journal of Applied Physiology*, *117*(5), 1005–1015. https://doi.org/10.1007/s00421-017-3589-x

Loenneke, J. P., Allen, K. M., Mouser, J. G., Thiebaud, R. S., Kim, D., Abe, T., & Bemben, M. G. (2015). Blood flow restriction in the upper and lower limbs is predicted by limb circumference and systolic blood pressure. *European Journal of Applied Physiology*, *115*(2), 397–405. https://doi.org/10.1007/s00421-014-3030-7

Lorenz, D. S., Bailey, L., Wilk, K. E., Mangine, R. E., Head, P., Grindstaff, T. L., & Morrison, S. (2021). Blood flow restriction training. *Journal of Athletic Training*, *56*(9), 937–944. https://doi.org/10.4085/418-20

Mike, J., Kerksick, C. M., & Kravitz, L. (2015). How to incorporate eccentric training into a resistance training program. *Strength & Conditioning Journal*, *37*(1), 5–17. https://doi.org/10.1519/SSC.0000000000000114

Paschalis, V., Koutedakis, Y., Jamurtas, A. Z., Mougios, V., & Baltzopoulos, V. (2005). Equal volumes of high and low intensity of eccentric exercise in relation to muscle damage and performance. *The Journal of Strength & Conditioning Research*, *19*(1), 184.

Patterson, S. D., Hughes, L., Warmington, S., Burr, J., Scott, B. R., Owens, J., Abe, T., Nielsen, J. L., Libardi, C. A., Laurentino, G., Neto, G. R., Brandner, C., Martin-Hernandez, J., & Loenneke, J. (2019). Blood flow restriction exercise: considerations of methodology, application, and safety. *Frontiers in Physiology*, *10*, 533. https://doi.org/10.3389/fphys.2019.00533

Pignanelli, C., Petrick, H. L., Keyvani, F., Heigenhauser, G. J. F., Quadrilatero, J., Holloway, G. P., & Burr, J. F. (2020). Low-load resistance training to task failure with and without blood flow restriction: muscular functional and structural adaptations. *American Journal of Physiology-Regulatory, Integrative and Comparative Physiology*, *318*(2), R284–R295. https://doi.org/10.1152/ajpregu.00243.2019

Proppe, C. E., Rivera, P. M., Hill, E. C., Housh, T. J., Keller, J. L., Smith, C. M., Anders, J. P. V., Schmidt, R. J., Johnson, G. O., & Cramer, J. T. (2022). The effects of blood flow restriction resistance training on indices of delayed onset muscle soreness and peak power. *Isokinetics and Exercise Science*, *30*(2), 167–175. https://doi.org/10.3233/IES-210158

Proppe, C., Rivera, P., Beltran, E., & Hill, E. (2022). Neuromuscular and mean force changes during a fatiguing bout of exercise with and without blood flow restriction. *Comparative Exercise Physiology*, 1–8. https://doi.org/10.3920/CEP220023

Spencer, S., Thompson, B. J., Bressel, E., Louder, T., & Harrell, D. C. (2023). Transfer effects of a multiple-joint isokinetic eccentric resistance training intervention to nontraining-specific traditional muscle strength measures. *Sports*, *11*(1), 9. https://doi.org/10.3390/sports11010009

Sullivan, S. W., Fleet, N. A., Brooks, V. A., Bido, J., Nwachukwu, B. U., & Brubaker, P. H. (2021). Comparison of different functional tests for leg power and normative bilateral asymmetry index in healthy collegiate athletes. *Open Access Journal of Sports Medicine*, *Volume 12*, 119–128. https://doi.org/10.2147/OAJSM.S315162

Swearingen, J., Lawrence, E., Stevens, J., Jackson, C., Waggy, C., & Davis, D. S. (2011). Correlation of single leg vertical jump, single leg hop for distance, and single leg hop for time. *Physical Therapy in Sport*, *12*(4), 194–198. https://doi.org/10.1016/j.ptsp.2011.06.001

Tesch, P. A., Dudley, G. A., Duvoisin, M. R., Hather, B. M., & Harris, R. t. (1990). Force and EMG signal patterns during repeated bouts of concentric or eccentric muscle actions. *Acta Physiologica Scandinavica*, *138*(3), 263–271. https://doi.org/10.1111/j.1748-1716.1990.tb08846.x

Thiebaud, R. S., Yasuda, T., Loenneke, J. P., & Abe, T. (2013). Effects of low-intensity concentric and eccentric exercise combined with blood flow restriction on indices of exercise-induced muscle damage. *Interventional Medicine and Applied Science*, *5*(2), 53–59. https://doi.org/10.1556/imas.5.2013.2.1

van Melick, N., Meddeler, B. M., Hoogeboom, T. J., Nijhuis-van der Sanden, M. W. G., & van Cingel, R. E. H. (2017). How to determine leg dominance: the agreement between self-reported and observed performance in healthy adults. *PLOS ONE*, *12*(12), e0189876. https://doi.org/10.1371/journal.pone.0189876

Weeks, C., Thompson, B. J., Spencer, S. B., Fisher, C., & Althouse, D. (2023). Effects of multi-joint eccentric training on muscle function when combined with aquatic plyometric training: a minimal dose, mixed training study. *Journal of Musculoskeletal and Neuronal Interactions*, *23*(4), 386-396.

Yamanaka, T., Farley, R. S., & Caputo, J. L. (2012). Occlusion training increases muscular strength in division Ia football players. *Journal of Strength and Conditioning Research*, *26*(9), 2523–2529. https://doi.org/10.1519/JSC.0b013e31823f2b0e

Yasuda, T., Fujita, T., Miyagi, Y., Kubota, Y., Sato, Y., Nakajima, T., Bemben, M. g., & Abe, T. (2006). Electromyographic responses of arm and chest muscle during bench press exercise with and without KAATSU. *International Journal of KAATSU Training Research*, *2*(1), 15–18. https://doi.org/10.3806/ijktr.2.15

Yasuda, T., Loenneke, J. P., Thiebaud, R. S., & Abe, T. (2012). Effects of blood flow restricted low-intensity concentric or eccentric training on muscle size and strength. *PLoS ONE*, *7*(12), e52843. https://doi.org/10.1371/journal.pone.0052843