European Journal of Applied Physiology (2019) 119:2363–2373
https://doi.org/10.1007/s00421-019-04220-8

ORIGINAL ARTICLE

Eccentric and concentric blood flow restriction resistance training on indices of delayed onset muscle soreness in untrained women

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Received: 11 April 2019 / Accepted: 25 August 2019 / Published online: 31 August 2019
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Abstract

Purpose Unaccustomed exercise can result in delayed onset muscle soreness (DOMS), particularly as a result of the eccentric phase of the muscle contraction. Resistance training combined with venous blood flow restriction (*v*BFR) may attenuate DOMS, but the available information in this regard is conflicting. Therefore, the purpose of this study was to examine the effects of low-load eccentric *v*BFR (Ecc-*v*BFR) and concentric *v*BFR (Con-*v*BFR) resistance training on indices of DOMS.

Methods Twenty-five previously untrained women completed seven days of either Ecc-*v*BFR ($n = 12$) or Con-*v*BFR ($n = 13$) forearm flexion resistance training at a velocity of 120° s^{-1} on an isokinetic dynamometer. The Ecc-*v*BFR group used a training load that corresponded to 30% of eccentric peak torque and the Con-*v*BFR group used a training load that corresponded to 30% of concentric peak torque.

Results There were no differences between Ecc-*v*BFR and Con-*v*BFR at any of the seven training sessions on any of the indices of DOMS. There were no decreases in the maximal voluntary isometric contraction torque which increased at days 6 and 7. Similarly, there were no changes in perceived muscle soreness, pain pressure threshold, elbow joint angle, or edema (as assessed by echo intensity via ultrasound) across the seven training sessions.

Conclusions The Ecc-*v*BFR and Con-*v*BFR low-load training protocols were not associated with DOMS and there were no differences between protocols when performed using the same relative training intensity. These findings suggested that both unaccustomed eccentric and concentric low-load training did not result in DOMS when combined with *v*BFR.

Keywords Low load · Muscle damage · Blood flow · Eccentric · Low intensity

Abbreviations

Ecc-*v*BFR	Eccentric venous blood flow restriction
Con-*v*BFR	Concentric venous blood flow restriction
*v*BFR	Venous blood flow restriction
DOMS	Delayed onset muscle soreness
MVIC	Maximal voluntary isometric contraction
PPT	Pain pressure threshold
1RM	One repetition maximum
MD	Minimal difference
SEM	Standard error of measurement
ICC	Intraclass correlation coefficient

Communicated by William J. Kraemer.

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Introduction

Recent studies (Abe et al. 2006; Fujita et al. 2008; Laurentino et al. 2012) have examined the effects of venous blood flow restriction (*v*BFR) versus non-*v*BFR resistance training on muscle strength and hypertrophy. In general, compared to low-load non-*v*BFR, low-load *v*BFR resistance training elicits greater increases in muscle strength and similar increases in hypertrophy (Abe et al. 2006; Fujita et al. 2008; Laurentino et al. 2012). In addition, low-load *v*BFR resistance training results in muscle hypertrophy and increases in muscle strength that are comparable to those of high-load non-*v*BFR resistance training (Karabulut et al. 2010; Takarada et al. 2000; Ellefsen et al. 2015). Thus, it has been suggested

(Loenneke et al. 2012) that low-load *v*BFR resistance training for muscle adaptation is an attractive alternative to resistance training programs that require heavy loads or exercising to exhaustion which may not be practical following surgery, in older populations, or during periods of immobilization. Additionally, *v*BFR combined with passive mobilization reduced muscle wasting in older adults in an intensive care unit (Barbalho et al. 2019). Therefore, *v*BFR combined with exercise or passive mobilization may be a practical alternative to elicit muscle adaptation. Like unaccustomed exercise, however, the application of *v*BFR combined with or without low-load resistance training may elicit delayed onset muscle soreness (DOMS).

Typically, high contractile forces associated with eccentric contractions can result in *z*-line streaming and open stretch-activated calcium channels (Zhang et al. 2012). As a result, extracellular calcium infiltrates the muscles and activates calpain proteins that result in the degradation of muscle proteins (Verburg et al. 2005; Zhang et al. 2012). Macrophages and neutrophils accumulate at the site of muscle injury and increase the production of proinflammatory cytokines (Tidball 2005; Kawanishi et al. 2016). The resultant inflammation increases muscle edema, and group III and IV afferent nerve endings are more easily excited leading to an increased perception of pain (Clarkson and Hubal 2002). Thus, indirect indices of DOMS have been used to quantify the magnitude of muscle damage (Warren et al. 1999). For example, mechanical disruption of muscle proteins and calcium-mediated proteolysis decreases the maximal force generating capacity of the muscle assessed by maximal voluntary isometric contraction (MVIC) (Warren et al. 1999). Inflammation as a result of muscle damage can shorten the range of motion and is associated with muscle edema which can be quantified using ultrasound (Warren et al. 1999; Damas et al. 2016a). Increased sensitivity of group III and IV afferent nerve endings increased perceived muscle soreness and sensitivity of pain (Warren et al. 1999; Andersen et al. 2006). Sensitivity to pain has been evaluated using a pain pressure threshold (PPT) device to examine myofascial pain syndrome, arthritis, and DOMS (Andersen et al. 2006). Collectively, indirect assessment of DOMS provide insight to the magnitude of muscle damage associated with exercise.

It has been argued, however, that eccentric-based exercise can be used safely in clinical settings and that the association between eccentric contractions and DOMS is "outdated" [page 2 (Lepley et al. 2017)] and is observed primarily after high intensity or volume-lengthening exercise. Furthermore, the authors (Lepley et al. 2017, 2018) suggested that compared to typical concentric-based rehabilitation techniques, eccentric-based rehabilitation was superior at restoring muscle strength and neural function following injury. Together, it is possible that eccentric-based exercise combined with *v*BFR may be used to improve muscle adaptation and rehabilitation practices. On the contrary, *v*BFR may exacerbate DOMS via ischemic reperfusion (Idstrom et al. 1990).

The effects of low-load *v*BFR resistance training on indices of DOMS, however, are conflicting. For example, Umbel et al. 2009 reported that concentric *v*BFR (Con-*v*BFR) increased muscle soreness to a greater extent than eccentric *v*BFR (Ecc-*v*BFR) when assessed 24 and 48 h after leg extension muscle actions performed to failure at 35% of MVIC. There were, however, no changes in MVIC for either condition (Umbel et al. 2009). For the forearm flexors, Thiebaud et al. (2013) reported no changes in MVIC or range of motion 24 h after Ecc-*v*BFR or Con-*v*BFR performed at 30% of concentric 1RM (Thiebaud et al. 2013). For Con-*v*BFR, muscle soreness remained unchanged, but increased at 24 to 72 h post-exercise as a result of Ecc-*v*BFR (Thiebaud et al. 2013). Thus, the available information (Umbel et al. 2009; Thiebaud et al. 2013) regarding the effects of low-load Ecc-*v*BFR versus Con-*v*BFR with regard to muscle soreness is inconclusive.

The disparate findings among the previous investigations (Umbel et al. 2009; Thiebaud et al. 2013) may be due to the relative training intensities. That is, eccentric training at 30% 1RM and 35% MVIC equates to roughly 10% of eccentric peak torque (Yasuda et al. 2013). Thus, additional studies are needed to examine the effects of Ecc-*v*BFR and Con-*v*BFR on indices of DOMS performed at the same relative training intensity. In addition, exercise-induced edema from muscle damage may persist a week or longer following unaccustomed exercise (Damas et al. 2016a, b), but no previous investigations have tracked the changes in edema over a 2-week period following unaccustomed *v*BFR exercise. Furthermore, during non-*v*BFR exercise, repeated bouts of exercise on separate days did not further exacerbate indices of DOMS (Buckner et al. 2017; Smith et al. 1994), but no previous investigations have examined repeated bouts of Ecc-*v*BFR or Con-*v*BFR on indices of DOMS. Therefore, the primary purpose of this study was to examine the effects of low-load Ecc-*v*BFR and Con-*v*BFR resistance training on indices of DOMS. As a secondary purpose, rating of perceived exertion was examined after each set of Ecc- *v*BFR and Con-*v*BFR to determine the subjects' tolerance to this training modality. Based on the previous investigations (Umbel et al. 2009; Thiebaud et al. 2013), we hypothesized that there would be no changes in MVIC or PPT throughout the 2-week period for either Ecc-*v*BFR or Con-*v*BFR. During the first week, however, we hypothesized that edema and muscle soreness would increase and elbow joint angle would decrease before returning to baseline levels after two weeks of Ecc-*v*BFR and Con-*v*BFR (Umbel et al. 2009; Thiebaud et al. 2013). In addition, we hypothesized that Ecc-*v*BFR and Con-*v*BFR would result in similar rating of perceived exertion as both groups would be exercising at the same relative training intensity.

Methods

Subjects

Twenty-five women volunteered to participate in this investigation and were randomly assigned to either Ecc-*v*BFR ($n = 12$; mean age ± SD = 21.7 ± 1.0 years; body mass = 56.0 ± 6.6 kg; height = 166.4 ± 6.7 cm) or Con-*v*BFR ($n = 13$; mean age ± SD = 22.0 ± 1.6 years; body mass = 56.1 ± 5.3 kg; height = 166.3 ± 5.1 cm). The subjects were part of a larger multi-independent and -dependent variable study that have been examined previously (Hill et al. 2018, 2019) for purposes unrelated to the present study. There was no overlap, however, for the muscle soreness data in this study and our previous studies (Hill et al. 2018, 2019). Furthermore, this study involves all subjects for which there were complete data sets for all dependent variables. The subjects had no known cardiovascular, pulmonary, metabolic, muscular, and/or coronary heart disease, or regularly used prescription medication. All subjects were recreationally active at the time of testing and participated in activities including running, bicycling, soccer, and volleyball, but no subjects had been actively participating in resistance training for at least the past six months. The subjects visited the laboratory on nine occasions (Table 1) during the Fall semester (September and October) and performed the testing procedures at the same time of day (± 2 h). The subjects were asked to maintain their current diet, sleeping, and exercise habits throughout the duration of the study and were asked to refrain from the use of supplements or starting other resistance training interventions (research or otherwise). Subjects were excluded if they were currently taking any supplements or participating in caloric restriction dietary practices. The baseline visit was used for reliability purposes only. The study was approved by the University Institutional Review Board for Human Subjects and all subjects completed a health history questionnaire and signed a written informed consent prior to testing.

Experimental design

A randomized, repeated measures, between-group, parallel design was used for this study. Twenty-five women were randomly assigned to either low-load Ecc-*v*BFR or low-load Con-*v*BFR. Venous BFR was applied using a KAATSU resistance band and *v*BFR was determined for each subject as 40% of the lowest amount of pressure needed to completely occlude the brachial artery as indicated by ultrasound (Loenneke et al. 2016). Subjects assigned to Ecc-*v*BFR used a load that corresponded

Table 1 Overview of the procedures performed at each visit

Baseline	Testing and training day 1	Testing and training days 2–6	Testing day 7
Assessments of DOMS: elbow joint angle, muscle soreness, echo intensity via ultrasound, and PPT	Assessments of DOMS: elbow joint angle, muscle soreness, echo intensity via ultrasound, and PPT	Assessments of DOMS: elbow joint angle, muscle soreness, echo intensity via ultrasound, and PPT	Assessments of DOMS: elbow joint angle, muscle soreness, echo intensity via ultrasound, and PPT
Determination of MVIC	Determination of concentric peak torque, eccentric peak torque, and MVIC	Determination of MVIC	Determination of MVIC
Determination of *v*BFR target pressure	Determination of *v*BFR target pressure		
	75 (1 × 30, 3 × 15) concentric or eccentric forearm flexion repetitions at 30% of testing day 1 concentric or eccentric peak torque performed with *v*BFR at 40% of arterial occlusion pressure	75 (1 × 30, 3 × 15) concentric or eccentric forearm flexion repetitions at 30% of testing day 1 concentric or eccentric peak torque performed with *v*BFR at 40% of arterial occlusion pressure	

The baseline visit was used for reliability purposes only

DOMS delayed onset muscle soreness, *MVIC* maximal voluntary isometric contraction, *PPT* pain pressure threshold, *vBFR* venous blood flow restriction

to 30% of eccentric peak torque and Con-*v*BFR used a load that corresponded to 30% of concentric peak torque. In total, six training days were performed at a rate of three days per week. Prior to each exercise session and 48-h after the last training day, indices of DOMS were assessed for a total of seven testing days performed within a 2-week period (Table 1). Each exercise session consisted of 75 eccentric (Ecc-*v*BFR) or concentric (Con-*v*BFR) isokinetic muscle actions of the forearm flexors performed over four sets (1 × 30, 3 × 15) and each set was separated by 30 s of rest. All exercise procedures were performed using an isokinetic dynamometer at a velocity of 120° s^{-1} and were performed at the same time of day (± 2 h). During each of the seven sessions, MVIC, muscle soreness, PPT, elbow joint angle, and edema were measured.

Procedures

Familiarization

The first laboratory visit consisted of an orientation session to familiarize the subjects with the testing protocols. During the orientation, subjects performed submaximal and maximal isometric muscle actions as well as submaximal and maximal eccentric and concentric isokinetic muscle actions of the forearm flexors at 120° s^{-1} on a Cybex 6000 isokinetic dynamometer. To familiarize the subjects with the exercise protocols, the subjects also practiced performing eccentric or concentric isokinetic muscle actions at 30% of their eccentric or concentric peak torque, respectively. Torque was visually tracked using real-time torque displayed on a computer monitor.

Eccentric and concentric exercise protocols

The subjects in both the Ecc-*v*BFR and Con-*v*BFR groups completed six training days (Table 1). Each session consisted of 75 eccentric or concentric muscle actions of the forearm flexors performed over four sets (1 × 30, 3 × 15) and each set was separated by 30 s of rest (Thiebaud et al. 2013; Loenneke et al. 2016; Counts et al. 2016; Yasuda et al. 2013). The exercise protocol was randomly assigned to either the dominant or non-dominant arm. All muscle actions were performed at a velocity of 120° s^{-1} and all eccentric or concentric muscle actions were followed by a passive concentric or eccentric muscle action, respectively, that was assisted by the investigator (E.C.H). The Ecc-*v*BFR and Con-*v*BFR training interventions were performed at the same relative intensity. Specifically, the Ecc-*v*BFR training group performed 75 eccentric muscle actions of the forearm flexors at 30% of testing day 1 eccentric peak torque and the Con-*v*BFR training group performed 75 concentric forearm flexion muscle actions at 30% of testing day 1 concentric peak torque. Thus, the relative training intensity, velocity and tempo, number of repetitions performed, and rest between sets were identical between the Ecc-*v*BFR and Con-*v*BFR exercise protocols. The relative training intensity, repetitions, rest between sets, and frequency of training were consistent with the previous investigations (Thiebaud et al. 2013; Loenneke et al. 2016; Counts et al. 2016; Yasuda et al. 2013) that have examined low-load *v*BFR.

Indices of DOMS

On each of the seven testing days and prior to the warm-up or exercise protocol, muscle soreness, PPT, elbow joint angle, and edema were determined (Table 1). Muscle soreness was assessed using a Visual Analog Scale and the subjects were asked to provide a value from 0 to 10 where 0 corresponded to "no soreness" and 10 corresponded to "severe soreness" (Buckner et al. 2017). Muscle soreness was evaluated while the subject was asked to resist the investigator as the investigator attempted to forcibly extend the subjects forearm from a flexed to extended position (Buckner et al. 2017). PPT was determined using a pressure algometer (Wagner FPX, Greenwhich, CT, USA) with a 1 cm^2 flat rubber tip that was applied gradually to the biceps brachii at 66% of the distance from the olecranon to the fossa cubit. Based on the methods of Umbel et al. (2009), the subjects were asked to identify when the force applied was "slightly uncomfortable" and the force (kg) at which this occurred was recorded. Elbow joint angle was assessed using a goniometer (Smith & Nephew Rolyan, Inc., Menomonee Falls, WI, USA) and was determined as the angle between the forearm and arm when the subject stood with their arm hanging freely at their side (Thiebaud et al. 2013). Edema as assessed by echo intensity was determined using ultrasound (Damas et al. 2016a). Ultrasound images of the arm (biceps brachii) were obtained using a portable brightness mode (B-mode) ultrasound imaging device (GE Logiqe, USA) and a multi-frequency linear-array probe (12L-Rs; 5–13 MHz; 38.4 mm field-of-view). All ultrasound measurements were performed at a sampling rate of 10 MHz and at a gain of 58 dB. Ultrasound images were analyzed using ImageJ software (Version 1.47v., National Institutes of Health, Bethesda, MD, USA). Echo intensity, as assessed by gray-scale analysis [0 arbitrary unit (AU) corresponds to black image, 255 AU corresponds to white image] was performed using the histogram function and was determined at 66% of the distance from the medial acromion of the scapula to the fossa cubit. Great care was taken to ensure that consistent, minimal pressure was applied with the probe to limit compression of the artery. To enhance acoustic coupling and reduce near field artifacts, a generous amount of water-soluble transmission gel was applied to the skin prior to each measurement.

Blood flow measurements were assessed at an insonation angle of 60° to the brachial artery. All measurements were taken while the subjects were lying in the supine position on the isokinetic dynamometer with both arms and legs supported. Blood flow was assessed from the brachial artery proximal to the antecubital fossa using Pulsed Wave Doppler. Blood flow was used to determine the cuff pressure needed to completely occlude the brachial artery (assessed at baseline and first training day).

Determination of MVIC

After the resting indices of DOMS were determined, the subjects performed a warm-up consisting of 10 submaximal (approximately 50% effort), concentric and eccentric muscle actions of the forearm flexors performed at 120° s^{-1}. Following the warm-up, the subjects rested for 5 min and then performed two MVIC muscle actions of the forearm flexors. The MVIC muscle actions were performed at 45° (0°–120° of forearm flexion, where 0° corresponds to full extension at the elbow) sustained for a period of 3 s.

Venous BFR

Venous BFR was applied using a 30-mm wide cuff (KAATSU Master, Sato Sports Plaza, Tokyo, Japan) placed on the most proximal portion of the upper arm. The cuff pressure was initially applied at 30 mmHg and progressively inflated and deflated over a 60 s period until the target pressure was reached. Target pressure was calculated during the baseline and first exercise session as 40% of the lowest amount of pressure needed to completely occlude the brachial artery as indicated by ultrasound (Counts et al. 2016; Loenneke et al. 2013, 2016). Previous investigations (Counts et al. 2016; Loenneke et al. 2013, 2016) have indicated that 40% of occlusion pressure induces similar responses as 90% of occlusion pressure when combined with low-load training (30% 1RM). The cuff remained inflated during the duration of the training session and was deflated immediately after completing the 75 repetitions. The total duration of *v*BFR was approximately 5 min.

Rating of perceived exertion

On the first testing and training visit, the subjects were asked to provide their rating of perceived exertion after each set of training. Specifically, the subjects were asked to provide a rating of perceived exertion using the Borg 6–20 Scale (Noble and Robertson 1996) immediately following the first set of 30 repetitions, and following the second, third, and fourth sets of 15 repetitions for both Ecc-*v*BFR and Con-*v*BFR groups. The subjects were familiarized with the Borg Scale during the baseline and first testing and training day visits. The Borg Scale has been used for various exercise modalities to provide insight of sensations such as strain, intensity, discomfort, and fatigue felt as a result of exercise (Noble and Robertson 1996).

Data analysis

Reliability

Test–retest reliability for MVIC, muscle soreness, PPT, elbow joint angle, and edema was assessed from the baseline and first testing day data. Repeated measures ANOVAs were used to assess systematic error, and model 2,1 (Shrout and Fleiss 1979) was used to calculate intraclass correlation coefficients (ICCs), standard errors of measurement (SEM), and minimal difference (MD) needed to consider a change as "real" (Weir 2005). The 95% confidence intervals for the means of the dependent variables were calculated with the student's *t* distribution.

Statistical analyses

MVIC, muscle soreness, PPT, elbow joint angle, and edema were examined using separate 2 (Group [Ecc-*v*BFR and Con-*v*BFR]) × 7 (testing days) mixed factorial ANOVAs. In addition, rating of perceived exertion was examined using a separate 2 (Group [Ecc-*v*BFR and Con-*v*BFR]) × 4 (training set) mixed factorial ANOVAs. Significant interactions were decomposed with follow-up mixed factorial or repeated measures ANOVAs and Bonferroni-corrected-dependent samples *t* tests. Greenhouse–Geisser corrections were applied when sphericity was not met according to Maulchy's test of sphericity and partial eta-squared effect sizes (η_p^2) were calculated for each ANOVA. All statistical analyses were performed using IBM SPSS v. 25 (Armonk, NY) and an alpha of $p \leq 0.05$ was considered statistically significant for all comparisons.

Results

Reliability

Table 2 includes the test–retest reliability and MD values from the baseline to the first testing day measurements of MVIC, PPT elbow joint angle, and echo intensity. Muscle soreness remained unchanged at a value of 0 (on a 0–10 scale) for the baseline and first testing day. There were no mean differences for baseline versus first testing day ($p > 0.05$) for any of the variables. The ICCs for MVIC, PPT, elbow joint angle, and echo intensity ranged from $R = 0.887$–0.990 and the SEM values ranged from 1.0 to

Table 2 Test–retest reliability assessed from the baseline versus the first training day ($n = 25$) for maximal voluntary isometric contraction torque (MVIC), pain pressure threshold (PPT), elbow joint angle (ROM), and ultrasound echo intensity

	MVIC	PPT	ROM	Echo intensity
Baseline	21.1 ± 5.0 Nm	1.98 ± 1.24 kg	166.6° ± 3.5°	109.2 ± 10.8 Au
0 week	20.5 ± 6.0 Nm	1.97 ± 1.18 kg	167.0° ± 3.3°	108.9 ± 10.3 Au
p value	0.486	0.882	0.195	0.992
ICC	0.887	0.990	0.945	0.897
$ICC_{95\%}$	0.647–0.934	0.977–0.996	0.873–0.976	0.760–0.955
SEM	2.5 Nm	0.21 kg	1.6°	5.4 Au
MD	7.6 Nm	0.65 kg	5.1°	16.9 Au
Grand mean	11.8%	10.5%	1.0%	5.0%

p value (ANOVA for systematic error)

ICC intraclass correlation coefficient, $ICC_{95\%}$ ICC 95% confidence interval, *SEM* standard error of the measurement, *MD* minimal difference

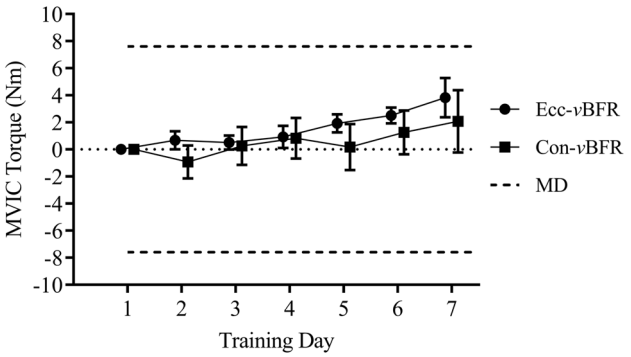

Fig. 1 The absolute mean (± SE) changes in maximal voluntary isometric contraction (MVIC) torque (Nm) as a result of eccentric venous blood flow restriction (Ecc-*v*BFR) and concentric *v*BFR (Con-*v*BFR) bouts across seven testing and training days performed within a 2-week period. The upper and lower bound minimal difference (MD) values needed for a change to be considered "real" is plotted and derived using standard error of measurement (SEM) values from the reliability data in Table 2 and using the equation, $MD = SEM \times 2^{1/2} \times df$ (Weir 2005). Ecc-*v*BFR = filled circles, Con-*v*BFR = filled squares, MD = dashed lines

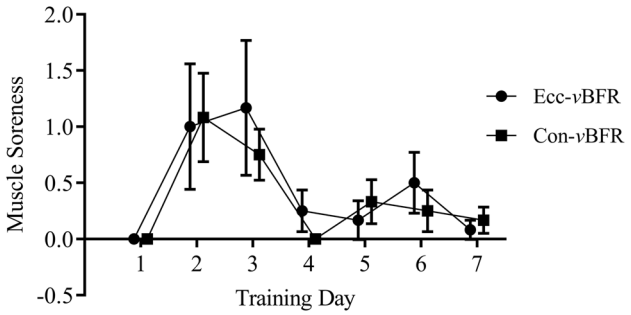

Fig. 2 The absolute mean (± SE) changes in muscle soreness (assessed using a 0–10 Visual Analog Scale) as a result of eccentric venous blood flow restriction (Ecc-*v*BFR) and concentric *v*BFR (Con-*v*BFR) bouts across seven testing and training days performed within a 2-week period. Ecc-*v*BFR = filled circles, Con-*v*BFR = filled squares

11.8% of the grand mean, respectively. Furthermore, the MD for a change to be considered "real" was 7.6 Nm for MVIC, 0.65 kg for PPT, 5.1° for elbow joint angle, and 16.9 Au for echo intensity (Weir 2005).

MVIC

There was no significant group × testing day interaction ($p = 0.572$, η_p^2 0.035) for MVIC. There was a main effect for testing day ($p < 0.001$, η_p^2 0.190), but no main effect for group ($p = 0.168$, η_p^2 0.084). Follow-up main effect analyses for the testing day (collapsed across group) indicated that MVIC torque increased from testing day 2 to testing days 6 and 7, and MVIC torque increased from testing day 3 to testing day 7. There were, however, no decreases in MVIC torque across the 2 weeks of training. In addition, the changes in MVIC torque did not exceed the MD at any of the testing days (Fig. 1).

Muscle soreness

There was no significant group × testing day interaction ($p = 0.907$, η_p^2 0.016) for muscle soreness. There was a main effect for testing day ($p < 0.001$, η_p^2 0.189), but no main effect for group ($p = 0.625$, η_p^2 0.011). There were, however, no significant post hoc analyses across testing day for muscle soreness (Fig. 2).

PPT

There was no significant group × testing day interaction ($p = 0.682$, η_p^2 0.029) for PPT. There was a main effect for testing day ($p = 0.016$, η_p^2 0.110), but no main effect for group ($p = 0.641$, η_p^2 0.010). There were, however, no significant post hoc analyses across testing day (collapsed across group)

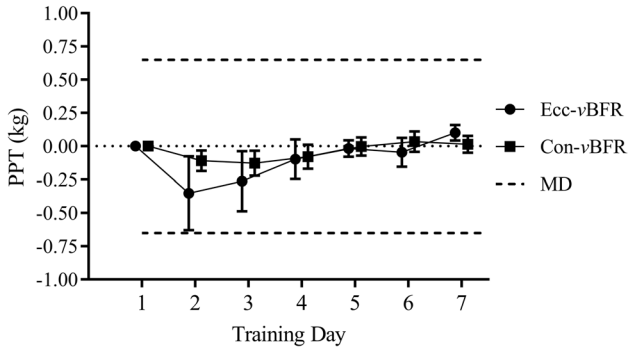

Fig. 3 The absolute mean (± SE) changes in pain pressure threshold (PPT) measured in kilograms of force (kg) as a result of eccentric venous blood flow restriction (Ecc-*v*BFR) and concentric *v*BFR (Con-*v*BFR) bouts across the seven testing and training days performed within a 2-week period. The upper and lower bound minimal difference (MD) values needed for a change to be considered "real" is plotted and derived using standard error of measurement (SEM) values from the reliability data in Table 2 and using the equation, MD = SEM × $2^{1/2}$ × *df* (Weir 2005). Ecc-*v*BFR = filled circles, Con-*v*BFR = filled squares, MD = dashed lines

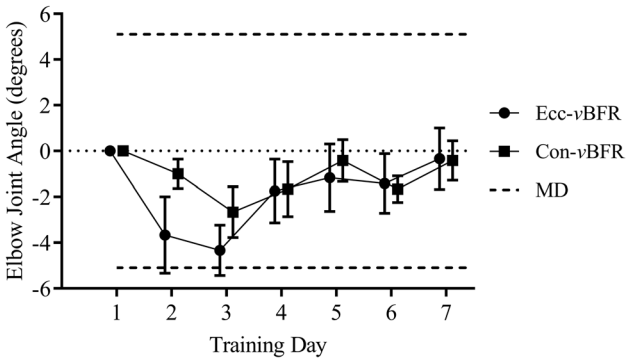

Fig. 4 The absolute mean (± SE) changes in elbow joint angle (degrees) as a result of eccentric venous blood flow restriction (Ecc-*v*BFR) and concentric *v*BFR (Con-*v*BFR) bouts across the seven testing and training days performed within a 2-week period. The upper and lower bound minimal difference (MD) values needed for a change to be considered "real" is plotted and derived using standard error of measurement (SEM) values from the reliability data in Table 2 and using the equation, MD = SEM × $2^{1/2}$ × *df* (Weir 2005). Ecc-*v*BFR = filled circles, Con-*v*BFR = filled squares, MD = dashed lines

for PPT. In addition, the changes in PPT did not exceed the MD at any of the testing days (Fig. 3).

Elbow joint angle

There was no significant group × testing day interaction ($p = 0.581$, η_p^2 0.035) for elbow joint angle. There was a main effect for testing day ($p = 0.001$, η_p^2 0.148), but no main effect for group ($p = 0.804$, η_p^2 0.003). Post hoc analyses indicated that elbow joint angle was lower at testing day 3 compared to testing days 1, 5, and 7. In addition, the changes in elbow joint angle did not exceed the MD at any of the testing days (Fig. 4).

Echo intensity

There was no significant group × testing day interaction ($p = 0.889$, η_p^2 0.017) for echo intensity. There was a main effect for testing day ($p = 0.025$, η_p^2 0.102), but no main effect for group ($p = 0.170$, η_p^2 0.084). There were, however, no significant post hoc analyses across the testing day for echo intensity. In addition, the changes in echo intensity did not exceed the MD at any of the testing days (Fig. 5).

Rating of perceived exertion

There was no significant group × set interaction ($p = 0.505$, η_p^2 0.031) for rating of perceived exertion. There were, however, main effects for group ($p = 0.005$, η_p^2 0.303) and set ($p = 0.006$, η_p^2 0.170). Post hoc analyses indicated that rating of perceived exertion was lower for Ecc-*v*BFR (mean ± SD; 11.65 ± 0.73) than Con-*v*BFR (mean ± SD; 14.83 ± 0.73), collapsed across set. In addition, rating of perceived exertion was lower following set 2 (mean ± SD; 12.75 ± 0.52) than following sets 3 (mean ± SD; 13.75 ± 0.61) and 4 (mean ± SD; 13.85 ± 0.65), but there was no difference between sets 1 (mean ± SD; 12.58 ± 0.55) and 2 or among sets 1, 3, or 4, collapsed across group.

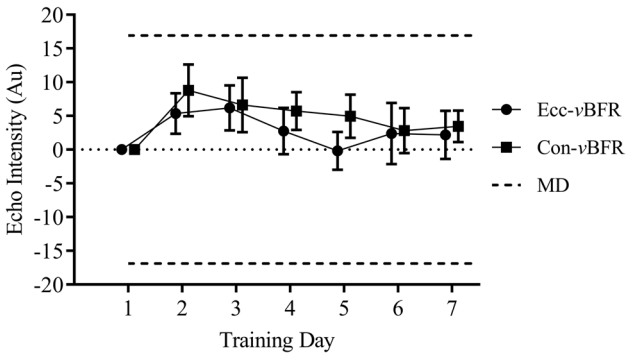

Fig. 5 The absolute mean (± SE) changes in edema (assessed via echo intensity [au]) as a result of eccentric venous blood flow restriction (Ecc-*v*BFR) and concentric *v*BFR (Con-*v*BFR) bouts across the seven testing and training days performed within a 2-week period. The upper and lower bound minimal difference (MD) values needed for a change to be considered "real" is plotted and derived using standard error of measurement (SEM) values from the reliability data in Table 2 and using the equation, MD = SEM × $2^{1/2}$ × *df* (Weir 2005). Ecc-*v*BFR = filled circles, Con-*v*BFR = filled squares, MD = dashed lines

Discussion

The findings of the present study indicated that neither the Ecc-*v*BFR nor Con-*v*BFR resulted in DOMS. Specifically, based on the MD values, there were no real changes in MVIC, muscle soreness, PPT, elbow joint angle, or edema (assessed via echo intensity) throughout the 2-week training intervention for either mode. In addition, both Ecc-*v*BFR and Con-*v*BFR training modalities were perceived as fairly light to somewhat hard as indicated by rating of perceived exertion (Noble and Robertson 1996). Interestingly, despite using the same relative training load, rating of perceived exertion was lower for Ecc-*v*BFR compared to Con-*v*BFR.

The findings of the present study were not consistent with the previous investigations (Umbel et al. 2009; Thiebaud et al. 2013) that have examined low-load Ecc-*v*BFR and Con-*v*BFR. For example, for the leg extensors, Umbel et al. (2009) reported that muscle soreness increased to a greater extent at 24 and 48 h after Con-*v*BFR than Ecc-*v*BFR performed to failure at 35% of MVIC. In addition, there were decreases in MVIC at 48 h as a result of Con-*v*BFR, but MVIC was unchanged following Ecc-*v*BFR (Umbel et al. 2009). For both conditions, PPT and vastus lateralis cross-sectional area remained unchanged (Umbel et al. 2009). However, unlike the present study, the protocol utilized in the study of Umbel et al. (2009) involved performing leg extension muscle actions to failure, which may have induced a greater physiological stress and subsequent muscle damage. On the contrary, using a set and repetition scheme similar to the present study, for the forearm flexors, four sets (1×30, 3×15) of dumbbell bicep curls at 30% of 1RM increased muscle soreness at 24 and 48 h following Ecc-*v*BFR, but muscle soreness remained unchanged as a result of Con-*v*BFR (Thiebaud et al. 2013). There were, however, no changes in range of motion, MVIC, or biceps brachii muscle thickness at 24, 48, or 72 h after either condition (Thiebaud et al. 2013). Thus, for the leg extensors, Con-BFR resulted in DOMS as assessed by MVIC and muscle soreness (PPT and muscle size remained unchanged), but for the forearm flexors, Ecc-BFR resulted in DOMS as assessed by muscle soreness (range of motion, MVIC, and muscle size remained unchanged) (Umbel et al. 2009; Thiebaud et al. 2013). Unlike the previous investigations (Umbel et al. 2009; Thiebaud et al. 2013) that have reported mixed findings, the present study demonstrated there were no changes in any of the indirect indices related to DOMS as a result of Ecc-*v*BFR or Con-*v*BFR.

The differences between the present findings with those of Umbel et al. (2009) and Thiebaud et al. (2013) were likely due to methodological differences. For example, in the present study, the relative training intensities were the same for both Ecc-*v*BFR (30% of eccentric peak torque) and Con-*v*BFR (30% of concentric peak torque) which equated to different absolute training loads of 9.8 ± 1.9 Nm and 5.5 ± 1.1 Nm, respectively. In the studies of Umbel et al. (2009) and Thiebaud et al. (2013), the same absolute training load was used for both Ecc-*v*BFR and Con-*v*BFR. Consistent with the present findings, eccentric muscle actions exhibit greater force capabilities relative to concentric muscle actions (Herzog 2014). Therefore, when using the same absolute load (different relative training intensities) based on the concentric 1RM, the eccentric phase of the muscle action is underloaded relative to the concentric phase (Parr et al. 2009; Yasuda et al. 2013) which may have contributed to the divergent responses between Ecc-*v*BFR and Con-*v*BFR on indices of DOMS reported previously (Umbel et al. 2009; Thiebaud et al. 2013). In addition, the present study examined a sample of untrained women ($n = 25$), while Umbel et al. (2009) examined a pooled sample of untrained men ($n = 8$) and women ($n = 7$) and Thiebaud et al. (2013) examined untrained men ($n = 10$). Women and men may respond differently to exercise-induced muscle damage and exhibit different perceptions of muscle soreness and pain (Hubal and Clarkson 2009; Dannecker et al. 2012; Sipaviciene et al. 2013). Consequently, subjective ratings of DOMS such as muscle soreness and PPT may be affected by individual perceptions of muscle soreness and pain in addition to exercise-induced muscle damage. MVIC and range of motion, however, are not subjective measures of DOMS and are the recommended indirect assessment techniques of DOMS (Warren et al. 1999). This may explain the differences observed between the present study with those of Thiebaud et al. (2013) who reported that Ecc-BFR increased muscle soreness, but all other indices of DOMS (including MVIC and range of motion) remained unchanged for both Ecc-BFR and Con-BFR. Therefore, it is also possible that there are muscle-specific responses to Ecc-BFR and Con-BFR for indices of DOMS.

The present findings, however, were consistent with the previous investigations (Curty et al. 2017; Fujita et al. 2008) that have examined low- and high-load *v*BFR resistance training. For example, Curty et al. (2017) reported that forearm flexion Ecc-*v*BFR performed at 130% of 1RM was not associated with DOMS assessed at 24 and 48 h post-exercise. On the contrary, non-*v*BFR eccentric performed at 130% of 1RM decreased the range of motion and increased the arm circumference assessed at 24 h (Curty et al. 2017). Fujita et al. (2008) reported that over a 6-day period, 12 resistance training sessions of leg extension *v*BFR performed at 20% of 1RM did not result in DOMS, but increased muscle strength and size by 6.7% and 3.5%, respectively. In addition, a recent review (Loenneke et al. 2014) reported that

reciprocal concentric–eccentric dynamic constant external resistance low-load *v*BFR was not associated with DOMS. Together, the present findings in conjunction with the previous investigations (Curty et al. 2017; Fujita et al. 2008) indicated that low- and high-load *v*BFR were not associated with DOMS.

It has been hypothesized (Idstrom et al. 1990) that *v*BFR resistance training may cause ischemia–reperfusion and induce muscle damage. Ischemia–reperfusion describes the irreversible loss of muscle function that occurs between 2.5 and 6 h of complete blood flow occlusion (Idstrom et al. 1990). Although *v*BFR resistance training is often 5 min in duration, it has been hypothesized that the accelerated rate of ATP metabolism associated with exercise could decrease the onset time of ischemia–reperfusion to 20 min or less (Welsh and Lindinger 1993). The current recommendations for *v*BFR, however, advise to occlude only venous blood flow, while arterial blood flow remains unaffected (Loenneke et al. 2012). Therefore, under conditions when *v*BFR is applied during resistance or endurance training (Hill et al. 2018; Abe et al. 2006), it is unlikely that *v*BFR would result in ischemia–reperfusion which necessitates the occlusion of both arterial and venous blood flow. In addition, our findings suggested that neither Ecc-*v*BFR nor Con-*v*BFR was related to DOMS and were likely not associated with ischemia–reperfusion as the restriction pressure was set below arterial occlusion (40% of arterial occlusion pressure).

It has been postulated (Sudo et al. 2015; Curty et al. 2017) that *v*BFR may attenuate DOMS by suppressing mechanical deformation and the opening of stretch-activated calcium channels preventing calcium-mediated proteolysis (Sudo et al. 2015). In addition, *v*BFR may increase the recruitment of fast-twitch motor units (Loenneke et al. 2011) that augments muscle protein synthesis via upstream regulators (namely S6K1) of the mTOR pathway (Sudo et al. 2015). Together, this would suggest that *v*BFR resistance training would attenuate exercise-induced muscle damage and stimulate muscle hypertrophy. It has also been postulated that *v*BFR may attenuate the infiltration of neutrophils following damaging exercise and reduce inflammation (Curty et al. 2017). For example, following a damaging bout of exercise, inflammation was reduced when neutrophils were blocked using an antibody (Kawanishi et al. 2016). In response to muscle injury, neutrophils upregulate macrophages that activate proinflammatory cytokines including TNF-α and IL-6 (Tidball 2005; Kawanishi et al. 2016). TNF-α and IL-6, however, upregulate myogenic satellite cells that promote muscle regeneration following muscle injury (Crameri et al. 2004). Therefore, under these conditions, *v*BFR would adversely affect muscle regeneration following damaging exercise by suppressing the effects of neutrophils on myogenic satellite cells in response to muscle injury. Thus, the lack of DOMS in the present study and reported previously (Curty et al. 2017; Fujita et al. 2008) were likely unrelated to a blunted neutrophil response as this would, theoretically, adversely affect muscle regeneration and imply that *v*BFR resulted in DOMS.

Summary

The findings of the present study indicated that neither Ecc-*v*BFR nor Con-*v*BFR resulted in DOMS as assessed by MVIC, muscle soreness, PPT, elbow joint angle, and edema (assessed via echo intensity). It has been suggested that *v*BFR resistance training may cause ischemia–reperfusion (the irreversible loss of muscle function that occurs between 2.5 and 6 h of complete blood flow occlusion) and induce muscle damage. The current practices of *v*BFR resistance training, however, occlude venous blood flow only and for a duration of approximately 5 min. In addition, our findings suggested that neither Ecc-*v*BFR nor Con-*v*BFR was related to DOMS and was likely not associated with ischemia–reperfusion as the restriction pressure was set below arterial occlusion (40% of arterial occlusion pressure). The lack of DOMS associated with *v*BFR resistance training may be due to cuff-induced suppression of mechanical deformation and the inhibition of stretch-activated calcium channels preventing calcium-mediated proteolysis. Lastly, both Ecc-*v*BFR and Con-*v*BFR training modalities were considered fairly light to somewhat hard as indicated by rating of perceive exertion. Together, these findings suggested that Ecc-*v*BFR or Con-*v*BFR may serve as favorable alternatives to high-load resistance training or low-load resistance training to failure and for populations that may be less tolerable to exercise stress.

Limitations

The present study used indirect assessments of DOMS to make inferences on the magnitude of muscle damage as a result of low-load eccentric and concentric training. Specifically, the present study examined DOMS by the indirect assessments of MVIC torque, elbow joint angle, PPT, perceived muscle soreness, and muscle edema. MVIC torque and changes in the range of motion, however, are recommended indirect assessment techniques of DOMS (Warren et al. 1999) and may provide valuable insight to the magnitude of muscle damage. Subjective measures of DOMS, like PPT and perceived muscle soreness, however, may reflect individual perceptions of DOMS which are variable among subjects and may limit the between-group comparisons of Ecc-*v*BFR versus Con-*v*BFR. To counterbalance this effect, the subjects were randomly assigned to either Ecc-*v*BFR or Con-*v*BFR. The present study examined DOMS in a sample of untrained women and, consequently, these findings

may not extend to other populations (i.e., men) (Hubal and Clarkson 2009; Dannecker et al. 2012; Sipaviciene et al. 2013). Lastly, DOMS was assessed three times per week over a period of two weeks, while DOMS typically peaks 24–72 h following an initial bout of unaccustomed exercise (Warren et al. 1999). In the present study, the first assessment of DOMS was measured 48 h after the initial bout of training which may not have captured the acute responses (i.e., < 48 h) of DOMS.

Acknowledgements This research was supported by the National Strength and Conditioning Association Doctoral Research Grant and NASA Nebraska Space Grant (Grant No. 44-0307-1019-457). All data are presented honestly, without fabrication, falsification, or data manipulation.

Author contributions ECH was a substantial contributor to study concept and design, carried out data acquisition, analysis, and interpretation, and was the primary author. TJH was the primary manuscript reviser. CMS, JLK, RJS, and GOJ assisted with subject recruitment. All authors approved the final version of this manuscript.

Compliance with ethical standards

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

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