

## SHORT COMMUNICATION

## Effects of blood flow restriction on motor unit recruitment patterns during fatiguing isometric leg extensions

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**Objectives:** Objective: Despite growing evidence supporting low-load resistance training with blood flow restriction (LL+BFR), the neuromuscular recruitment patterns during fatiguing LL+BFR exercise remain unclear. This investigation examined motor unit recruitment patterns of the vastus lateralis before and after fatiguing exercise.

**Methods:** Fourteen women performed unilateral isometric leg extension at 50% of maximal voluntary isometric contraction (MVIC) to failure with and without BFR. Repetitions to failure were recorded, and pre- and post-exercise MVIC was assessed. Before and after each exercise intervention, participants completed isometric trapezoidal contractions while surface electromyography (sEMG) was recorded from the vastus lateralis. sEMG signals were decomposed to identify individual motor units to analyze the relationship between recruitment threshold (RT; %MVIC) vs. mean firing rate (MFR, pps) and peak motor unit amplitude (MUamp, mV) vs. MFR.

**Results:** Both interventions resulted in similar decreases in MVIC peak torque from pre- (203.13±53.97 Nm) to post-exercise (143.61±36.93 Nm), but fewer repetitions were needed during BFR (20.3±8.2) compared to non-BFR (25.7±15.4). Similar increases occurred from pre- to post-exercise in slope (-0.21±0.07 pps/%MVIC; -0.27±0.07 pps/%MVIC) and y-intercept (17.60±3.87 pps; 20.02±3.83 pps) for the RT and MFR relationship, and y-intercept increased from pre- (22.46±3.00 pps) to post-exercise (25.81±4.49 pps) for the MUamp and MFR relationship.

**Conclusion:** These results suggest both exercise interventions led to the early recruitment of higher-order motor units and increased firing rate of active motor units post-exercise. However, LL+BFR achieved these changes in fewer repetitions, suggesting LL+BFR is a repetition-efficient mode of exercise for eliciting acute changes in motor unit recruitment.

(*Journal of Trainology* 2026;15(1):1-5)

**Key words:** ■ muscular failure ■ neuromuscular recruitment ■ resistance exercise

### INTRODUCTION

Blood flow restricted (BFR) exercise is a variation of exercise that has gained interest from researchers and clinicians.<sup>1</sup> Low-load resistance training (20-50% of one repetition maximum [1RM]) with BFR (LL+BFR; 40-80% arterial occlusion pressure [AOP]) has been shown to elicit similar increases in hypertrophy and similar, or slightly attenuated, increases in strength compared to traditional high-load resistance (>70% of 1RM) training.<sup>2</sup> The ability to achieve positive neuromuscular and musculoskeletal adaptation while using lower loads has made LL+BFR a useful tool for practitioners working with populations who may not be able to lift heavier loads.<sup>3</sup>

Although a growing body of evidence supports the efficacy of LL+BFR, less is known about the physiological adaptations driving strength and hypertrophy changes. Strength adaptations following chronic resistance training are largely due to neuromuscular adaptations, and hypertrophy following chronic LL+BFR may result from early type II muscle fiber recruitment.<sup>4</sup> For example, in untrained men, higher-order motor units were recruited earlier in an isometric trapezoidal con-

traction following 5×15 unilateral knee extensions at 20% of 1RM with BFR compared to non-BFR exercise.<sup>5</sup> When recruitment thresholds (RT) of individual motor units were plotted against mean firing rate (MFR), the line of best fit exhibited a steeper slope and higher y-intercept following LL+BFR compared to non-BFR exercise, reflecting the early recruitment of higher-order motor units at lower force production and an elevated firing rate of active motor units.<sup>5</sup>

Although LL+BFR accelerates fatigue compared to non-BFR exercise,<sup>6</sup> more data are needed on neuromuscular recruitment patterns during LL+BFR to volitional failure, a commonly utilized protocol,<sup>7</sup> as this may elicit different responses than fixed-volume protocols, such as that used by Fatela et al. (2019).<sup>5</sup> Although fatiguing exercise leads to higher-order motor unit recruitment, it remains unclear whether LL+BFR elicits neuromuscular recruitment patterns that differ from those observed during non-BFR exercise when both are performed to volitional failure. In trained males, similar motor unit recruitment responses were observed during submaximal (50% of maximal voluntary iso-

Received January 31, 2026; accepted April 16, 2026

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Communicated by Takashi Abe, Ph.D.

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*Journal of Trainology* 2026;15(1):1-5 ©2026 The Active Aging Research Center <http://trainology.org>

metric contraction [MVIC]) isometric elbow flexion muscle actions completed to fatigue with and without BFR.<sup>8</sup> The slope of the motor unit amplitude (MUamp) and RT increased similarly in both interventions, suggesting fatiguing elbow flexor exercise promoted early recruitment of higher-order motor units, regardless of BFR application. Despite these findings, it remains unclear whether neuromuscular responses to LL+BFR are consistent across populations, training statuses, muscle groups, and exercise protocols, each of which may elicit unique neuromuscular responses. The purpose of this investigation was to examine motor unit recruitment patterns of the vastus lateralis before and after fatiguing exercise performed to volitional failure with and without BFR.

## METHODS

### Participants

Fourteen recreationally active females (21.4±1.5 years, 165.5±7.3 cm, 64.9±8.6 kg) with no known cardiovascular, pulmonary, metabolic, or muscular disease volunteered for this investigation. This investigation was approved by the University Institutional Review Board for Human Subjects, and all participants provided written informed consent.

### Protocol

Participants completed one consent/familiarization visit and one testing visit. During the testing visit, one leg was randomly assigned to the BFR intervention and the other to the non-BFR intervention. Before exercise, participants completed a 5-minute warm-up on a stationary cycle ergometer. Participants were then seated on a dynamometer (Biodex System 3, Biodex Medical Systems, Inc., Shirley, NY, USA) and the system was adjusted so the axis of motion of the lever arm was aligned with the axis of rotation of the knee. Participants then completed three five-second MVICs with two minutes of rest. The highest peak torque generated among the three attempts was used for data analysis and to determine the exercise load.

Participants then completed a trapezoidal contraction by attempting to match a live force trace to a target line displayed on a computer screen. Trapezoidal contractions were completed at 80% of MVIC with a positive slope of 10% MVIC/second (8-second increase), an 8-second plateau, and a negative slope of 10% MVIC/second (8-second decrease). Following the MVIC and trapezoidal contractions, participants completed 5-second isometric contractions at 50% of the highest MVIC with 3 seconds of rest until failure. Failure was defined as the inability to maintain the target force for the full contraction during three consecutive contractions. Following exercise, participants completed one MVIC and then a trapezoidal contraction at 80% of the initial MVIC. All MVICs, trapezoidal contractions, and exercise repetitions were performed at 90° of knee flexion.

### Blood Flow Restriction

The AOP of the leg assigned to the BFR intervention was assessed while the participant was supine. An 11-cm wide cuff (SC10D, Hokanson Inc., Bellevue, WA, USA) connected

to a rapid inflation device (Hokanson Rapid Cuff Inflation System; Hokanson Inc., Bellevue, WA, USA) was attached to the proximal aspect of the leg. The cuff was progressively inflated while blood flow through the posterior tibial artery was monitored using Doppler ultrasound. AOP was defined as the lowest pressure required to occlude blood flow through the posterior tibial artery. During the BFR intervention, the cuff was inflated to 60% AOP immediately before the first isometric contraction and deflated after the last repetition.

### Surface Electromyography

A 4-pin silver electromyography sensor (Delsys Trigno Galileo, Delsys, Inc., Natick, MA, USA) was placed on the vastus lateralis according to SENIAM guidelines<sup>9</sup> after the area was shaved, abraded, and cleaned. The analog sEMG signals were digitized at 2,222 Hz and bandpass-filtered between 20 and 450 Hz. Signals were decomposed using the Precision Decomposition III algorithm (Delsys, Inc., Natick, MA, USA) to identify unique motor unit action potential trains.<sup>10</sup> The Precision Decomposition III algorithm has been demonstrated to accurately identify individual motor units during isometric contractions with negligible differences from additional analysis techniques.<sup>11,12</sup> For each detected motor unit with >90% reconstruct-and-test accuracy, the RT (% of MVIC), mean firing rate (MFR, pps), and peak motor unit amplitude (MUamp, mV) were determined.

### Statistical Analysis

A linear regression line was fitted to assess the relationship between RT (%MVIC) and MFR for each pre- and post-exercise trapezoidal contraction. The slope coefficients and y-intercepts were determined and used in subsequent analyses. To assess the relationship between peak MUamp and MFR, an exponential regression line ( $y=Ae^{Bx}$ ) was fitted to each pre- and post-exercise trapezoidal contraction, where y is equal to MFR, x is peak MUamp, A is the y-intercept of MFR when MUamp is zero, and x is the rate of decay coefficient ( $MFR=Ae^{B(MUamp)}$ ).<sup>13,14</sup> Exponential slope coefficients and y-intercepts were recorded and used for subsequent analyses.

Repetitions to failure were analyzed using a paired-samples *t*-test. MVIC peak torque, slopes, and y-intercepts were analyzed using separate 2 (Intervention [BFR, non-BFR])×2 (Time [pre, post]) repeated-measures ANOVAs. Significant interactions were decomposed using Bonferroni-corrected paired-sample *t*-tests. Partial eta-squared effect sizes ( $\eta_p^2$ ) were calculated for each ANOVA and Hedges' *g* effect size for *t*-tests. An alpha of  $p \leq 0.05$  was considered statistically significant for all comparisons. GraphPad Prism v.9.2 (San Diego, CA, USA) was used for linear and curvilinear regressions, IBM SPSS v.31 (Armonk, NY, USA) was used for all other statistical analyses.

## RESULTS

### Repetitions and MVIC

Participants completed significantly ( $p=0.008$ ,  $g=0.427$ ) more repetitions during non-BFR (25.7±15.4) than during BFR (20.3±8.2). There was no significant ( $p=0.194$ ,

$\eta_p^2=0.110$ ) Intervention $\times$ Time interaction or main effect for Intervention ( $p=0.062$ ,  $\eta_p^2=0.214$ ), but there was a significant main effect for Time ( $p<0.001$ ,  $\eta_p^2=0.889$ ) for MVIC peak torque. Collapsed across Intervention, MVIC decreased ( $p<0.001$ ,  $g=-2.294$ ) from pre- ( $203.13\pm 53.97$  Nm) to post-exercise ( $143.61\pm 36.93$  Nm). The average number of motor units recorded and used for analyses was  $16.4\pm 5.1$ .

### RT and Mean Firing Rate

There was no significant ( $p=0.440$ ,  $\eta_p^2=0.610$ ) Intervention $\times$ Time interaction or main effect for Intervention ( $p=0.737$ ,  $\eta_p^2=0.012$ ), but there was a significant main effect for Time ( $p=0.016$ ,  $\eta_p^2=0.455$ ) for the slope of the relationship between RT and MFR. Collapsed across Intervention, slope became more negative ( $p=0.016$ ,  $g=-0.667$ ) from pre ( $-0.21\pm 0.07$  pps/%MVIC) to post-exercise ( $-0.27\pm 0.07$  pps/%MVIC) (Figure 1A).

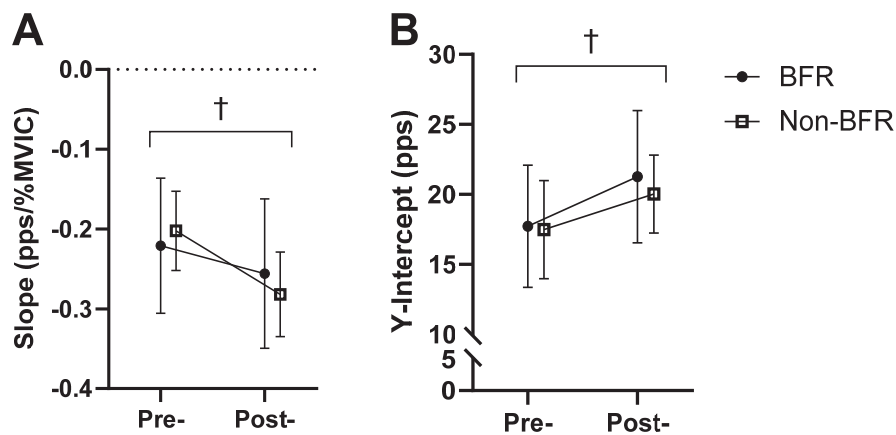
There was no significant ( $p=0.266$ ,  $\eta_p^2=0.122$ ) Intervention $\times$ Time interaction or main effect for Intervention

( $p=0.430$ ,  $\eta_p^2=0.063$ ), but there was a significant main effect for time ( $p<0.001$ ,  $\eta_p^2=0.717$ ) for the y-intercept of the relationship between RT and MFR. Collapsed across Intervention, the y-intercept increased ( $p<0.001$ ,  $g=1.205$ ) from pre ( $17.60\pm 3.87$  pps) to post-exercise ( $20.02\pm 3.83$  pps) (Figure 1B).

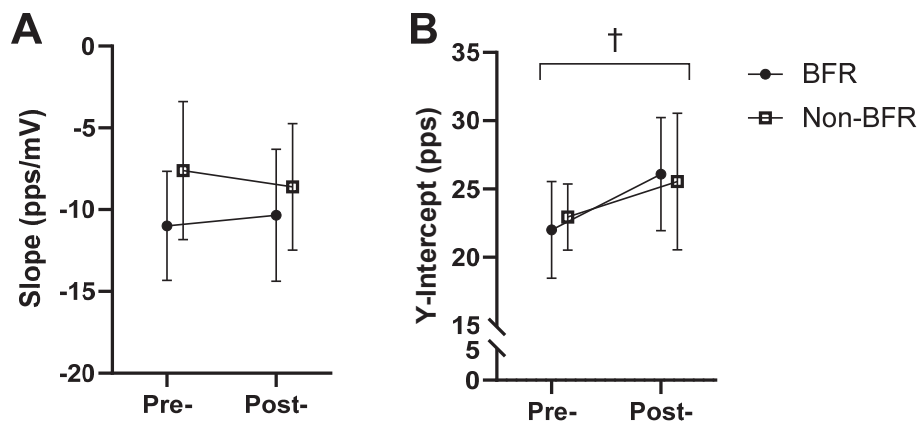
### Peak Motor Unit Amplitude and Mean Firing Rate

There was no significant ( $p=0.124$ ,  $\eta_p^2=0.220$ ) Intervention $\times$ Time interaction or main effect for Intervention ( $p=0.135$ ,  $\eta_p^2=0.209$ ) for Time ( $p=0.667$ ,  $\eta_p^2=0.019$ ) for the slope of the relationship between MUamp and MFR (Figure 2A).

There was no significant ( $p=0.348$ ,  $\eta_p^2=0.088$ ) Intervention $\times$ Time interaction or main effect for Intervention ( $p=0.863$ ,  $\eta_p^2=0.003$ ), but there was a significant main effect for Time ( $p=0.004$ ,  $\eta_p^2=0.581$ ) for the y-intercept of the relationship between MUamp and MFR. Collapsed across Intervention, y-intercept increased ( $p=0.004$ ,  $g=0.838$ ) from



**Figure 1.** Mean and standard deviation values for the (A) slope and (B) y-intercept for the relationship between mean motor unit firing rate (MFR; pulses per second [pps]) and recruitment threshold (RT; %MVIC). † signifies a significant ( $p < 0.05$ ) main effect from pre- to post-exercise.



**Figure 2.** Mean and standard deviation values for the (A) slope and (B) y-intercept for the relationship between mean motor unit firing rate (MFR; pulses per second [pps]) and peak motor unit amplitude (MUamp, mV). † signifies a significant ( $p < 0.05$ ) main effect from pre- to post-exercise.

pre (22.46±3.00 pps) to post-exercise (25.81±4.49 pps) (Figure 2B).

## DISCUSSION

The purpose of this investigation was to examine motor unit recruitment patterns following fatiguing exercise at 50% MVIC with and without BFR. In the present investigation, both interventions elicited similar levels of fatigue, as assessed by similar decreases in MVIC peak torque from pre- (203.13±53.97 Nm) to post-exercise (143.61±36.93 Nm); however, fewer repetitions were required to reach fatigue during the BFR intervention (20.3±8.2) compared to the non-BFR intervention (25.7±15.4). Furthermore, the results of the present investigation indicated that, in general, motor unit recruitment patterns responded similarly following fatiguing isometric exercise at 50% MVIC with and without BFR. Specifically, there were similar increases from pre- to post-exercise in the slope (-0.21±0.07 pps/%MVIC; -0.27±0.07 pps/%MVIC, respectively) and y-intercept (17.60±3.87 pps; 20.02±3.83 pps, respectively) for the relationship between RT and MFR, indicating the early recruitment of higher-order motor units post-exercise. There was also an increase in the y-intercept from pre- (22.46±3.00 pps) to post-exercise (25.81±4.49 pps), but no change in the rate of decay for the relationship between MUamp and MFR, suggesting a shift upward and to the right of the curve, indicating an increase in the firing rate of the recorded motor units and/or the recruitment of higher-order motor units. These results suggested that when LL+BFR and non-BFR exercise at 50% MVIC are performed to similar levels of fatigue, similar motor unit recruitment responses are elicited regardless of BFR application; however, LL+BFR elicited these responses more efficiently (i.e., fewer repetitions) compared to non-BFR exercise.

In general, fatiguing exercise alters neuromuscular recruitment patterns, as demonstrated in the present investigation. Specifically, during submaximal non-fatigued contractions, lower-order motor units are recruited first.<sup>15,16</sup> As motor units fatigue or greater force is required, higher-order motor units are progressively recruited, following the Henneman size principle, and the firing rate of lower-order motor units increases.<sup>15,16</sup> Described as the Onion Skin Scheme, lower-order motor units have higher initial firing rates that are scaled as fatigue accumulates or force output increases, such that lower-order motor units consistently have higher firing rates than higher-order motor units.<sup>17,18</sup> This was observed in the present investigation during the trapezoidal contractions. After the fatiguing exercise interventions, the RT and MFR slope increased, suggesting higher-order motor units were recruited earlier in the contraction (e.g., at a lower percentage of MVIC) to meet the increasing force requirements. Additionally, the increase in the MUamp and MFR y-intercept, but consistent rate of decay, indicated a shift upward and to the right of the MUamp and MFR curve. This shift may have been due to an increase in the firing rate of activated motor units already recruited at a lower percent of MVIC, reflecting the Onion Skin Scheme.<sup>17,18</sup>

The relatively high level of fatigue (41.45% decrease in MVIC) observed in the present investigation may be a potent exercise stimulus. Fatigue, in general, is one of several mechanisms that may stimulate muscle protein synthesis. Specifically, training to muscular failure is hypothesized to maximize motor unit recruitment and provide a robust stimulus to induce muscle protein synthesis in all recruited muscle fibers.<sup>19</sup> Although high levels of fatigue can be desirable to elicit positive neuromuscular and musculoskeletal adaptations, achieving such high levels of fatigue with traditional low-load exercise often requires a substantial repetition volume, which may not always be practical or tolerable in all settings. The results of the present investigation provide evidence of the efficiency (i.e., fewer repetitions to failure) of LL+BFR compared to non-BFR exercise, suggesting that BFR may be beneficial in situations where high repetition volumes are undesirable, impractical, or not feasible. Collectively, the results of the present investigation suggest that LL+BFR provides a viable and repetition-efficient option for eliciting neuromuscular adaptations comparable to low-load exercise to failure at 50% MVIC, but with a lower number of repetitions or volume.

## DISCLOSURE STATEMENT

The authors report no conflicts of interest.

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