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Original Article

Acute effects of low load blood flow restricted and non restricted exercise on muscle excitation, neuromuscular efficiency, and average torque

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Abstract

Objectives: The purpose of this investigation was to examine the acute effects of low-load blood flow restriction (LLBFR) and low-load (LL) resistance exercise on muscle excitation, neuromuscular efficiency, and average torque. **Methods**: Eleven men (age±SD=22±3yrs) randomly performed LLBFR and LL that consisted of 30 unilateral leg extensions at 30% of one-repetition maximum while surface electromyography (sEMG) and torque were simultaneously assessed. Polynomial regression analyses and slope comparisons were performed to examine patterns of responses and rates of change. **Results**: sEMG amplitude increased for LLBFR (9 of 11) and LL (8 of 11) and between composite responses (R^2=0.939-0.981). For LLBFR, sEMG amplitude increased to a greater extent for 5 of the 11 individual and for the composite responses. Similarly, neuromuscular efficiency decreased for LLBFR (8 of 11) and LL (5 of 11) as well as the composite responses r^2=0.902-0.929, but the decrease was larger for LLBFR than LL for the individual (4 of 11) responses. For average submaximal concentric torque, there were individual increases, decreases, and no changes for the composite responses (R^2=0.198-0.325). **Conclusion**: LLBFR elicited greater fatigue-induced increases in muscle excitation and decreases in neuromuscular efficiency than LL, but neither LLBFR nor LL affected average submaximal concentric torque.

Keywords: BFR, EMG, Occlusion, Resistance, Submaximal

Introduction

Low-load (LL) resistance exercise performed to volitional failure elicits positive muscular adaptations in the absence of high mechanical tension. Specifically, LL resistance exercise increases muscle strength and muscle mass similarly to traditional high-load approaches, albeit smaller strength gains[1,2]. Applying BFR during LL resistance exercise, however, augments the physiological response and does not necessitate exercising to volitional failure. For example, 4-wks of LLBFR increased muscle strength to a greater degree than LL[3–5] and 12-16-wks of LLBFR elicited comparable changes in muscle strength and size as high-load[6,7]. Thus, LLBFR induces greater muscular adaptations than LL and is comparable to high-load resistance exercise.

It has been theorized that LLBFR induces greater physiological perturbations relative to LL resistance exercise[8]. Many of these physiological responses and subsequent proposed mechanisms, however, have largely been associated with mediating muscle hypertrophy which can be dissociated from changes in muscle strength[9]. Furthermore, when utilizing training loads of 30% of one repetition maximum (1RM), hypertrophic responses are similar between LLBFR and LL resistance exercise[5,10], while muscle strength increases to a greater extent with LLBFR than LL resistance exercise[5]. Thus, it is possible that one or more of these physiological responses also facilitates neuromuscular adaptations that may explain the greater strength adaptations associated with LLBFR than LL. For example, across fatiguing bouts of exercise, LLBFR increases

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muscle excitation assessed via surface electromyography (sEMG) to a greater extent than LL when exercise volume was similar[11,12]. Less is known, however, regarding the patterns of changes in muscle excitation across a fatiguing bout that may provide unique insight into the specific motor control strategies associated with LLBFR and LL resistance exercise. Furthermore, no previous investigations have examined the individual and composite patterns of responses between LLBFR and LL or examined the differences in the rates of change in muscle excitation.

The use of sEMG has also been utilized to examine neuromuscular efficiency which can be quantified as the ratio of muscle excitation relative to torque production[13], or more intuitively the ratio of torque production relative to muscle excitation[14]. This technique, referred to as electrical efficiency[13] or neuromuscular efficiency[14], has been applied to investigate neuromuscular characteristics including those associated with resistance training, modes of muscle actions, and symptomatic and asymptomatic populations[13,15,16]. Thus, examining the ratio of torque output relative to muscle excitation may identify BFR-induced differences in neuromuscular efficiency across acute fatiguing bouts of LLBFR and LL resistance exercise that may underlie chronic neuromuscular adaptations in response to chronic training.

To examine physiological differences between LLBFR and LL resistance exercise, it has been suggested to utilize a standard set and repetition scheme opposed to utilizing sets to failure[17]. That is, controlling for differences in exercise volume allows for a more robust examination of the effects of BFR apart from other known variables that affect the physiological responses to exercise[18]. However, when performing dynamic constant external resistance (DCER) exercise across a standard set and repetition scheme, there may still be differences in load range, velocity, and/or time under tension which can change without differences in exercise volume. Therefore, in addition to implementing a standard set and repetition scheme to control exercise volume, examining average torque across the exercise bouts would provide an indirect assessment of load range, velocity, and/or time under tension. Specifically, average torque reflects the volume of work per unit of time that is sensitive to changes in load range, velocity, and time under tension whereas exercise volume and load would remain unchanged. Therefore, the purpose of this investigation was to examine the acute effects of LLBFR and LL resistance exercise on muscle excitation, neuromuscular efficiency, and average torque. Based on previous investigations[11,12], it was hypothesized that the rates of change in muscle excitation and neuromuscular efficiency would be greater following an acute bout of LLBFR than LL resistance exercise, and average torque would be lower during LLBFR than LL.

Materials and Methods

Participants

Eleven men (n=11; mean age±SD=22±3 yrs; body mass=79.8±13.0 kg; height=174.6±10.8 cm) volunteered to participate in this investigation and randomly performed LLBFR and LL on separate days. The participants were recreationally active (Tier 1) at the time of testing and had no known cardiovascular, pulmonary, metabolic, muscular, and/or coronary heart disease, or regularly used prescription medication[19]. These participants were part of a larger multi-independent study and have been examined previously for purposes unrelated to the present investigation[20,21].

Experimental Design

A randomized, repeated measures, within-group, cross-over design was used for this study. Eleven men performed 30 submaximal (30% of 1RM) leg extension muscle actions with BFR (LLBFR) and without BFR (LL) that was randomly allocated on separate days. Blood flow restriction was achieved using a rapid cuff inflator (SC12D Hokanson Rapid Cuff Inflator; Hokanson Inc., Belleview, WA, USA). Across the 30 repetitions, neuromuscular and force assessments were collected during the concentric phase of each repetition.

Procedures

On the first laboratory visit, the participants were familiarized with the testing protocols. During the familiarization session, participants performed submaximal and maximal, DCER leg extension muscle actions on a plate-loaded, seated leg extension device (Power Lift & Connor Athletic Products, IA). The participants were also introduced to the stimulation procedures that were used to normalize the neuromuscular responses in subsequent visits.

Maximal Strength and Exercise Protocol

The participants performed a 5-minute warmup at a self-selected pace on a stationary cycle ergometer (Corival, Lode B.V., Groningen, Netherlands). Following the warmup, the participants were provided a rest period and were then fitted to the DCER leg extension device such that the lateral epicondyle of the femur aligned with the axis of rotation of the leg extension device. The participants then performed 1RM testing procedures consistent with the National Strength and Conditioning Association (Haff et al. 2016, Chapter 15) recommendations. Specifically, participants performed a light warm-up of 10 repetitions followed by 2-3 sets of 5 repetitions with progressively heavier loads until participants could no longer complete a leg extension muscle action through a full 90-degree range of motion. The heaviest load lifted throughout the entire range of motion was determined as the participant's 1RM and was used to determine the exercise load (i.e., 30% of 1RM).

The exercise protocol consisted of 30 unilateral, submaximal (30% of 1RM), DCER leg extension muscle actions that were performed through a full 90-degree range of motion which was identified using a handheld goniometer (Smith & Nephew Rolyan Inc., Menomonee Falls, WI USA) and monitored on a repetition-by-repetition basis by members of the research team. Each repetition was performed at a controlled cadence (1-s concentric, 1-s eccentric) that was paced by a metronome and monitored by the research team. The unilateral leg extension device was custom fitted with a pancake load cell (Honeywell Inc, Model 41, NC) that was used to quantify force during each repetition and delineate the concentric phase of each muscle action. Thus, average submaximal concentric torque was determined for each repetition of the 30-repetition protocol.

Blood Flow Restriction

Blood flow restriction was put onto the most proximal portion of the upper leg and applied using a rapid cuff inflator (SC12D Hokanson Rapid Cuff Inflator; Hokanson Inc., Belleview, WA, USA) and an 11-cm wide cuff. The pressure was initially applied at 30mmHg and intermittently and progressively inflated and deflated until target pressure was achieved. Optimal pressure was calculated as 60% of the lowest amount of pressure necessary to completely occlude posterior tibial artery blood flow as indicated by the ultrasound[23]. The cuff was inflated immediately prior to the 30 submaximal repetitions.

Stimulation Procedures for Signal Normalization

Singlet (50 μs) rectangular pulsed stimuli were performed to normalize the neuromuscular parameters (sEMG amplitude) and the average torque responses for the determination of neuromuscular efficiency. All stimuli were delivered at 400 volts, while only amperage was modulated. The potentiated stimuli were delivered while the leg was positioned at a 90-degree angle. Optimal stimulation location was determined by the simultaneous inspection of the evoked muscle action potentials and the subsequent torque response that was elicited from each stimulus. These exploratory singlet stimuli were delivered at a low amperage (25-50 mA) with a hand-held cathode (Compex Motor Point Pen, Compex, Mississauga, NU ON, Canada) and a disposal anode (Digitimer Ltd, Herthfordshire, UK) fixed over the greater trochanter during all stimuli. Following the determination of optimal stimulation location, the amperage was progressively increased by 20-50 mA until a plateau in the muscle compound action potentials and the corresponding torque response was observed. The amperage was then multiplied by 120% and this supramaximal stimulus was used to determine the maximum peak-to-peak amplitude (M_{P-P}) of the unrectified sEMG signal. The subsequent M_{P-P} and corresponding twitch torque values were used to normalize all sEMG amplitude values and average submaximal concentric torque when determining neuromuscular efficiency, respectively.

Electromyography

During the LLBFR and LL visits, pre-gelled surface electrodes (Ag/AgCl, AccuSensor, Lynn Medical, Wixom, MI, USA) were placed in a bipolar arrangement (50 mm center-to-center) on the vastus lateralis muscle of the exercising leg. The electrodes were placed at 66% of the distance from the anterior superior iliac spine to the lateral border of the patella[24] and the longitudinal axis of the bipolar electrodes were placed parallel to the angle of pennation (20°) of the muscle fibers[25]. The reference electrode was placed over the anterior superior iliac spine and prior to each electrode placement, the skin was shaved, carefully abraded, and cleaned with alcohol.

The raw sEMG signals were digitized at 2,000 Hz with a 32-bit analog-to-digital converter (Model MP150, Biopac Systems, Inc.) and stored on a personal computer (ATIV Book 9 Intel Core i7 Samsung Inc., Dallas, TX) for subsequent analyses. The sEMG signals were amplified (gain: x 1,000) using differential amplifiers (EMG 100, Biopac Systems, Inc., Santa Barbara, CA) and signal impedance was kept below 2M Ω. The sEMG signals were digitally bandpass filtered (fourth-order Butterworth, zero-phase shift) at 10-500 Hz and all signal processing was performed in LabVIEW (National Instruments, Austin, Texas) using custom written programs. The sEMG amplitude (μV root-mean-square, μVrms) values were calculated across the 90-degree range of motion. As each repetition was controlled with a metronome at a cadence which corresponded to a 1-s concentric and 1-s eccentric muscle action, each sEMG amplitude value was derived from approximately 2,000 data points or from a time period of 1-s. The signals were not, however, limited to or extended to 2,000 data points as each repetition varied marginally (±200 data points) across the fatiguing protocols.

Torque Assessments

During each muscle action, the raw voltages were determined with a custom-fitted pancake load cell (Honeywell Inc, Model 41, NC) that were sampled at 10,000 Hz. The raw voltages were filtered (high pass 15 Hz) and analyzed offline (LabVIEW v. 12.0, National Instruments, Austin, TX, USA). Force was then calculated from a linear regression equation (R^2=0.99) that was derived from voltages and corresponding external loads that were hung from the lever arm (0-100 kg in 5 kg increments). This force (N) was then multiplied by lever arm length on a subject-by-subject basis to determine torque (Nm).

Normalization

The absolute sEMG amplitude values during the submaximal, DCER muscle actions were normalized to the previously determined M_{P-P} (i.e., % M_{P-P}) that were determined on each testing visit. For the determination of neuromuscular efficiency, average submaximal concentric torque for each individual repetition was normalized to the corresponding twitch torque achieved during the M_{P-P} (i.e., average submaximal concentric torque/M_{P-P} twitch torque).

Statistical Analyses

Polynomial regression analyses (first, second, and third order) were used to examine the individual and composite

Table 1. The individual and composite results for the polynomial regression analyses, linear slope coefficients, coefficients of determination (r^2/R^2), and linear slope coefficient comparisons of the normalized electromyographic amplitude (% M_{p-p}) versus repetition relationships for the low-load blood flow restriction (LLBFR) and low-load non-blood flow restricted (LL) protocols. The regression analyses were examined across 10 time points that were derived from averaging (incrementally) 3 of the 30 repetitions of the LLBFR and LL exercise bouts that were performed at 30% of one repetition maximum.

	LLBFR			LL			Linear slope comparison	Natural log slope comparison
Participant	Relationship	Slope (% M_{p-p}·repetition)	r^2/R^2	Relationship	Slope (% M_{p-p}·repetition)	r^2/R^2	*p*-value	*p*-value
1	Quadratic	0.841	0.976	Linear	0.491	0.756		0.002
2	Linear	0.418	0.635	Linear	0.193	0.596	0.092	
3	Linear	0.720	0.884	Linear	0.149	0.775	0.016	
4	Linear	0.322	0.471	Linear	0.263	0.797	0.654	
5	Linear	0.141	0.477	NS	0.033	0.045		0.193
6	Linear	0.266	0.833	NS	0.042	0.108		<0.001
7	Linear	0.121	0.471	Linear	0.113	0.701	0.882	
8	Linear	0.347	0.863	Linear	0.191	0.694	0.032	
9	NS	0.067	0.133	Quadratic	0.244	0.913		0.065
10	Quadratic	0.385	0.819	Linear	0.532	0.941		0.585
11	NS	0.042	0.148	NS	0.013	0.008		0.678
Composite	Linear	0.293	0.939	Linear	0.206	0.981	0.007	

***Note**. In the event of a 2nd or 3rd order polynomial, or a non-significant (NS) relationship was observed between one or both slopes to be compared, both relationships were then natural log transformed and the subsequent slopes were then compared.*

patterns of responses for normalized sEMG amplitude, neuromuscular efficiency, and average submaximal concentric torque across the fatiguing LLBFR and LL exercise bouts. The regression analyses were derived from 10 time points "repetitions" where each time point or "repetition" corresponds to the average of 3 repetitions across the 30-repetition set (i.e., repetition 1 corresponds to the average of repetitions 1-3… repetition 10 corresponds to the average of repetitions 28-30). The F-test was used to determine if the increment in proportion of variance accounted for by a higher-order polynomial was significant.

The linear slope coefficients from the linear regression analyses were then compared as described in detail elsewhere[26,27]. Briefly, a common regression coefficient is derived from the pooled sums of products and squares between the LLBFR and LL conditions. If the proportion of variance accounted for by an individual or composite slope coefficient was greater than the proportion of variability accounted for by the common regression coefficient, then it was concluded that the slopes between the LLBFR and LL conditions were different. In the event of a 2nd or 3rd order polynomial, or a non-significant relationship was observed between one or both slopes to be compared, both relationships were then natural log transformed and the subsequent slopes were compared using the same procedures as described above. All statistical analyses were performed using IBM SPSS v. 27 (Armonk, NY) and an alpha of $p \leq 0.05$ was considered statistically significant for all regression analyses. For the analyses of slope coefficients, we used a more liberal alpha value of 0.10 in an effort to limit type II error among our slope comparisons[28].

Results

sEMG Amplitude

For the individual LLBFR responses, there were linear (7 of 11 participants), quadratic (2 of 11 participants), and non-significant (2 of 11 participants) increases among the normalized sEMG amplitude versus repetitions relationships (Table 1).

For the individual LL responses, there were linear (7 of 11 participants), quadratic (1 of 11 participants), and non-significant (3 of 11 participants) increases among the normalized sEMG amplitude versus repetitions relationships (Table 1).

The analyses of slope comparisons among the individual sEMG amplitude versus repetitions slopes were larger for 5 of the 11 participants during LLBFR than LL. There were, however, no differences in the slopes for 5 of the 11 participants and for 1 of the 11 participants the slope was smaller for LLBFR than LL (Table 1).

For the composite responses, there were composite linear increases for LLBFR (R^2=0.939) and LL (R^2=0.981) among the normalized sEMG amplitude versus repetitions

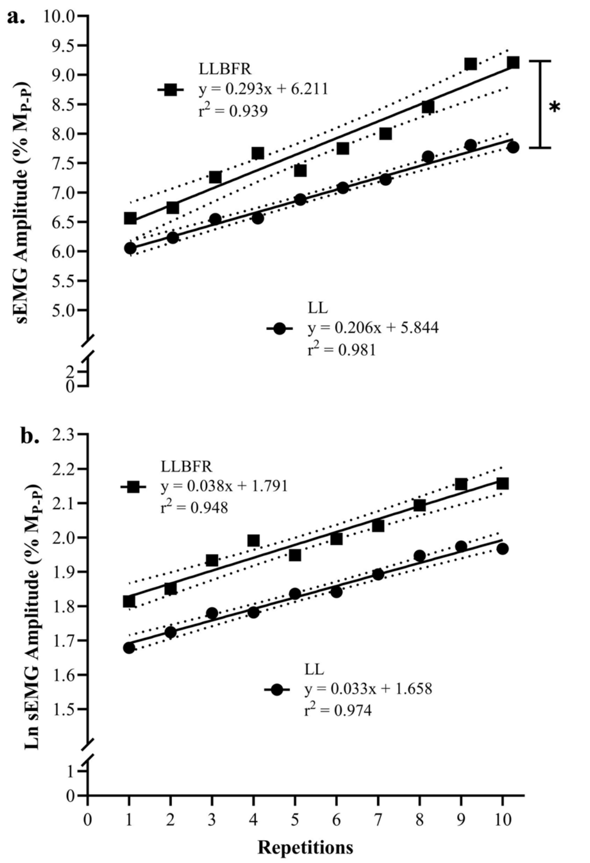

Figure 1. The composite patterns of responses (± 95% confidence intervals) for normalized (to maximum peak-to-peak amplitude of the potentiated singlet [M_{P-P}]) surface electromyographic (sEMG) amplitude (% M_{P-P}) (1a) and natural log transformed normalized sEMG amplitude (1b) across 30 repetitions of low-load blood flow restriction (LLBFR, filled squares) and low-load non-blood flow restriction (LL, filled circles) resistance exercise. The regression analyses were derived from 10 time points "repetitions" where each time point or "repetition" corresponds to the average of 3 repetitions across the 30-repetition set (i.e., repetition 1 corresponds to the average of repetitions 1-3… repetition 10 corresponds to the average of repetitions 28-30). *Denotes a significant (p<0.10) difference in the rate of change between the linear slope coefficients.

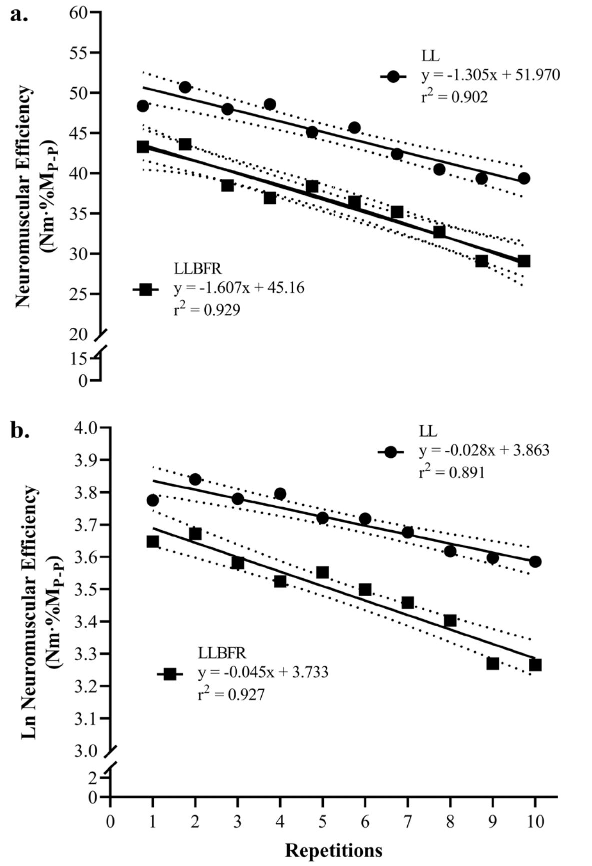

Figure 2. The composite patterns of responses (± 95% confidence intervals) for neuromuscular efficiency – the ratio of normalized (to maximum twitch torque of the potentiated singlet) average submaximal concentric torque [Nm] relative to normalized (to maximum peak-to-peak amplitude of the potentiated singlet [M_{P-P}]) electromyographic amplitude [% M_{P-P}] (2a) and natural log transformed neuromuscular efficiency (Nm·% M_{P-P}) (2b) across 30 repetitions of low-load blood flow restriction (LLBFR, filled squares) and low-load non-blood flow restriction (LL, filled circles) resistance exercise. The regression analyses were derived from 10 time points "repetitions" where each time point or "repetition" corresponds to the average of 3 repetitions across the 30-repetition set (i.e., repetition 1 corresponds to the average of repetitions 1-3… repetition 10 corresponds to the average of repetitions 28-30).

relationships (Table 1). The analysis of slope comparisons between the composite sEMG amplitude versus repetitions slopes was larger for LLBFR (0.293 % M_{P-P}) than LL (0.206 % M_{P-P}) (Figure 1).

Neuromuscular Efficiency

For the individual LLBFR responses, there were linear decreases (7 of 11 participants), a quadratic decrease (1 of 11 participants) and non-significant decreases (2 of 11 participants) and an increase (1 of 11 participants) among the neuromuscular efficiency versus repetitions relationships (Table 2).

For the individual LL responses, there were linear decreases (5 of 11 participants) and non-significant decreases (6 of 11 participants) among the neuromuscular efficiency versus repetitions relationships (Table 2).

The analyses of slope comparisons among the individual electrical efficiency versus repetitions slopes were smaller (i.e., larger rate of reduction) for 4 of the 11 participants

Table 2. The individual and composite results for the polynomial regression analyses, linear slope coefficients, coefficients of determination (r^2/R^2), and linear slope coefficient comparisons of neuromuscular efficiency – the ratio of normalized (to maximum twitch torque of the potentiated singlet) average submaximal concentric torque [Nm] relative to normalized (to maximum peak-to-peak amplitude of the potentiated singlet [M_{P-P}]) electromyographic amplitude [% M_{P-P}] versus repetition relationships for the low-load blood flow restriction (LLBFR) and low-load non-blood flow restricted (LL) protocols. The regression analyses were examined across 10 time points that were derived from averaging (incrementally) 3 of the 30 repetitions of the LLBFR and LL exercise bouts that were performed at 30% of one repetition maximum.

	LLBFR			LL			Linear slope comparison	Natural log slope comparison
Participant	Relationship	Slope (Nm·%M_{P-P}·repetition)	r^2/R^2	Relationship	Slope (Nm·%M_{P-P}·repetition)	r^2/R^2	*p*-value	*p*-value
1	Linear	-2.586	0.809	NS	-0.663	0.319		0.091
2	Linear	-0.782	0.438	Linear	-1.589	0.568	0.184	
3	Linear	-4.558	0.780	Linear	-4.089	0.752	0.699	
4	NS	-0.164	0.065	NS	-1.701	0.378		0.195
5	NS	0.307	0.049	NS	-0.007	<0.001		0.597
6	Linear	-1.607	0.864	NS	-0.209	0.349		<0.001
7	Linear	-0.873	0.553	NS	-0.235	0.038		0.041
8	Linear	-1.773	0.918	Linear	-1.788	0.557	0.980	
9	NS	-0.076	0.012	NS	-0.427	0.082		0.682
10	Quadratic	-2.375	0.934	Linear	-2.783	0.746		0.561
11	Linear	-3.196	0.754	NS	-0.865	0.252		0.028
Composite	Linear	-1.607	0.929	Linear	-1.305	0.902	0.185	

Note. *In the event of a 2nd or 3rd order polynomial, or a non-significant (NS) relationship was observed between one or both slopes to be compared, both relationships were then natural log transformed and the subsequent slopes were then compared.*

Table 3. The individual and composite results for the polynomial regression analyses, linear slope coefficients, coefficients of determination (r^2/R^2), and linear slope coefficient comparisons of the average submaximal concentric torque (Nm) versus repetition relationships for the low-load blood flow restriction (LLBFR) and low-load non-blood flow restricted (LL) protocols. The regression analyses were examined across 10 time points that were derived from averaging (incrementally) 3 of the 30 repetitions of the LLBFR and LL exercise bouts that were performed at 30% of one repetition maximum.

	LLBFR			LL			Linear slope comparison	Natural log slope comparison
Participant	Relationship	Slope (Nm·repetition)	r^2/R^2	Relationship	Slope (Nm·repetition)	r^2/R^2	*p*-value	*p*-value
1	NS	2.039	0.224	NS	1.142	0.154		0.971
2	NS	1.310	0.170	NS	-0.335	0.099		0.127
3	NS	-0.264	0.024	NS	-0.853	0.132		0.540
4	Linear	2.301	0.828	NS	2.541	0.314		0.747
5	Linear	2.936	0.821	NS	0.547	0.067		0.020
6	Quadratic	-3.064	0.921	NS	-0.721	0.258		0.004
7	NS	-1.186	0.131	Linear	2.123	0.634		0.020
8	Linear	-3.264	0.800	NS	0.482	0.091		<0.001
9	NS	0.708	0.107	NS	2.723	0.372		0.319
10	NS	-1.667	0.307	Linear	1.155	0.691		0.013
11	Linear	-6.506	0.825	NS	-2.188	0.180		0.035
Composite	NS	-0.605	0.325	NS	0.601	0.198		0.017

Note. *In the event of a 2nd or 3rd order polynomial, or a non-significant (NS) relationship was observed between one or both slopes to be compared, both relationships were then natural log transformed and the subsequent slopes were then compared.*

during LLBFR than LL. There were, however, no differences in the slopes for 7 of the 11 participants (Table 2).

For the composite responses, there was a linear decrease for the LLBFR (r^2=0.929) and a linear decrease for the LL (r^2=0.902) neuromuscular efficiency versus repetitions relationships (Table 2). The analysis of slope comparisons between the composite neuromuscular efficiency versus repetitions slopes was not different between LLBFR (-1.607 Nm·%M_{P-P}) and LL (-1.305 Nm·%M_{P-P}) (Figure 2).

Average Submaximal Concentric Torque

For the individual LLBFR responses, there were linear increases (2 of 11 participants) and decreases (2 of 11 participants), a quadratic decrease (1 of 11 participants), and non-significant increases (3 of 11 participants) and decreases (3 of 11 participants) among the average submaximal concentric torque versus repetitions relationships (Table 3).

For the individual LL responses, there were linear increases (2 of 11 participants) and non-significant increases (5 of 11 participants) and decreases (4 of 11 participants) among the average submaximal concentric torque versus repetitions relationships (Table 3).

The analyses of slope comparisons among the individual sEMG amplitude versus repetitions slopes were smaller for 5 of the 11 participants during LLBFR than LL. There were, however, no differences in the slopes for 5 of the 11 participants and for 1 of the 11 participants the slope was larger for LLBFR than LL (Table 3).

For the composite responses, there was a non-significant decrease for the LLBFR (R^2=0.325) and a non-significant increase for the LL (R^2=0.198) average submaximal concentric torque versus repetitions relationships (Table 3). The analysis of slope comparisons between the composite average submaximal concentric torque versus repetitions slopes was smaller for LLBFR (-0.605 Nm) than LL (0.601 Nm) (Figure 3).

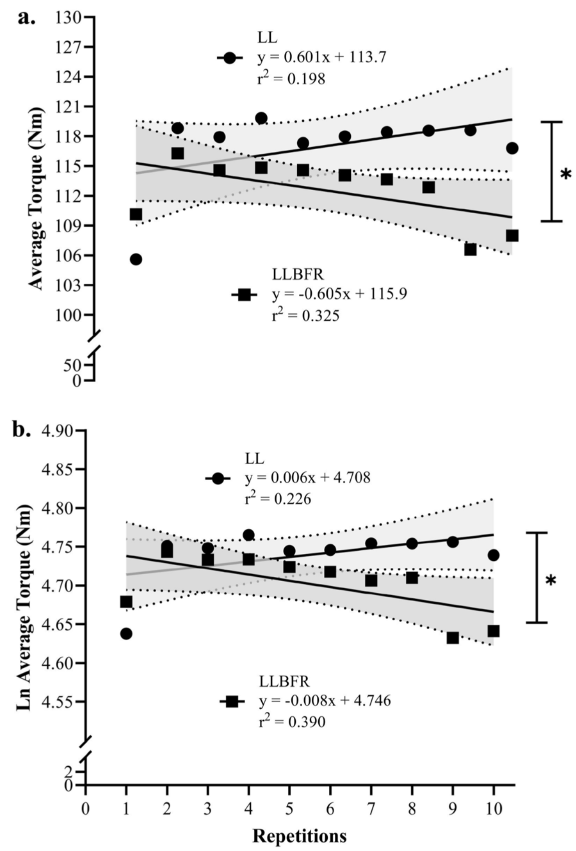

Figure 3. The composite patterns of responses (± 95% confidence intervals) for average concentric torque (Nm) (2a) and natural log transformed average concentric torque (Nm) (2b) across 30 repetitions of low-load blood flow restriction (LLBFR, filled squares) and low-load non-blood flow restriction (LL, filled circles) resistance exercise. The regression analyses were derived from 10 time points "repetitions" where each time point or "repetition" corresponds to the average of 3 repetitions across the 30-repetition set (i.e., repetition 1 corresponds to the average of repetitions 1-3... repetition 10 corresponds to the average of repetitions 28-30). *Denotes a significant (p<0.10) difference in the rate of change between the linear slope coefficients. The 95% confidence intervals are shaded in dark gray (LLBFR) and light gray (LL) to delineate the two data sets from each other.

Discussion

This was the first study to examine the individual and composite patterns of responses for sEMG amplitude, average submaximal concentric torque, and neuromuscular efficiency across repetitions of LLBFR and LL resistance exercise. Overall, LLBFR elicited larger rates of change in sEMG amplitude, average submaximal concentric torque, and neuromuscular efficiency (Figures 1-3). The individual responses were partially consistent with the composite responses, although there was large variability which is not atypical when examining individual patterns of responses across fatiguing exercise[29].

Muscle Excitation

There were increases in sEMG amplitude across repetitions for the individual (17 of 22) and composite responses for LLBFR and LL resistance exercise (Table 1, Figure 1). The progressive increases in sEMG amplitude likely reflected a fatigue-induced increase in motor unit recruitment and/or firing rate as there were no changes in exercise load that remained at 30% of 1RM. While changes in sEMG amplitude may also reflect the effects of motor unit synchronization or non-physiological factors[30–32], the short exercise bout, within subjects design, and the implementation of an unaccustomed bout of exercise would attenuate these contributions and/or be minimally represented relative to motor unit recruitment and/or firing rate changes which increase from 0 to 60-80% and 0 to 100% of maximal strength, respectively[33,34]. Furthermore, the increases in sEMG amplitude across

LLBFR and LL were partially consistent with previous investigations[11,12]. For example, during 3 sets of sustained, isometric, leg extension muscle actions performed at 20% of maximal voluntary isometric contraction (MVIC) torque, sEMG amplitude of the vastus lateralis increased to a greater extent during LLBFR (approximately 55-95% of MVIC) than LL (approximately 45-55% of MVIC)[12]. Additionally, during the first set of 30 DCER leg extension muscle actions performed at 30% of 1RM, sEMG amplitude increased to a greater extent following LLBFR than LL for the vastus medialis, although increased similarly for the vastus lateralis and rectus femoris[11]. In the subsequent three sets of 15 repetitions, however, sEMG amplitude increased to a greater extent for LLBFR than LL when assessed from the vastus lateralis and vastus medialis[11]. In this previous investigation[11], sEMG amplitude was also assessed during the concentric-only phase of each muscle action, but unlike the present investigation, sEMG amplitude was only evaluated during the first three and last three repetitions of each set which may be less informative than examining changes across the entire exercise bout. Nonetheless, the present findings, in conjunction with previous investigations[11,12], indicated that LLBFR typically elicits greater increases in muscle excitation for the vastus lateralis and vastus medialis muscles than LL across submaximal exercise bouts.

The larger rate of increase in sEMG amplitude for LLBFR than LL supports the application of BFR to augment increases in muscle excitation across an exercise bout. LLBFR has been theorized to expedite the recruitment of type II motor units possibly due to localized hypoxia[8,35]. The application of BFR also limits the removal of metabolites which in excess, activates group III and IV afferent nerve endings and adversely affects excitation-contraction dynamics[36]. Thus, to overcome these physiological effects of fatiguing exercise with BFR, it has been postulated[20] that efferent neural drive increases during LLBFR resistance exercise and may explain the larger downstream increases in muscle excitation (sEMG amplitude) observed in the present study. Collectively, our findings indicated that LLBFR elicited larger increases in muscle excitation than LL under volume and load-matched conditions.

Neuromuscular Efficiency

This was the first study to examine acute changes in neuromuscular efficiency during LLBFR and LL resistance exercise. Neuromuscular efficiency has been used to track neural function as a result of resistance training, among neurological conditions, and to identify efficiency during various modes of exercise[13,15,16]. For example, we had previously reported that 4 weeks of LLBFR and LL reduced electrical efficiency (positive adaptation), although these changes were collapsed across mode of contraction (eccentric, isometric, concentric) and group (including the control group)[10]. Furthermore, these changes did not exceed the minimal difference necessary to be considered "real"[10]. Neural adaptations as a result of LLBFR and/or LL have largely been considered absent, reversed, or inferior to traditional high-load resistance exercise approaches[2,5,10,37]. We have previously demonstrated superior neural adaptations following 6 weeks of high-load versus LL resistance training[2], and there were no differences in sEMG and mechanomyographic responses between LLBFR and LL following 4 weeks of resistance training[5]. In the present study, there were larger decreases in neuromuscular efficiency (Nm·% M_{P-P}) for LLBFR than LL for 4 of 11 individual responses, but not between the composite responses. Furthermore, there were linear and quadratic decreases for 8 of 11 individual responses for LLBFR, but 5 linear increases for LL. The larger and more prevalent decreases in neuromuscular efficiency for LLBFR were likely due to the more pronounced increases in sEMG amplitude also observed for LLBFR as average submaximal concentric torque was relatively unaffected (Figures 1-3). Acutely, these findings suggested that LLBFR requires greater muscle excitation per unit of torque relative to un-restricted conditions. It is plausible, that the reduced efficiency and greater muscle excitation associated with LLBFR facilitates neuromuscular adaptions and contributes, in part, to the superior strength adaptations following chronic LLBFR than LL. For example, relative to LL, high-load resistance exercise elicits greater chronic neural adaptations[2] and acute intra-set increases in muscle excitation[38]. While the mechanisms underlying neuromuscular adaptations is not well understood[39], it is possible that enhancing muscle excitation would induce more physiological stress onto the neuromuscular system promoting or requiring an adaptative response.

Average Submaximal Concentric Torque

The average submaximal concentric torque responses were, in general, unaffected across the exercise bouts of LLBFR and LL. While the slope coefficients were different (6 of 11 of the individual slopes and between the composite slopes) and opposite in direction (5 of 11), there were no significant relationships for 15 of 22 individual responses and no significant relationships between the composite responses (Table 3, Figure 3). The lack of change across time is consistent with the nature of the DCER exercise which utilizes a constant external load performed at a controlled pace. As average torque is the product of force produced as a function of time, it could be speculated that factors known to affect the physiological responses to resistance exercise[18] including time under tension and exercise volume were similar between LLBFR and LL protocols. Despite a lack of differences in average submaximal concentric torque, the fatiguing nature of the exercise bouts can still affect the average load maintained across an exercise bout. For example, when time under tension and exercise volume were controlled utilizing an isokinetic dynamometer, mean power decreased across a fatiguing bout of exercise performed using a submaximal load that may have reflected reductions in the time duration spent at or near target force[40]. While the external load cannot change during DCER exercise, subtle deviations in velocity as a result of muscle fatigue can induce meaningful changes in average torque across repetitions. Thus, in general, while there were no significant relationships in average torque across time, there were differences in the slope coefficients that may reflect small deviations in velocity and subsequently the determination of average submaximal concentric torque (Figure 3). It is possible, therefore, that with more repetitions and/or additional sets of exercise there may be significant and divergent relationships for average submaximal concentric torque across LLBFR and LL conditions.

Conclusion

There were larger rates of change among the slope coefficients of the individual relationships for sEMG amplitude and electrical efficiency for LLBFR than LL. For both LLBFR and LL, however, sEMG amplitude increased and electrical efficiency decreased across the 30 submaximal repetitions that likely reflected a fatigue-induced increase in motor unit recruitment and/or firing rate and reduced efficiency (i.e., increased muscle excitation per unit of torque production). The average submaximal concentric torque responses were relatively stable across the 30 repetitions for both LLBFR and LL, although the slope coefficients were different for some of the individual slopes and composite slopes. Collectively, LLBFR elicited greater fatigue-induced increases in sEMG amplitude and decreases in neuromuscular efficiency than LL, but neither LLBFR nor LL affected average submaximal concentric torque across a bout of low-load DCER muscle actions.

Ethics approval

This study was approved by the University Institutional Review Board for Human Participants (IRB ID: STUDY00001036) and all participants completed a health history questionnaire and signed a written informed consent prior to testing.

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