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Blood flow restriction does not augment low force contractions taken to or near task failure

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Abstract
Low-load exercise performed to or near task failure appears to result in similar skeletal muscle adaptations as low-load exercise with the addition of blood flow restriction (BFR). However, there may be a point where the training load becomes too low to stimulate an anabolic response without BFR. This study examined skeletal muscle adaptions to very low-load resistance exercise with and without BFR. Changes in muscle thickness (MTH), strength, and endurance were examined following 8-weeks of training with a traditional high-load [70% 1RM,(7000)], low-load [15% 1RM,(1500)], low-load with moderate BFR [15%1RM+40%BFR(1540)], or low-load with greater BFR [15% 1RM+80%BFR(1580)]. 1RM strength changes were greater in the 7000 condition [2.09 (95% CI=1.35-2.83) kg] compared to all low-load conditions. For isometric and isokinetic strength, there were no changes. For endurance, there was a main effect for time [mean pre to post change = 7.9 (4.3–11.6) repetitions]. At the 50% site, the mean change in MTH in the 7000 condition [0.16 (0.10-0.22) cm] was greater than all low-load conditions. For the 60% site, the mean change in MTH [0.15 (0.08-0.22)] was greater than all low-load conditions. For the 70% site there was a main effect for time [mean pre to post change = 0.09 (0.05–0.14 cm)]. All groups increased muscle size; however, this response was less in all very low training conditions compared to high-load training. 1RM strength increased in the 7000 condition only, with no other changes in strength observed.
Keywords: muscle growth; strength; torque; occlusion training; swelling
Introduction

Low-load resistance exercise with the application of blood flow restriction (BFR) has been shown to result in similar increases in skeletal muscle size as traditional high-load resistance exercise (Fahs et al., 2015; Kim et al., 2017; Laurentino et al., 2012; Ozaki et al., 2013). This technique facilitates similar benefits as high-load resistance exercise, while removing the need for a heavy external load. This may be advantageous for individuals recovering from injury (Ohta et al., 2003), individuals of advanced age (Vechin et al., 2015), or individuals who simply do not prefer to lift heavy weights. Despite the growing popularity of BFR, it has been shown that low-loads [30-40% one repetition maximum (1RM)] by themselves (without the application of BFR) result in similar muscular adaptations as low-loads with BFR, as long as exercise is performed to volitional failure (Fahs et al., 2015; Farup et al., 2015).

Considering that low-load exercise performed to volitional failure appears to result in similar skeletal muscle adaptation as low-load exercise with the addition of BFR, it is not presently clear if there is a point at which BFR is absolutely necessary to elicit an anabolic skeletal muscle response. However, there is some evidence that BFR may become more important (if not essential) when even lower (i.e., <30% 1RM) external loads are implemented. For example, Lixandrão et al. (2015) found that higher arterial occlusion pressures (AOP) augmented muscle growth when training with a 20% 1RM load, but had no greater effect when a 40% 1RM load was used. This study provided some indication that pressure may be important at lower relative training loads (i.e., 20% 1RM); however, authors employed a standardized exercise protocol where each group performed 2-3 sets of 15 repetitions. Had all individuals performed exercise to volitional failure, it seems reasonable to suggest that investigators may have observed a more
homogeneous growth response across conditions (Dankel et al., 2017A). However, recent acute work from our laboratory led us to hypothesize that there may be a point (10-15% 1RM) where the training load becomes too low to meaningfully disturb blood flow, making it difficult to even reach failure (as indicated by an ability to easily complete all goal repetitions)(Dankel et al., 2017B). If exercising with a high degree of effort (i.e. at or near failure) is important for muscle growth, then the application of BFR may be essential at these very low-loads where failure may be difficult to reach. Thus, the purpose of the present study was to examine changes in muscle size, strength and local muscular endurance following 8 weeks of very low-load resistance exercise with and without the application of restrictive pressure, and to compare these adaptations to traditional high-load resistance exercise.

Methods

Study Overview

Non-resistance trained men and women between the ages of 18-35 were recruited to participate in this study. On the initial pre visit, it was determined if the participant met the inclusion criteria. Participants were excluded from the study if they regularly used tobacco products within the previous 6 months, had a BMI 30 kg/m², had an orthopedic injury preventing exercise, or took medication for hypertension. Participants were also excluded if they met at least two of the following risk factors for thromboembolism: diagnosed with Crohn’s disease, past fracture of the hip, pelvis, or femur, major surgery within the last 6 months, varicose veins, family or personal history of deep vein thrombosis, or if they had a family or personal history of pulmonary embolism (Motykie et al., 2000). If participants were eligible, they proceeded to complete an informed consent document, PAR-Q, and have their height and body mass measured. Next,
participants had their muscle thickness measured in both arms. Participants were then familiarized with the unilateral elbow flexion exercise by practicing the movement with no external load. On the second pre visit, participants were tested for their unilateral 1RM test in both arms followed by a test of muscular endurance for each arm. In addition, participants were familiarized with isokinetic and isometric testing in the upper body (1-2 sub-maximal attempts on each arm). For the third visit, participants performed isokinetic and isometric testing for each arm. The following week, participants began the eight-week training protocol consisting of two training sessions per week with at least 24h separating each visit. Participants had each of their arms assigned to a condition in a random counter-balanced fashion so that each arm completed 1 of the following 4 conditions: (1) very low-load resistance training [15% 1RM, no pressure (1500)]; (2) very low-load training with low levels of BFR [15% 1RM + 40% AOP (1540)]; (3) very low-load training with high levels of BFR pressure [15% 1RM + 80% AOP (1580)]; and (4) traditional high-load resistance training [70% 1RM; no pressure (7000)]. Thus, each participant was assigned to two of four possible training conditions. Both arms trained each day in a counter-balanced fashion. The lower body was also trained (as part of a larger study) and that data is presented elsewhere (Jessee et al., 2018). Measures of muscle thickness were taken at the midpoint of the training study (beginning of week 4). Participants were asked to avoid exercise 24 hours prior to all pre-testing visits. At least 48 hours following the last training session, post measurements were taken over three separate days, similar to the pre-visits. The study received approval from the University’s Institutional Review Board.
Training Programs

Participants exercised with either a high-load (70% 1RM) or a very low-load (15% 1RM) with and without blood flow restriction. Exercise consisted of unilateral elbow flexion exercise completed to volitional failure or 90 reps per set, whichever occurred first. Ninety repetitions represents 3 minutes of continuous exercise which would equal the time-frame used by Holm et al. (2008), and it would minimize participant strain. Further, if the contractions were not generating a sufficient amount of fatigue, the stimulus would likely become more aerobic (i.e., mitochondrial protein synthesis > myofibrillar protein synthesis) with time (Burd et al., 2012). Each set for the high-load condition was separated by 90s of rest and the very low-load conditions were separated by 30s of rest. Exercise was performed to the beat of a metronome, with the concentric and eccentric portions of the lift each lasting for 1s (total of a 2s per repetition). For the BFR conditions, the same protocol used for very low-load training was employed with the addition of a 5 cm wide nylon cuff (SC5, Hokanson Inc., Belleville, WA, USA), at the top of the limb which was inflated to 40% or 80% of the individual’s resting AOP. This led to an average applied pressure of 57 mmHg for the 1540 condition and 110 mmHg for the 1580 condition (Mattocks et al., 2019). The standing arterial occlusion pressure was determined by placing an MD6 Doppler probe (Hokanson, Bellevue, WA, USA) at the radial or artery to detect a pulse. The pressure cuff was then inflated and was increased by 1 mmHg increments until a pulse was no longer present. The cuff remained inflated for the duration of the protocol including rest periods and was deflated and removed upon completion of the final set. The AOP was determined prior to exercise each visit.
Given the large volume of exercise associated with the low-load protocols, we gradually increased the number of sets performed for all exercise conditions. Specifically, all groups performed 1 set of exercise on the first training session, 2 sets of exercise on the second training session, 3 sets of exercise on the third and fourth exercise sessions and 4 sets for all training sessions thereafter. For all conditions, the training load remained the same for the duration of the study.

**Muscle Thickness**

All B-mode ultrasound measurements were made using a GE LOGIQ e (Fairfield, CT, USA) ultrasound unit with a wide-band linear array probe (GE L4-12t) at 8-10 MHz depending on tissue depth. Muscle thickness was measured as the distance between the muscle-bone and muscle-adipose interface. Three different measurement locations were taken on the anterior upper arm of both arms at 50%, 60% and 70% the distance from the acromion process to the lateral epicondyle. Two images were taken at each site and stored on an external drive to be analyzed later. Muscle thickness was taken as the average of the two values. During analysis, the tester was blinded to group assignment. The reliability for this tester was determined using a small sample (n=4) of individuals tested over an 8 week time period. The mean difference (SD) was -0.01 (0.09) cm with a %CV of 1%.

**Strength Testing**

We tested the unilateral strength of the participant’s arms using the dumbbell elbow flexion exercise. We assessed the one-repetition maximum on both arms (1-RM; the heaviest weight they can lift one time with good form). Participants performed each attempt with their back
against a wall. To ensure the full range of motion was completed, the investigator handed the participant the weight while the arm is fully extended. Verbal encouragement was provided during all attempts. The smallest increment for strength assessment was 0.22 kg. The stability of the 1RM test in our laboratory was determined using a sample of individuals (n=51) tested over a 6 week time period. The mean difference (SD) was 0.4 (1.4) kg with a %CV of 4%.

Isokinetic and isometric maximal voluntary contractions (MVC) were tested on a dynamometer (Biodex Quickset System 4). Each participant was seated in the dynamometer with the chair adjusted for each individual. Participants were strapped down to limit movement and isolate the elbow flexor muscles. The settings were recorded to ensure the same testing conditions for both the pre and post measures. For isokinetic testing, the participants were given 3 attempts at 60 and 180°/s, with 60s of rest between each attempt. Next, the participant completed two 3-8s isometric MVC’s at 60° of elbow flexion with 60s rest between attempts. Participants were provided visual feedback during all dynamometry testing. Verbal encouragement was provided during all attempts. The stability of the isokinetic test at 60°/s in our laboratory was determined using a sample of individuals (n=51) tested over a 6 week time period. The mean difference (SD) was -0.5 (3.2) Nm with a %CV of 5%. We do not have this same information for isokinetic at 180°/s or isometric but hypothesize it would look similar to that of 60°/s.

Muscle Endurance

The participants completed as many repetitions as possible on the dumbbell elbow flexion exercise using 42.5% of their pre-test 1RM, to a metronome of 1 second for the concentric and 1 second for the eccentric portion of the lift; totaling 2s per repetition. The test was terminated if
they were not able to keep pace to the metronome or could not lift the load through a full range of motion. The last successful repetition completed was used for analysis. Participants rested for 5 minutes between each arm.

Statistics
All statistics were analyzed using SPSS 24.0 statistical software package (SPSS Inc., Chicago, IL). In order to examine changes in all strength and muscle thickness values across time between groups, while accounting for our within/between subject design, two-factor (condition x time) analysis of variance was used to analyze all strength (4 conditions x 2 time points) and muscle thickness (4 conditions x 3 time points) measures. Special consideration was taken to account for the dependency created because each participant contributed observations in two of the four possible training conditions and at multiple time points. ANOVA models were estimated using covariance pattern models. Two different error covariance structures were compared prior to hypothesis testing: compound symmetry and unstructured. Akaike’s Information Criterion (AIC) and Schwarz’s Bayesian Criterion (BIC) values were compared to determine the most appropriate model. If there was a significant condition x time interaction (p ≤ 0.05), we examined simple effects. Otherwise, main effects of time and condition were examined.

Results
Demographics and repetitions are displayed as mean (SD). All other data is represented by the mean change (95% CI). A total of 40 individuals (males=20, females = Age 21.5 (2.4) yrs; Height: 1.72 (0.09) cm; Body mass: 68.4 (11.5) kg; BMI: 23.0 (2.9)) completed the study. Baseline values for muscle performance and muscle thickness are detailed in Table 1.
Repetitions Performed

Repetitions across sets are displayed for training visit 5 (first visit where 4 sets were performed) and the final training visit in Table 2. Although the goal was to reach volitional failure, this was not always possible with the low loads used. Using the mid-point (training visit 8) for reference, all participants in the high load training condition were reaching failure, with 95%, 52% and 31% of participants reaching failure by the fourth set of exercise in the 1580, 1540 and 1500 groups respectively.

Muscular Performance

For 1RM strength (Figure 1A), there was a condition x time interaction (p = 0.003) with the 7000 condition showing the greatest change in strength compared to low-load conditions which did not increase. There was no condition x time interaction or main effect of condition or time for isometric strength (Figure 1B), isokinetic strength at 60°/sec (Figure 1C) or isokinetic strength at 180°/sec (Figure 1D). For muscular endurance (Figure 2), there was no condition x time interaction (Figure 2, p = 0.375) or main effect of condition (p=0.914) but there was a main effect of time [mean change = 7.9 (4.3, 11.6) repetitions, p <0.001].

Muscle Thickness

For the 50% site and the 60% site (Table 3), there was a condition x time interaction (50% site: p = 0.004, 60% site: p=0.014)) with the 7000 condition having a greater pre to post and mid to post change in size than the low-load conditions. There were no differences between conditions in the change in muscle thickness from the pre to mid time points (p > 0.05). For the 70% site (Table
there was no condition x time interaction (p = 0.308) or main effect of condition (p=0.958) but there was a main effect of time (p=0.001). Muscle thickness increased from pre-testing to the midpoint [mean change = 0.06 (0.01– 0.10) cm, p = 0.005] and remained elevated above baseline at post-testing [mean change = 0.09 (0.05 – 0.14 cm] (p < 0.001). Muscle size also increased from the midpoint to the post-testing time point [mean change = 0.03 (0.003 – 0.06) cm] (p = 0.035).

Discussion

We found that all training conditions produced skeletal muscle growth; however, the growth response in all very low-load training conditions (regardless of pressure) was less robust compared to the high-load training condition. In addition, 1RM strength increased in the high-load training condition, with no changes in any strength measure observed in any of the very low-load training conditions (regardless of pressure).

Muscle Size and Strength

Increases in 1RM strength were only observed in the high-load training condition. This occurred despite muscle growth in all conditions, albeit the growth response was less in the low-load training conditions (e.g. growth occurred at all sites with high-load). The difference in strength change is not a novel finding, as low-loads often underperform compared to traditional high-load resistance training. For example, Mitchell et al. (2012) found that low-load training (30% 1RM) increased dynamic muscle strength but not to the same extent as a condition that had repeated practice lifting a heavy load (80% 1RM). Authors performed a follow up study and found that the periodic practice of the 1RM strength test could eliminate the difference observed between
high-load and low-load training in each of the simple machine based strength skills (i.e., machine guided shoulder press, machine guided knee extension, and leg press) (Morton et al., 2016). In the present study, we utilized an even lower load which seems incapable of inducing changes in 1RM strength. This is similar to the findings of Kacin and Strazar (2011), who observed increases in muscle size with no change in performance measures when examining adaptations to 4 weeks of knee extension exercise performed at 15% of MVC with the application of restrictive pressure. This is in contrast to Holm et al. (2008), who observed small increases in 1RM strength following 12 weeks of unilateral knee extension exercise performed using 15.5% of 1RM; however, these increases were less than those observed with high-load resistance training (19 ± 2% vs 36 ± 5%). In addition, investigators assessed 1RM strength on 4 separate occasions over the course of the study, which may have had an influence on the strength adaptations. Of note, we limited the exposure with strength testing to only two occasions (pre and post). Lixandrao et al. (2015) using a relative load of 20% 1RM with or without different levels of BFR, did observe a change in 1RM strength following 12 weeks of exercise. However, this change was smaller than that observed by the higher load training condition. Jessee et al. (2018) examined strength adaptations following 8-weeks of high-load (70% 1RM) or very low-load (15% 1RM, with and without BFR) knee extension exercise, finding that 1RM strength only increased in the high load training group. Despite this, authors noted similar changes in isometric and isokinetic strength at 180°/s between all groups (Jessee, et al., 2018). Thus, training at 15% 1RM in the lower body may have a greater ability to render changes in isometric and isokinetic strength tasks compared to 15% in the upper body.
In the present study, all conditions increased muscle thickness. However, the overall growth response appeared most robust in the 7000 condition compared to all low-load conditions (particularly at the 50% and 60% sites). High-loads, low-loads and low-loads with the application of BFR have all been shown to result in similar changes in skeletal muscle size (Mitchell, et al., 2012; Ogasawara, et al., 2013). However, as the load becomes increasingly lighter (15% of 1RM), with or without BFR, the stimulus does not appear effective at producing a homogenous growth response across the muscle in the upper body. Holm et al (2008) noted inferior changes in muscle size using loads of 15.5% of 1RM (10 sets of 36) following 12 weeks of unilateral knee extension when compared to traditional high-load resistance training (70% 1RM, 10 sets of 8). In addition, Lixandrão et al. (2015) found that intensities as low as 20% 1RM with moderate pressure applied (40% AOP) produced no muscle growth in the lower body. In addition, authors observed greater increases in muscle size with increasing exercise intensity (20% 1RM < 40% < 80%), with higher pressures (80% AOP) appearing more important for growth when lower loads are used (20% 1RM). That study seemed to suggest that BFR may be important when lower training loads are employed; however, it is important to note that Lixandrão et al. (2015) used a standardized exercise protocol (2-3 sets of 15 repetitions) that did not attempt to induce failure like the present study, or produce a high-level of fatigue as likely (10 sets of 36 repetitions) seen in the Holm et al (2008) investigation. Jessee et al. (2018) observed similar changes in muscle size following 8 weeks of high load (70% 1RM) or very low-load (15% 1RM, with and without BFR) knee extension exercise while implementing the same exercise protocol of the present study (90 repetitions per set or failure). Although 15% 1RM was an effective stimulus for skeletal muscle growth in the lower body, it was insufficient in the
upper body to produce changes in muscle size similar to high load training. Further, the application of BFR could not compensate for the insufficient stimulus.

*Isometric and Isokinetic Strength*

Interestingly, we observed no changes in any measure of isometric or isokinetic strength in any of the training conditions. Undoubtedly, strength mechanisms are poorly understood; however, it has been previously demonstrated that isometric and isokinetic strength measures can increase following isotonic training programs (Counts et al., 2016; Mattocks et al., 2017). We have previously suggested that multiple strength assessments may better capture strength adaptation following a resistance training protocol (Buckner et al., 2017A), however, changes in these non-specific strength tests were not observed within the present study. These non-specific tests have been hypothesized to provide a better comparison of changes in strength across training programs of differing loading patterns (e.g. high-load vs. low-load). Results of the present study suggest that two exposures (pre and post testing) in combination with our very low-load training protocols was not a sufficient enough stimulus to augment strength outcomes on these tests (i.e., isometric and isokinetic testing). In addition, although the high-load condition increased isotonic strength, there was no carry-over to these non-specific strength tests in the upper body. Overall, it seems the further a performance or strength task deviates from the training program, the more difficult it is to estimate what changes will occur (Buckner et al., 2019).

*Local Muscle Endurance*

In the present study, we observed a similar increase in local muscular endurance across all groups. Although all low-load training conditions performed more repetitions compared to the
high-load training group on a weekly basis, the testing load chosen (42.5% 1RM) did not cater to “specificity” of either group. Schoenfeld et al. (2015) found that low-load training (25–35 repetitions to muscle failure) resulted in improvements in bench press muscular endurance, whereas high-load training (8–12 repetitions to muscular failure) saw no improvements. Authors hypothesized that their results may be explained by divergent adaptations at the muscle fiber level; however, the endurance catered to specificity of the low-load group, which may also explain these findings (i.e., low-load group trained at 30–50% 1RM and endurance test was performed with 50% 1RM). In addition, Schoenfeld (2015) used the baseline 1RM for the pre endurance test and the post 1RM for the post endurance test. In the present study, we used the same load for pre and post endurance testing. In doing so, the high-load training condition was tested with a lower relative percentage of their 1RM compared to the very low-load training conditions (since that was the only group to increase 1RM strength). Thus testing at a lower relative load post training may explain increases in the high-load training condition. Low-load training conditions may have increased muscular endurance as a result of physiological or psychophysiological adaptations. Physiological adaptations could include greater angiogenic gene expression/capillarization resulting from the metabolic disturbance associated with this type of exercise (Ferguson et al., 2018; Larkin et al., 2012) and/or there might have been psychophysiological changes that occurred from becoming more accustomed to the discomfort associated with performing a large number of repetitions (Mattocks, et al., 2019). For the 1500 condition, participants exercised for the greatest amount of time (amounting to 12 minutes of total exercise for a single exercise). Thus, this group may have experienced an overall more aerobic like stimulus (Burd et al., 2012). Interestingly, when examining the same conditions in the lower body, Jessee et al. (2018) found that muscular endurance increased more when very
low-load (15% 1RM) training was combined with high restrictive pressures (80% AOP). Given this inconsistency, future studies are necessary to better understand the influence of exercise load and restrictive pressures on endurance adaptations in both the upper and lower body.

Limitations

The present study was not without limitations. The design utilized allowed the possibility of some cross-over occurrence on strength measures. However, our results seem to indicate that no cross-over of strength occurred amongst the conditions. It is of note that the exercise load was not progressed throughout the study which we view as a strength with respect to this study design. For example, we were attempting to determine if BFR could augment a training load that was perhaps too low for adaptation; had 15% 1RM conditions been progressed it would have limited the ability to elucidate whether adaptation was due to progressed load or BFR. Further, we felt that progressing the load in 7000 and not the other conditions would create a greater limitation to the specific aims of the study. Next, we inferred changes in muscle size from muscle thickness measured by B-mode ultrasound which is not the gold standard estimate of MRI. Although the magnitude of change may differ between estimates of muscle growth, B-mode ultrasound has been shown to track similarly with more sophisticated methods, such as MRI (Franchi et al., 2018; Loenneke et al., 2019). In addition, another concern with imaging is whether the increase in size is due to skeletal muscle growth or edema. To try and account for the impact of edema (Buckner et al., 2017B), we confirmed that each muscle had the capacity to swell within each measurement time point (Supplementary Table 1). Lastly, it may be considered a limitation that some individuals reached failure and others did not within a given set. As stated earlier, if individuals reached 90 repetitions, they were stopped as anything over that time frame
would be more aerobic in nature. This resembled a time frame used previously by Holm et al. (2008) and we felt the benefits gained by stopping outweighed the limitations. Interestingly, despite the majority of individuals reaching volitional failure in the 1580 condition, this still did not make up for the lack of stimulus resulting from the very low-load. Nevertheless, the inability to train to failure in all conditions is a limitation and must be considered when interpreting these findings.

Conclusions

Results of the present study provide important insight regarding the efficacy of BFR when very low exercise loads are implemented. Primarily, our results demonstrated that loads of 15% (regardless of pressure applied) produce skeletal muscle growth. However, this response was not as robust as that observed following high-load resistance training. In addition, training loads of 15% (with or without the application of BFR) do not produce increases in measures of muscle strength. These findings seem to suggest that BFR cannot be used to compensate for an insufficient external load. In addition, these results suggest that loads as low as 15% 1RM do not provide adaptations comparable to high-load resistance training. Future research should further investigate the lowest effective load, particularly for rendering changes in muscle size.
References


**FIGURE LEGEND**

**Figure 1: Muscle Strength**
Changes in isotonic one repetition maximum strength (A), isometric strength (B), isokinetic strength 60°/sec (C) and isokinetic strength 180°/sec (D) across conditions. All data are presented as mean change (95% confidence interval). 1500: 15% one repetition maximum (1RM) with no blood flow restriction; 1540: 15% 1RM with 40% arterial occlusion pressure; 1580: 15% 1RM with 80% arterial occlusion pressure; and 7000: 70% 1RM with no blood flow restriction.

**Figure 2: Muscular Endurance**
Changes in the number of repetitions to task failure. All data are presented as mean change (95% confidence interval). 1500: 15% one repetition maximum (1RM) with no blood flow restriction; 1540: 15% 1RM with 40% arterial occlusion pressure; 1580: 15% 1RM with 80% arterial occlusion pressure; and 7000: 70% 1RM with no blood flow restriction.
Table 1. Baseline values for muscle performance and muscle thickness. No variability is noted for the baseline values because we were interested in the change from baseline. The variability of that response is noted in subsequent tables and figures.

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1500: 15% one repetition maximum (1RM) with no blood flow restriction; 1540: 15% 1RM with 40% arterial occlusion pressure; 1580: 15% 1RM with 80% arterial occlusion pressure; and 7000: 70% 1RM with no blood flow restriction.
Table 2. Repetitions across sets for visits 5 (first visit where 4 complete sets were performed) and 16 (final training visit). Data are presented as mean (SD). No statistical analysis was performed as repetitions were not a question of interest.

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<td>Visit 16</td>
<td>Visit 5</td>
<td>Visit 16</td>
<td>Visit 5</td>
</tr>
<tr>
<td>1500</td>
<td>90 (0)</td>
<td>90 (0)</td>
<td>77 (19)</td>
<td>88 (8)</td>
<td>70 (30)</td>
<td>86 (13)</td>
<td>68 (30)</td>
</tr>
<tr>
<td>1540</td>
<td>87 (5)</td>
<td>90 (0)</td>
<td>68 (30)</td>
<td>81 (21)</td>
<td>60 (31)</td>
<td>80 (23)</td>
<td>55 (34)</td>
</tr>
<tr>
<td>1580</td>
<td>71 (18)</td>
<td>78 (21)</td>
<td>44 (32)</td>
<td>60 (31)</td>
<td>32 (28)</td>
<td>47 (33)</td>
<td>31 (31)</td>
</tr>
<tr>
<td>7000</td>
<td>15 (3)</td>
<td>22 (7)</td>
<td>9 (2)</td>
<td>12 (3)</td>
<td>6 (2)</td>
<td>8 (3)</td>
<td>5 (3)</td>
</tr>
</tbody>
</table>

1500: 15% one repetition maximum (1RM) with no blood flow restriction; 1540: 15% 1RM with 40% arterial occlusion pressure; 1580: 15% 1RM with 80% arterial occlusion pressure; and 7000: 70% 1RM with no blood flow restriction.
Table 3. Changes in muscle thickness at the 50%, 60%, and 70% sites (cm). All data are presented as mean change (95% confidence interval).

<table>
<thead>
<tr>
<th></th>
<th>Pre vs. Mid</th>
<th>Mid vs. Post</th>
<th>Pre vs. Post</th>
</tr>
</thead>
<tbody>
<tr>
<td>50% site</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1500</td>
<td>0.104 (0.041-0.167)*a</td>
<td>-0.038 (-0.092 - 0.015)*a</td>
<td>0.066 (0.003 - 0.128)**a</td>
</tr>
<tr>
<td>1540</td>
<td>0.043 (-0.043 - 0.103)*a</td>
<td>0.001 (-0.05 - 0.052)*a</td>
<td>0.044 (-0.016 - 0.103)*a</td>
</tr>
<tr>
<td>1580</td>
<td>0.058 (-0.003 - 0.12)*a</td>
<td>0.011 (-0.041 - 0.063)*a</td>
<td>0.069 (0.008 - 0.13)*a</td>
</tr>
<tr>
<td>7000</td>
<td>0.053 (-0.009 - 0.115)*a</td>
<td>0.11 (0.058 - 0.162)*b</td>
<td>0.163 (0.101 - 0.225)*b</td>
</tr>
</tbody>
</table>

60% site [mean change in cm (95% Confidence Interval)]

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1500</td>
<td>0.048 (-0.012-0.108)*a</td>
<td>0.002 (-0.046 - 0.05)*a</td>
<td>0.05 (-0.02 - 0.12)*a</td>
</tr>
<tr>
<td>1540</td>
<td>0.083 (0.026 - 0.141)*a</td>
<td>-0.023 (-0.069 - 0.023)*a</td>
<td>0.061 (-0.006 - 0.127)*a</td>
</tr>
<tr>
<td>1580</td>
<td>0.068 (0.01 - 0.127)*a</td>
<td>-0.016 (-0.064 - 0.031)*a</td>
<td>0.052 (-0.017 - 0.12)*a</td>
</tr>
<tr>
<td>7000</td>
<td>0.055 (-0.003 - 0.113)*a</td>
<td>0.096 (0.048 - 0.144)*b</td>
<td>0.151 (0.082 - 0.22)*b</td>
</tr>
</tbody>
</table>

70% site [mean change in cm (95% Confidence Interval)]

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1500†</td>
<td>0.045 (-0.19, 0.11)</td>
<td>0.025 (-0.026, 0.076)</td>
<td>0.071 (-0.003, 0.144)</td>
</tr>
<tr>
<td>1540†</td>
<td>0.076 (0.14, 0.139)</td>
<td>0.003 (-0.046, 0.052)</td>
<td>0.073 (0.003, 0.144)</td>
</tr>
<tr>
<td>1580†</td>
<td>0.071 (-0.007, 0.135)</td>
<td>-0.044 (-0.094, 0.006)</td>
<td>0.115 (0.042, 0.188)</td>
</tr>
<tr>
<td>7000†</td>
<td>0.062 (-0.003, 0.127)</td>
<td>0.076 (0.026, 0.126)</td>
<td>0.138 (0.026, 0.126)</td>
</tr>
</tbody>
</table>

1500: 15% one repetition maximum (1RM) with no blood flow restriction; 1540: 15% 1RM with 40% arterial occlusion pressure; 1580: 15% 1RM with 80% arterial occlusion pressure; and 7000: 70% 1RM with no blood flow restriction. For the 50% and 60% sites, an *indicates a value that is significantly different from zero within each time point and if conditions contain at least one of the same letter, they are not different from each other within each time point. For the 70% site, a † signifies a time effect.
**Supplementary Table 1: Change in muscle thickness following an acute training bout**

<table>
<thead>
<tr>
<th></th>
<th>Pre</th>
<th>Mid</th>
<th>Post</th>
</tr>
</thead>
<tbody>
<tr>
<td>1500</td>
<td>0.352 (0.286-0.418)</td>
<td>0.434 (0.368-0.500)</td>
<td>0.380 (0.314-0.446)</td>
</tr>
<tr>
<td>1540</td>
<td>0.339 (0.276-0.403)</td>
<td>0.441 (0.378-0.504)</td>
<td>0.438 (0.375-0.501)</td>
</tr>
<tr>
<td>1580</td>
<td>0.360 (0.295-0.424)</td>
<td>0.512 (0.447-0.576)</td>
<td>0.496 (0.431-0.560)</td>
</tr>
<tr>
<td>7000</td>
<td>0.141 (0.076-0.205)</td>
<td>0.361 (0.297-0.426)</td>
<td>0.363 (0.298-0.427)</td>
</tr>
</tbody>
</table>

The swelling response observed at pre, mid and post training. The ability of a muscle to swell provides some indication that the muscle wasn’t swollen prior to measurement. Values are lower during the “pre” time point since exercise was progressed and individuals only performed 1 set of exercise. Values are displayed across conditions for pre, mid and post training study. All values are presented as means (95% CI).
Main Effect of Time: p<0.001