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ORIGINAL ARTICLE

# Low intensity blood flow restriction training: a meta-analysis

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**Abstract** The primary objective of this investigation was to quantitatively identify which training variables result in the greatest strength and hypertrophy outcomes with lower body low intensity training with blood flow restriction (LI-BFR). Searches were performed for published studies with certain criteria. First, the primary focus of the study must have compared the effects of low intensity endurance or resistance training alone to low intensity exercise with some form of blood flow restriction. Second, subject populations had to have similar baseline characteristics so that valid outcome measures could be made. Finally, outcome measures had to include at least one measure of muscle hypertrophy. All studies included in the analysis utilized MRI except for two which reported changes via ultrasound. The mean overall effect size (ES) for muscle strength for LI-BFR was 0.58 [95% CI: 0.40, 0.76], and 0.00 [95% CI: −0.18, 0.17] for low intensity training. The mean overall ES for muscle hypertrophy for LI-BFR training was 0.39 [95% CI: 0.35, 0.43], and −0.01 [95% CI: −0.05, 0.03] for low intensity training. Blood flow restriction resulted in significantly greater gains in strength and hypertrophy when performed with resistance training than with walking. In addition, performing LI-BFR 2–3 days per week resulted in the greatest ES compared to 4–5 days per week. Significant correlations were found between ES for strength development and weeks of duration, but not for muscle hypertrophy. This meta-analysis provides insight into the impact of different variables on muscular strength and hypertrophy to LI-BFR training.

**Keywords** KAATSU · Hypertrophy · Strength · Vascular occlusion training

## Introduction

The American College of Sports Medicine (ACSM) recommends lifting a weight of at least 70% 1RM to achieve muscular hypertrophy as it is believed that anything below this intensity rarely produces substantial muscle growth (ACSM 2009). However, numerous studies using low intensity exercise combined with blood flow restriction (LI-BFR) have shown muscle hypertrophy to occur with a training intensity as low as 20% 1RM (Abe et al. 2005b, c; Madarame et al. 2008; Yasuda et al. 2010). In further support of LI-BFR, a recent review looking at potential safety issues of this type of training concluded that it offered no greater risk than traditional exercise (Loenneke et al. 2011). LI-BFR has been combined with several different types of exercise (e.g. knee extension, knee flexion, leg press, cycling, walking, elbow flexion, bench press) and most have observed significant increases in muscle hypertrophy (Abe et al. 2006, 2010a, b; Madarame et al.

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2008; Takarada et al. 2000; Yasuda et al. 2010), strength (Abe et al. 2006, 2010a, b; Madarame et al. 2008; Takarada et al. 2000; Yasuda et al. 2010), and endurance (Kacin and Strazar 2011). Interestingly, although increases in skeletal muscle hypertrophy and strength do not typically occur from an "Aerobic" mode of exercise, increased size and strength have been observed from both slow walk training (Abe et al. 2006) and cycling combined with LI-BFR (Abe et al. 2010a). Previous literature has discussed the benefits and mechanisms of blood flow restricted training in depth [for reviews please see (Loenneke and Pujol 2009; Loenneke et al. 2010; Manini and Clark 2009; Wernbom et al. 2008; Loenneke and Pujol 2011)].

Published studies hypothesize that blood flow restriction training induces skeletal muscle hypertrophy through a variety of mechanisms [for a review please see (Loenneke et al. 2010)], however, a definitive mechanism has yet to be elucidated. Proposed mechanisms include increased fiber type recruitment, metabolic accumulation, stimulation of muscle protein synthesis, and cell swelling, although it is likely that many of the aforementioned mechanims work together.

Throughout the LI-BFR literature there exist many significant differences in study design, specifically with respect to different training variables (e.g. mode of exercise, days per week, duration, rest intervals, exercise intensity, exercise volume). Little work has been completed to identify which variables are the most important to consider when designing an optimal LI-BFR training program. A robust and quantitative approach to the problem can be provided in the form of a meta-analysis of the data. The primary objective of this investigation was to quantitatively identify which training variables result in the greatest strength and muscle hypertrophy outcomes when combining low intensity exercise with blood flow restriction.

## Methods

### Literature search

Searches were performed for published studies with a number of criteria. First, the primary focus of the study must have compared the effects of low intensity endurance or resistance training alone to low intensity exercise with some form of blood flow restriction. Second, to be considered for our analysis, subject populations had to have similar baseline characteristics (e.g. both untrained and trained) so that valid outcome measures could be made. Finally, the outcome measures had to include at least one measure of muscle hypertrophy as this is currently suggested to be a primary mechanism responsible for all outcome measures of functionality (Loenneke et al. 2010). Studies reporting muscle hypertrophy as a percentage increase were excluded due to the inability to calculate an effect size. All studies included in the analysis utilized MRI except for two which reported changes in hypertrophy via ultrasound. In addition, due to the paucity of data on LI-BFR of the upper body, only studies investigating the lower body were included. Electronic databases searched included Science Citation Index, National Library of Medicine, Sport Discus, Google Scholar, and MEDLINE were searched in February 2011 back to the earliest available time that met the specifications of this meta-analysis when Abe et al. (2005c) published a foundational study on blood flow restriction training.

Exclusion of studies with irrelevant content and doublets was carried out in three steps. First, the titles of the articles were read, followed by reading of the abstracts, and finally the entire article was read. The reference lists of relevant articles were, in turn, scanned for additional articles (published or unpublished) that met the inclusion criteria. Conference abstracts and proceedings were excluded. Relevant studies were selected and searched for data necessary to compute effect size and descriptive information regarding the training protocol. Table 1 is composed of all studies meeting our meta-analysis requirements and Table 2 lists the studies excluded from analysis.

### Coding of studies

Each study was read and coded by the primary investigator for descriptive information including gender and training experience. For both endurance and resistance training, we coded for frequency, mean training intensity, volume (duration of endurance and sets of strength training), and type of training split utilized. For training, frequency was coded by the number of days per week that participants trained their lower bodies. Pressure of the cuff was coded through a range dependent upon the initial and final pressure of each study. Volume for resistance and endurance training, respectively, was coded as number of repetitions performed, and average duration of the endurance training session. Because the range of repetitions was not large enough to compare within modes we compared total volume of work between all modalities. Training status was defined as untrained, recreationally active, trained, and athlete. Participants must have been performing a structured resistance-training program for at least 1 year prior to the study's onset in order to be considered as trained. In order to be considered for the athlete category, participants must have been competitive athletes at the collegiate or professional level. As described previously by Rhea et al. (2003) all studies included in the analysis were coded twice by the primary investigator to minimize coder drift.

**Table 1** Studies included in the analysis

| Citation | Age (years) | Gender | Training status | Exercise mode | Exercise intensity | Frequency of training | Length of training | Protocol | Measure of hypertrophy |
|---|---|---|---|---|---|---|---|---|---|
| Abe et al. (2005c) | <25 | M | Rec. active | Squat and knee flexion | 20% 1RM | 12× week | 2 weeks | 3 sets of 15 repetitions; 30 sec rest | MRI |
| Abe et al. (2005b) | <25 | M | Athlete | Squat and knee flexion | 20% 1RM | 14× week | 8 days | 3 sets of 15 repetitions; 30 sec rest | Ultrasound |
| Abe et al. (2006) | <25 | M | Rec. active | Treadmill walking | 50 M/Min | 12× week | 3 weeks | 52-min walking bouts; 1 min rest | MRI |
| Abe et al. (2009) | <25 | M | Rec. active | Treadmill walking | 50 M/Min | 6× week | 3 weeks | 52-min walking bouts; 60 sec rest | MRI |
| Abe et al. (2010b) | >50 | M/F | Rec. active | Treadmill walking | 67 M/Min | 5× week | 6 weeks | 20 minutes walking | Ultrasound |
| Abe et al. (2010a) | <25 | M | Rec. active | Cycling | 40% $VO_{2max}$ | 3× week | 8 weeks | 15 minutes cycling | MRI |
| Beekley et al. (2005) | <25 | M | Rec. Active | Treadmill walking | 50 M/Min | 12× week | 3 weeks | 52-min walking bouts; 60 sec rest | MRI |
| Fujita et al. (2008) | <25 | M | Rec. Active | Knee extension | 20% 1RM | 12× week | 6 days | 30-15-15-15 repetitions; 30 sec rest | MRI |
| Kacin and Strazar (2011) | <25 | M | Rec. Active | Unilateral knee extension | 15% MVC | 4× week | 4 weeks | 4 sets to volitional fatigue | MRI |
| Madarame et al. (2008) | <25 | M | Untrained | Knee extension and knee flexion | 30% 1RM | 2× week | 10 weeks | 30,15,15 repetitions; 30 sec rest | MRI |
| Ozaki et al. (2011) | >50 | M/F | Untrained | Treadmill walking | 45% HRR | 4× week | 10 weeks | 20 minutes walking | MRI |

### Calculation and analysis of effect size

Pre- and post-effect sizes (ES) were calculated with the following formula: [(Posttest mean − pretest mean)/pretest standard deviation]. ES were then adjusted for sample size bias (Rhea 2004; Rhea et al. 2003). This adjustment consists of applying a correction factor to adjust for a positive bias in smaller sample sizes. Descriptive statistics were calculated and univariate analysis of variance by groups was used to identify differences between training status, gender, and age with level of significance set at $P < 0.05$. When a significant $F$ value was achieved, pairwise comparisons were performed using a Bonferroni post-hoc procedure. All calculations were made with SPSS statistical software package v.19.0 (SPSS Inc., Chicago, IL). The scale proposed by Rhea (2004) and Rhea et al. (2003) was used for interpretation of effect size magnitude. Coder drift was assessed by coding and then recoding all studies meeting our inclusion criteria. Per case agreement was determined by dividing the variables coded the same by the total number of variables (Rhea 2004; Rhea et al. 2003). The mean agreement for this analysis was 0.98.

## Results

Overall ES and moderating variables are presented in Tables 3 and 4. The 48 ES for muscle strength (28 ES for LI-BFR training and 20 ES for low intensity training) and 60 ES for muscle hypertrophy (31 ES for LI-BFR training and 29 ES for low intensity training) were obtained from a total of 11 primary studies which met our criteria (Table 1).

### Muscular strength

The mean overall ES for muscle strength for LI-BFR training was 0.58 [95% CI: 0.40, 0.76], and 0.00 [95% CI: −0.18, 0.17] for low intensity training (Table 1). Significant differences were found between blood flow restriction training and low intensity training ($P < 0.05$).

#### *Moderating variables for LI-BFR training*

Untrained groups gained more muscle strength than recreationally active groups, 1.38 [95% CI: 1.01, 1.76; $n = 6$] versus 0.37 [95% CI: 0.17, 0.57; $n = 21$] ($P < 0.05$), respectively (Table 3). Significant differences were found between 2–3 days per week and 4–5 day per week, 1.25 [95% CI: 0.84, 1.67; $n = 5$] versus 0.53 [95% CI: 0.21, 0.86; $n = 10$], respectively ($P < 0.05$), as well as between 4–5 days per week and 6–7 days per week, 0.53 [95% CI: 0.21, 0.86; $n = 10$] versus 0.29 [95% CI: 0.00,

**Table 2** Studies excluded from the analysis

| Citation | Age (years) | Gender | Training status | Exercise mode | Length Of training | Reason for exclusion |
|---|---|---|---|---|---|---|
| Abe et al. (2005a) | 47 | M | Rec. active | Knee extension | 7 days | Case study |
| Clark et al. (2010) | <25 | M/F | Untrained | Knee extension | 4 weeks | Hypertrophy not measured |
| Cook et al. (2010) | 18–50 | M/F | Not reported | Knee extension | 4 weeks | Training status not reported/atrophy model |
| Evans et al. (2010) | <25 | M | Rec. Active | Heel raises | 4 weeks | Hypertrophy not measured |
| Gualano et al. (2010) | 65 | M | N/A | Leg press, knee extension, squat | 12 weeks | Myopathy case study |
| Ishii et al. (2005) | 25–50 | F | Untrained | Knee up, bent-knee push up, leg raise, knee flexion, squat, lunge | 8 weeks | Simultaneous upper and lower body blood flow restriction |
| Karabulut et al. (2010) | >50 | M | Untrained | Leg press, knee extension | 6 weeks | Hypertrophy not measured |
| Karabulut et al. (2011) | >50 | M | Untrained | Leg press, knee extension | 6 weeks | Hypertrophy not measured |
| Kim et al. (2009) | <25 | M | Untrained | Leg press, knee extension, knee flexion | 3 weeks | Hypertrophy measured by DXA |
| Ohta et al. (2003) | 18–52 | M/F | Rec. active | Rehabilitation exercises | 16 weeks | Rehabilitation from surgery |
| Park et al. (2010) | <25 | M | Athlete | Treadmill walking | 2 weeks | Hypertrophy not measured |
| Patterson and Ferguson (2010) | <25 | F | Rec. active | Unilateral plantar flexion | 4 weeks | Hypertrophy not measured |
| Sakuraba and Ishikawa (2009) | <25 | M | Athlete | Isokinetic knee flexion/knee extension | 4 weeks | Hypertrophy not measured in control group |
| Sata (2005) | <25 | M | Rec. Active | Hip abduction, hip adduction, calf raise, squat, crunch, etc. | 6 weeks | Patella tendinitis case study |
| Shinohara et al. (1998) | <25 | M | Untrained | Isometric contractions | 4 weeks | Hypertrophy not measured |
| Sumide et al. (2009) | <25 | M | Untrained | Straight leg raise, hip joint abduction, hip joint adduction | 8 weeks | Hypertrophy not measured in control group |
| Takarada et al. (2002) | >50 | F | Untrained | Knee extension | 8 weeks | Hypertrophy Reported As % Change |
| Takarada et al. (2004) | <25 | M | Athlete | Knee extension | 8 weeks | Hypertrophy reported as % change |
| Yasuda et al. (2005) | 20–47 | M | Not reported | Squat and knee flexion | 2 weeks | Training status not reported |

**Table 3** Effect size for muscle strength

| Overall | LI-BFR | | | Low intensity | | |
|---|---|---|---|---|---|---|
| | Mean (95% CI)<br>0.58* (0.40, 0.76) | $N = 28$ | $P$ | Mean (95% CI)<br>−0.00 (−0.18, 0.17) | $N = 20$ | $P$ |
| Moderators | | | | | | |
| Gender | | | | | | |
| Male | 0.58 (0.29, 0.97) | 19 | >0.05 | 0.08 (−0.03, 0.20) | 11 | <0.05 |
| Female | I.D. | | | I.D. | | |
| Both | 0.58 (0.16, 1.01) | 9 | | −0.20 (−0.37, −0.02) | 9 | |
| Training status | | | | | | |
| Untrained | 1.38 (1.01, 1.76) | 6 | <0.05 | 0.32 (0.13, 0.51) | 6 | <0.05 |
| Recreationally active | 0.37 (0.17, 0.57) | 21 | | −0.10 (−0.20, −0.00) | 21 | |
| Athletes | I.D. | | | I.D. | | |
| Days per week | | | | | | |
| 2–3 | 1.25 (0.84, 1.67) | 6 | <0.05 | 0.27 (0.07, 0.47) | 6 | <0.05 |
| 4–5 | 0.53 (0.21, 0.86) | 10 | | −0.17 (−0.32, −0.14) | 10 | |
| 6–7 | 0.29 (−0.00, 0.58) | 12 | | −0.00 (−0.15, 0.13) | 12 | |
| Week of duration | | | | | | |
| ≤4 | 0.27 (0.03, 0.52) | 13 | <0.05 | 0.00 (−0.03, 0.04) | 19 | >0.05 |
| 5–8 | 0.49 (0.20, 0.79) | 9 | | −0.05 (−0.11, 0.15) | 7 | |
| 9–10 | 1.38 (1.02, 1.75) | 6 | | I.D. | | |
| Exercise mode | | | | | | |
| Isotonic | 1.08 (0.69, 1.46) | 8 | <0.05 | 0.28 (0.11, 0.44) | 8 | <0.05 |
| Walking | 0.42 (0.16, 0.67) | 18 | | −0.12 (−0.23, −0.02) | 18 | |
| Cycling | I.D. | | | 0.28 (0.11, 0.44) | | |
| Exercise intensity | | | | | | |
| 15–30% MVC/1RM | 1.08 (0.69, 1.46) | 8 | <0.05 | 0.28 (0.12, 0.44) | 8* | <0.05 |
| 50–60 (m/min) | 0.25 (−0.10, 0.61) | 9 | | −0.05 (−0.20, 0.09) | 9 | |
| 40–45% HRR/$V\text{O}_{2\max}$ | 0.50 (0.17, 0.83) | 11 | | −0.17 (−0.30, −0.03) | 11* | |
| Repetitions | | | | | | |
| 60–70 | 1.37 (0.98, 1.76) | 6 | <0.05 | 0.32 (0.13, 0.51) | 6 | <0.05 |
| Failure | I.D. | | | I.D. | | |
| 14–20 (min) | 0.39 (0.17, 0.60) | 20 | | −0.11 (−0.22, −0.01) | 20 | |
| Rest period (s) | | | | | | |
| 0 | 0.50 (0.19, 0.80) | 11 | <0.05 | −0.17 (−0.30, −0.03) | 11 | <0.05 |
| 30 | 1.22 (0.83, 1.60) | 7 | | 0.30 (0.13, 0.47) | 7 | |
| 60 | 0.25 (−0.08, 0.58) | 9 | | −0.05 (−0.20, 0.09) | 9 | |
| 120 | I.D. | | | I.D. | | |
| Cuff pressure (mmHg) | | | | | | |
| 140–220 | 0.50 (0.12, 0.88) | 11 | >0.05 | | | |
| 160–240 | 0.67 (0.35, 0.99) | 16 | | | | |
| 230 | I.D. | | | | | |

Overall ES and moderating variables for muscular strength. *I.D.* insufficient data (<5 ESs)

* Significant difference from low intensity training ($P < 0.05$)

0.58; $n = 12$] ($P < 0.05$), respectively (Table 3). Significant differences were found between ≤4 and 10 weeks of duration, 0.27 [95% CI: 0.03, 0.52; $n = 13$] versus 1.38 [95% CI: 1.02, 1.75; $n = 6$] ($P < 0.05$), respectively (Table 3). The isotonic exercise mode improved more muscle strength than walking exercise mode, 1.08 [95% CI: 0.69, 1.46; $n = 8$] versus 0.42 [95% CI: 0.16, 0.67; $n = 18$) ($P < 0.05$), respectively (Table 3). Significant differences were found between exercise intensity 15–30% MVC/1RM and 50–60 m/min, 1.08 [95% CI: 0.69, 1.46;

**Table 4** Effect size for muscle hypertrophy

| Overall | LI-BFR | | | Low Intensity | | |
|---|---|---|---|---|---|---|
| | Mean (95% CI)<br>0.39* (0.35, 0.43) | $N = 31$ | $P$ | Mean (95% CI)<br>−0.01 (−0.05, 0.03) | $N = 29$ | $P$ |
| Moderators | | | | | | |
| Gender | | | | | | |
| Male | 0.42 (0.37, 0.47) | 25 | <0.05 | 0.00 (−0.02, 0.03) | 25 | |
| Female | I.D. | | | I.D. | | |
| Both | 0.26 (0.16, 0.37) | 6 | | I.D. | | |
| Days per week | | | | | | |
| 2–3 | 0.48 (0.38, 0.58) | 6 | <0.05 | −0.00 (−0.07, 0.06) | 6 | >0.05 |
| 4–5 | 0.27 (0.18, 0.37) | 7 | | I.D. | | |
| 6–7 | 0.41 (0.35, 0.47) | 18 | | −0.00 (−0.04, 0.04) | 18 | |
| Week of duration | | | | | | |
| ≤4 | 0.41 (0.34, 0.47) | 19 | >0.05 | 0.00 (−0.03, 0.04) | 19 | >0.05 |
| 5–8 | 0.39 (0.29, 0.49) | 9 | | −0.05 (−0.11, 0.01) | 7 | |
| 9–10 | I.D. | | | I.D. | | |
| Exercise mode | | | | | | |
| Isotonic | 1.08 (0.69, 1.46) | 8 | <0.05 | 0.02 (−0.02, 0.06) | 13 | >0.05 |
| Walking | 0.42 (0.16, 0.67) | 18 | | −0.05 (−0.10, −0.05) | 12 | |
| Cycling | I.D. | | | I.D. | | |
| Exercise intensity | | | | | | |
| 15–30% MVC/1RM | 1.08 (0.69, 1.46) | 8 | <0.05 | 0.02 (−0.02, 0.069 | 13 | >0.05 |
| 50–60 (m/min) | 0.25 (−0.10, 0.61) | 9 | | −0.02 (−0.08, 0.03) | 8 | |
| 40–45% HRR/$VO_{2\max}$ | 0.50 (0.17, 0.83) | 11 | | −0.05 (−0.11, 0.00) | 8 | |
| Lower strength assessment | | | | | | |
| Isokinetic | I.D. | | >0.05 | I.D. | | >0.05 |
| Isotonic | 0.33 (0.26, 0.41) | 7 | | −0.03 (−0,10, 0.03) | 7 | |
| Isometric | 0.37 (0.30, 0.44) | 7 | | 0.00 (−0.06, 0.07) | 7 | |
| Repetitions | | | | | | |
| 60–70 | I.D. | | <0.05 | I.D. | | >0.05 |
| Failure | I.D. | | | I.D. | | |
| 14–20 (min) | 0.36 (0.30, 0.42) | 18 | | −0.03 (−0.07, 0.00) | 16 | |
| 45 (rep) | 0.51 (0.43, 0.60) | 8 | | 0.03 (−0.01, 0.09) | 8 | |
| Rest period (s) | | | | | | |
| 0 | 0.37 (0.28, 0.46) | 10 | >0.05 | −0.05 (−0.10, 0.00) | 8 | >0.05 |
| 30 | 0.44 (0.36, 0.53) | 12 | | 0.00 (−0.03, 0.05) | 12 | |
| 60 | 0.35 (0.25, 0.45) | 8 | | −0.02 (−0.08, 0.03) | 8 | |
| 120 | I.D. | | | I.D. | | |
| Cuff pressure (mmHg) | | | | | | |
| 140–220 | 0.37 (0.28, 0.46) | 10 | >0.05 | | | |
| 160–240 | 0.41 (0.34, 0.44) | 20 | | | | |
| 230 | I.D. | | | | | |

Overall ES and moderating variables for muscular hypertrophy. *I.D.* insufficient data (<5 ESs)

* Significant difference from low intensity training ($P < 0.05$)

$n = 8$] versus 0.42 [95% CI: −0.10, 0.61; $n = 9$] ($P < 0.05$), respectively (Table 3). The total volume of work done in a workout, of about 60–70 repetitions improved more muscle strength than 14–20 min of walking, 1.37 [95% CI: 0.98, 1.76; $n = 6$] versus 0.39 [95% CI: 0.17, 0.60; $n = 20$) ($P < 0.05$), respectively (Table 3). Significant differences were found between 0 s rest periods and 30 s rest periods, 0.50 [95% CI: 0.19, 0.80;

$n = 11$] versus 1.22 [95% CI: 0.83, 1.60; $n = 7$] ($P < 0.05$), respectively, as well as between 30 and 60 s rest periods, 1.22 [95% CI: 0.83, 1.60; $n = 7$] versus 0.25 [95% CI: −0.08, 0.58; $n = 9$] (Table 3). Correlational analysis identified significant relationships ($P < 0.01$) between ESfor strength development and weeks of training duration ($r = 0.67$).

### Muscular hypertrophy

The mean overall ES for muscle hypertrophy for LI-BFR training was 0.39 [95% CI: 0.35, 0.43], and −0.01 [95% CI: −0.05, 0.03] for low intensity training (Table 4). Significant differences were found between occlusion training and low intensity training ($P < 0.05$).

#### *Moderating variables for LI-BFR training*

An analysis of the differences in hypertrophy gains achieved for blood flow restriction training was performed in males as compared to combined gender groups to determine whether gender influenced hypertrophy gains. The male group gained more hypertrophy than the combined group, 0.42 [95% CI: 0.37, 0.47; $n = 25$] versus 0.26 [95% CI: 0.16, 0.37; $n = 6$] ($P < 0.05$), respectively (Table 4). Significant differences were found between 2–3 days per week and 4–5 days per week, 0.48 [95% CI: 0.38, 0.58; $n = 6$] versus 0.27 [95% CI: 0.18, 0.37; $n = 7$], respectively ($P < 0.05$). The isotonic exercise mode improved more muscle hypertrophy than the walking exercise mode, 0.44 [95% CI: 0.34, 0.47; $n = 13$] versus 0.31 [95% CI: 0.25, 0.38; $n = 14$) ($P < 0.05$), respectively (Table 4). Significant differences were found between exercise intensity 15–30% MVC/1RM and 50–60 m/min walking speed, 1.08 [95% CI: 0.69, 1.46; $n = 8$] versus 0.25 [95% CI: −0.10, 0.61; $n = 9$]. The total volume of work done in a workout with 45 repetitions improved more muscle hypertrophy than 14–20 min of walking, 0.51 [95% CI: 0.43, 0.60; $n = 8$] versus 0.36 [95% CI: 0.30, 0.42; $n = 18$] ($P < 0.05$), respectively (Table 4).

No significant relationships were found ($P > 0.05$) between ES for hypertrophy and weeks of duration.

## Discussion

The findings of this meta-analysis confirm previous ACSM recommendations that regular low intensity resistance training (not to muscular failure) does not provide an adequate stimulus to produce substantial increases in strength or muscle hypertrophy. However, when that same low intensity exercise is combined with blood flow restriction, significant increases are found comparable to a previous meta-analysis using higher intensities (HIT) (Krieger 2010) with both strength (LI-BFR 0.58 vs. HIT 0.80) and muscle hypertrophy (LI-BFR 0.39 vs. HIT 0.35). To our knowledge, this is the first meta-analysis completed on this novel mode of training, which shows the overall effect from manipulating different variables for training adaptation.

### Subject characteristics

Subjects who were previously untrained have greater increases in muscular strength than those who were recreationally active. This may also provide some explanation for the lower effect size observed with strength in the LI-BFR cohort compared to a previous meta-analysis on HIT resistance training which was composed almost exclusively of untrained subjects. No such comparison could be made for hypertrophy as a result of insufficient data from available studies. No studies meeting our criteria have been completed investigating LI-BFR using only females, thus for this analysis males were compared to a combined group made up of both males and females (males vs. males/females). The combined group observed significantly less muscle hypertrophy than the male only group, possibly due to a buffering effect of females. This would be consistent with previous research demonstrating that women experience smaller changes in muscle size compared with men (Ivey et al. 2000). A comparison across age groups could not be made due to insufficient data from the studies included in this analysis.

### Training frequency

The analysis found that strength and muscle hypertrophy were both significantly greater in the groups performing exercise 2–3 days per week compared to those exercising 4–5 days per week. It is possible that the gains were attenuated in the 4–5 day/week group from an overtraining response, even though the external resistance was low, however, it is more likely this overtraining response is more reflective of the frequency of training rather than the days trained per week, since 4 out of 7 studies in the 4–5 day/week group trained twice per day.

### Training duration

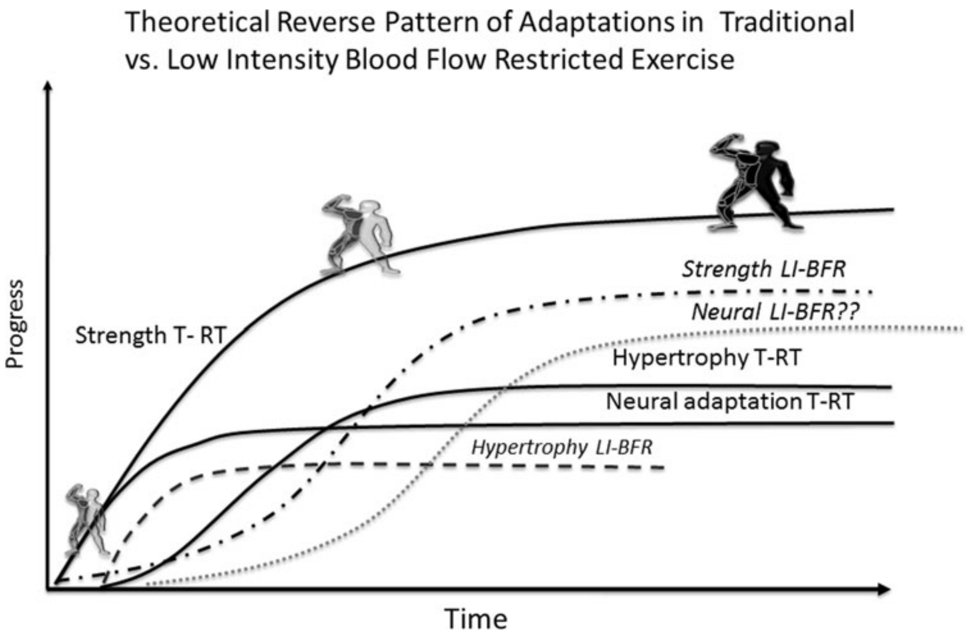
This investigation found that although the ES for muscular hypertrophy remains fairly constant from <4 weeks of training to 10 or more weeks of training, muscular strength responds much differently. The ESindicate that muscular strength does not significantly increase until the 10 week time point (Fig. 1). This finding is interesting because traditionally it has been thought that neural adaptations

**Fig. 1** The effect sizes (ES) for muscle strength and hypertrophy with low intensity blood flow restriction (LI-BFR) as it relates to duration of training

Strength $r = 0.67$; $p<0.01$

* Significantly different from ≤ 4 weeks of exercise training ($P < 0.05$)

**Fig. 2** Graphical representation of the theoretical interaction between strength, hypertrophy, and neural adaptations during both traditional resistance training (T-RT), and low intensity blood flow restricted exercise (LI-BFR) is shown. During T-RT strength increases at first primarily by changes in muscular hypertrophy followed latter by neural adaptations. For LI-BFR the opposite pattern may occur (adapted from Sale 1988)



increase strength during the first couple of weeks of exercise and muscle hypertrophy occurs later on in the training (>6 weeks). These data suggest that perhaps the traditional training adaptation paradigm is reversed with LI-BFR exercise. This may help to explain the findings of studies which report that the strength gains from LI-BFR exercise are a product of muscle hypertrophy and not neural adaptation (Fujita et al. 2008; Takarada et al. 2002, 2000; Yasuda et al. 2011). All of those studies with the exception of one (Takarada et al. 2000) trained <8 weeks. If the findings from this analysis are accurate and representative, then it is conceivable that neural adaptations for LI-BFR exercise do not occur until much later in the training program, and studies lasting <10 weeks would be unlikely to produce relative strength gains (maximal voluntary strength per unit muscle cross sectional area). In further support, correlational analyses found a significant relationship between the ES for strength and weeks of training, with no significant correlation found for hypertrophy. This possible reversal in the neural adaptation finding warrants further investigation before these phenomena can be definitively acknowledged. It is also possible that this finding is spurious and exclusive only to the two long-term (9–10 weeks) studies included in this analysis. While this finding is far from conclusive; however, Fig. 2 graphically depicts the possible theoretical interaction between strength, hypertrophy, and neural adaptations during both traditional resistance training, and LI-BFR exercise.

### Training modality and intensity/volume

The results indicate that isotonic exercise improved muscular strength and hypertrophy to a greater degree than walking. This difference is likely related to the amount of work completed by the muscle as well as the accumulation of metabolites. With resistance training, specific muscles are easily isolated and the metabolic accumulation is much larger than that observed with walking, which further highlights the importance of metabolic accumulation for ideal outcomes in strength and hypertrophy. An additional mechanism responsible for adaptations caused by LI-BFR may be acute cell swelling as this has been shown to stimulate an anabolic response in hepatocytes (Haussinger 1996). Regardless of the mechanism, significant differences exist between isotonic resistance training and walking with LI-BFR. Therefore, individuals capable of performing low intensity resistance training with blood flow restriction will see larger increases in strength and muscle hypertrophy compared to those walking with blood flow restriction. Subsequent alterations in muscular strength and muscle hypertrophy outcomes were also significantly dependent upon exercise intensity. To illustrate, resistance training with 15–30% MVC/1RM produced greater strength and size gains compared to walking at 50–60 m/min. However, these results are likely to be an artifact of the exercise modality, which the aforementioned analysis demonstrated can impact the overall effect. Similar results are present in relation to volume of exercise and rest interval. For example, greater gains in strength and size were found; however, the only two comparisons were made between repetitions completed and minutes walked. In addition, this analysis found that 30 s of rest between sets produced much greater strength gains than 60 s; however, every study using 60 s rest was a walking study. Thus, we suggest that future investigators specifically analyze the question of volume within a given exercise modality.

### Cuff pressures

Throughout the literature, numerous cuff pressures are used. Often, training studies begin at an overall low pressure and progress to high pressures throughout the training programs. For this analysis, two of our groups have overlap, but differed at where the initial training pressures began (140 vs. 160 mmHg) and where the final training pressures ended (160–240 mmHg). This overlap may have led to the non-significant finding, however it may also indicate that the absolute pressure needed for muscular adaptation is much less than commonly thought, especially when using a wider cuff to induce blood flow restriction (Crenshaw et al. 1988). In support of this, evidence suggests that higher restrictive cuff pressures (200 mmHg) are no more effective at increasing intramuscular metabolites than moderate pressures (~150 mmHg or 130% systolic BP) when using a wide (18.5 cm) cuff (Suga et al. 2010). The impact of cuff width was not able to be made from the current analysis, since most studies in this meta-analysis used a narrow cuff (5 cm), therefore the overall impact of cuff width on training adaptation remains unknown. Current research on acute LI-BFR exercise (Wernbom et al. 2008) and the data from this analysis do not suggest that higher pressures would be more effective than lower pressures for inducing training adaptations. However, no study to date has examined the impact of progressively increasing or maintaining restrictive cuff pressure during LI-BFR training so it is not clear if progressive increases in restrictive cuff pressure are necessary to produce muscular strength or hypertrophy.

### Limitations for endurance-based outcomes

The primary focus of our meta-analysis was the effects of blood flow restriction training on hypertrophy and strength training. However, it should be emphasized that our results do not necessarily apply to other outcomes such as endurance performance. For example, we found that greater training frequencies may not be ideal for hypertrophy and strength gains; however, they may be beneficial for endurance outcomes. This was illustrated by Kacin and Strazar (2011) who found that high frequency (4× week) LI-BFR resulted in small gains in hypertrophy, and no significant increases in strength. However, they found that the blood flow restricted group increased endurance performance by 63% as compared to 36% in the control condition. Moreover, while our results strongly indicate that a resistance exercise mode is ideal for strength and hypertrophy, a number of researchers have demonstrated that cycling under ischemic conditions may be a highly effective mode for increasing muscular endurance (Kaijser et al. 1990; Nygren et al. 2000; Sundberg et al. 1993). For the reason that endurance adaptations are an important, yet understudied, component of LI-BFR exercise training we suggest future research attempt to disseminate exactly what the ideal prescription is for those particular outcomes.

## Conclusions

This meta-analysis provides insight into the overall impact of different training variables on muscular strength and hypertrophy to LI-BFR training. Although only 11 studies met the inclusion criteria for this meta-analysis, general recommendations can be made from the results and patterns observed from this study. This analysis provides evidence and recommendations for future studies to use in order to maximize the muscular strength and hypertrophy response to this novel mode of training. It appears that blood flow restriction combined with low intensity resistance exercise produces a much greater response than blood flow restricted walking. Furthermore, LI-BFR training 2–3 days per week appears to maximize the training adaptation and there is some evidence that the neural adaptation to LI-BFR training does not occur at the beginning of a training program as it does with traditional resistance training. It appears that initial increases in strength may be due solely to muscle hypertrophy, while the neural impact on strength gains may occur much later with LI-BFR training. Although this finding may be true with LI-BFR training, longer-term studies are needed before a definitive conclusion can be made.

**Conflict of interest** The authors report no conflict of interest.

## References

Abe T, Beekley MD, Hinata S, Koizumi K, Sato Y (2005a) Day-to-day change in muscle strength and MRI-measured skeletal muscle size during 7 days KAATSU resistance training: a case study. Int J KAATSU Train Res 1(2):71–76

Abe T, Fujita S, Nakajima T, Sakamaki M, Ozaki H, Ogasawara R, Sugaya M, Kurano M, Yasuda T, Sato Y, Ohshima H, Mukai C, Ishii N (2010a) Effects of low-intensity cycle training with restricted leg blood flow on thigh muscle volume and $VO_{2max}$ in young men. J sports Sci Med 9:452–458

Abe T, Kawamoto K, Yasuda T, Kearns CF, Midorikawa T, Sato Y (2005b) Eight days KAATSU-resistance training improved sprint but not jump performance in collegiate male track and field athletes. Int J KAATSU Train Res 1(1):19–23

Abe T, Kearns CF, Fujita S, Sakamaki M, Sato Y, Brechue WF (2009) Skeletal muscle size and strength are increased following walk training with restricted leg muscle blood flow: implications for training duration and frequency. Int J KAATSU Train Res 5(1):9–15

Abe T, Kearns CF, Sato Y (2006) Muscle size and strength are increased following walk training with restricted venous blood flow from the leg muscle, Kaatsu-walk training. J Appl Physiol 100(5):1460–1466

Abe T, Sakamaki M, Fujita S, Ozaki H, Sugaya M, Sato Y, Nakajima T (2010b) Effects of low-intensity walk training with restricted leg blood flow on muscle strength and aerobic capacity in older adults. J Geriatr Phys Ther 33(1):34–40

Abe T, Yasuda T, Midorikawa T, Sato Y, Kearns CF, Inoue K, Koizumi K, Ishii N (2005c) Skeletal muscle size and circulating IGF-1 are increased after two weeks of twice daily “KAATSU” resistance training. Int J KAATSU Train Res 1(1):6–12

ACSM (2009) American College of Sports Medicine position stand. Progression models in resistance training for healthy adults. Med Sci Sports Exerc 41(3):687–708

Beekley MD, Sato Y, Abe T (2005) KAATSU-walk training increases serum bone-specific alkaline phophatase in young men. Int J KAATSU Train Res 1(2):77–81

Clark BC, Manini TM, Hoffman RL, Williams PS, Guiler MK, Knutson MJ, McGlynn ML, Kushnick MR (2010) Relative safety of 4 weeks of blood flow-restricted resistance exercise in young, healthy adults. Scand J Med Sci Sports. doi:10.1111/j.1600-0838.2010.01100

Cook SB, Brown KA, Deruisseau K, Kanaley JA, Ploutz-Snyder LL (2010) Skeletal muscle adaptations following blood flow-restricted training during 30 days of muscular unloading. J Appl Physiol 109(2):341–349

Crenshaw AG, Hargens AR, Gershuni DH, Rydevik B (1988) Wide tourniquet cuffs more effective at lower inflation pressures. Acta Orthop Scand 59(4):447–451

Evans C, Vance S, Brown M (2010) Short-term resistance training with blood flow restriction enhances microvascular filtration capacity of human calf muscles. J Sports Sci 28(9):999–1007

Fujita S, Brechue WF, Kurita K, Sato Y, Abe T (2008) Increased muscle volume and strength following six days of low-intensity resistance training with restricted muscle blood flow. Int J KAATSU Train Res 4(1):1–8

Gualano B, Neves M Jr, Lima FR, Pinto AL, Laurentino G, Borges C, Baptista L, Artioli GG, Aoki MS, Moriscot A, Lancha AH Jr, Bonfa E, Ugrinowitsch C (2010) Resistance training with vascular occlusion in inclusion body myositis: a case study. Med Sci Sports Exerc 42(2):250–254

Haussinger D (1996) The role of cellular hydration in the regulation of cell function. Biochem J 313(Pt 3):697–710

Ishii N, Madarame H, Odagiri K, Naganuma M, Shinoda K (2005) Circuit training without external load induces hypertrophy in lower-limb muscles when combined with moderate venous occlusion. Int J KAATSU Train Res 1:24–28

Ivey FM, Roth SM, Ferrell RE, Tracy BL, Lemmer JT, Hurlbut DE, Martel GF, Siegel EL, Fozard JL, Jeffrey Metter E, Fleg JL, Hurley BF (2000) Effects of age, gender, and myostatin genotype on the hypertrophic response to heavy resistance strength training. J Gerontol A Biol Sci Med Sci 55(11):M641–M648

Kacin A, Strazar K (2011) Frequent low-load ischemic resistance exercise to failure enhances muscle oxygen delivery and endurance capacity. Scand J Med Sci Sports. doi:10.1111/j.1600-0838.2010.01260.x

Kaijser L, Sundberg CJ, Eiken O, Nygren A, Esbjornsson M, Sylven C, Jansson E (1990) Muscle oxidative capacity and work performance after training under local leg ischemia. J Appl Physiol 69(2):785–787

Karabulut M, Abe T, Sato Y, Bemben MG (2010) The effects of low-intensity resistance training with vascular restriction on leg muscle strength in older men. Eur J Appl Physiol 108(1):147–155

Karabulut M, Bemben DA, Sherk VD, Anderson MA, Abe T, Bemben MG (2011) Effects of high-intensity resistance training and low-intensity resistance training with vascular restriction on bone markers in older men. Eur J Appl Physiol. doi:10.1007/s00421-010-1796-9

Kim SJ, Sherk VD, Bemben MG, Bemben DA (2009) Effects of short-term, low-intensity resistance training with vascular restriction on arterial compliance in untrained young men. Int J KAATSU Train Res 5(1):1–8

Krieger JW (2010) Single vs. multiple sets of resistance exercise for muscle hypertrophy: a meta-analysis. J Strength Cond Res 24(4):1150–1159

Loenneke JP, Pujol TJ (2009) The use of occlusion training to produce muscle hypertrophy. Strength Cond J 31(3):77–84

Loenneke JP, Pujol TJ (2011) Sarcopenia: an emphasis on occlusion training and dietary protein. Hippokratia 15(2):132–137

Loenneke JP, Wilson GJ, Wilson JM (2010) A mechanistic approach to blood flow occlusion. Int J Sports Med 31(1):1–4

Loenneke JP, Wilson JM, Wilson GJ, Pujol TJ, Bemben MG (2011) Potential safety issues with blood flow restriction training. Scand J Med Sci Sports 21(4):510–518

Madarame H, Neya M, Ochi E, Nakazato K, Sato Y, Ishii N (2008) Cross-transfer effects of resistance training with blood flow restriction. Med Sci Sports Exerc 40(2):258–263

Manini TM, Clark BC (2009) Blood flow restricted exercise and skeletal muscle health. Exerc Sport Sci Rev 37(2):78–85

Nygren AT, Sundberg CJ, Goransson H, Esbjornsson-Liljedahl M, Jansson E, Kaijser L (2000) Effects of dynamic ischaemic training on human skeletal muscle dimensions. Eur J Appl Physiol 82(1–2):137–141

Ohta H, Kurosawa H, Ikeda H, Iwase Y, Satou N, Nakamura S (2003) Low-load resistance muscular training with moderate restriction of blood flow after anterior cruciate ligament reconstruction. Acta Orthop Scand 74(1):62–68

Ozaki H, Miyachi M, Nakajima T, Abe T (2011) Effects of 10 weeks walk training with leg blood flow reduction on carotid arterial compliance and muscle size in the elderly adults. Angiology 62(1):81–86

Park S, Kim JK, Choi HM, Kim HG, Beekley MD, Nho H (2010) Increase in maximal oxygen uptake following 2-week walk training with blood flow occlusion in athletes. Eur J Appl Physiol 109(4):591–600

Patterson SD, Ferguson RA (2010) Increase in calf post-occlusive blood flow and strength following short-term resistance exercise training with blood flow restriction in young women. Eur J Appl Physiol 108(5):1025–1033

Rhea MR (2004) Determining the magnitude of treatment effects in strength training research through the use of the effect size. J Strength Cond Res 18(4):918–920

Rhea MR, Alvar BA, Burkett LN, Ball SD (2003) A meta-analysis to determine the dose response for strength development. Med Sci Sports Exerc 35(3):456–464

Sakuraba K, Ishikawa T (2009) Effect of isokinetic resistance training under a condition of restricted blood flow with pressure. J Orthop Sci 14(5):631–639

Sale DG (1988) Neural adaptation to resistance training. Med Sci Sports Exerc 20(5 Suppl):S135–S145

Sata S (2005) Kaatsu training for patella tendinitis patient. Int J KAATSU Train Res 1(1):29–32

Shinohara M, Kouzaki M, Yoshihisa T, Fukunaga T (1998) Efficacy of tourniquet ischemia for strength training with low resistance. Eur J Appl Physiol Occup Physiol 77(1–2):189–191

Suga T, Okita K, Morita N, Yokota T, Hirabayashi K, Horiuchi M, Takada S, Omokawa M, Kinugawa S, Tsutsui H (2010) Dose effect on intramuscular metabolic stress during low-intensity resistance exercise with blood flow restriction. J Appl Physiol 108(6):1563–1567

Sumide T, Sakuraba K, Sawaki K, Ohmura H, Tamura Y (2009) Effect of resistance exercise training combined with relatively low vascular occlusion. J Sci Med Sport 12(1):107–112

Sundberg CJ, Eiken O, Nygren A, Kaijser L (1993) Effects of ischaemic training on local aerobic muscle performance in man. Acta Physiol Scand 148(1):13–19

Takarada Y, Sato Y, Ishii N (2002) Effects of resistance exercise combined with vascular occlusion on muscle function in athletes. Eur J Appl Physiol 86(4):308–314

Takarada Y, Takazawa H, Sato Y, Takebayashi S, Tanaka Y, Ishii N (2000) Effects of resistance exercise combined with moderate vascular occlusion on muscular function in humans. J Appl Physiol 88(6):2097–2106

Takarada Y, Tsuruta T, Ishii N (2004) Cooperative effects of exercise and occlusive stimuli on muscular function in low-intensity resistance exercise with moderate vascular occlusion. Jpn J Physiol 54(6):585–592

Wernbom M, Augustsson J, Raastad T (2008) Ischemic strength training: a low-load alternative to heavy resistance exercise? Scand J Med Sci Sports 18(4):401–416

Yasuda T, Abe T, Sato Y, Midorikawa T, Kearns CF, Inoue K, Ryushi T, Ishii N (2005) Muscle fiber cross-sectional area is increased after two weeks of twice daily KAATSU-resistance training. Int J KAATSU Train Res 1(2):65–70

Yasuda T, Fujita S, Ogasawara R, Sato Y, Abe T (2010) Effects of low-intensity bench press training with restricted arm muscle blood flow on chest muscle hypertrophy: a pilot study. Clin Physiol Funct Imaging 30(5):338–343

Yasuda T, Ogasawara R, Sakamaki M, Ozaki H, Sato Y, Abe T (2011) Combined effects of low-intensity blood flow restriction training and high-intensity resistance training on muscle strength and size. Eur J Appl Physiol. doi:10.1007/s00421-011-1873-8