Geng *et al. Sports Medicine - Open* (2024) 10:58
https://doi.org/10.1186/s40798-024-00719-3

Sports Medicine - Open

**SYSTEMATIC REVIEW** **Open Access**

# Potential Moderators of the Effects of Blood Flow Restriction Training on Muscle Strength and Hypertrophy: A Meta-analysis Based on a Comparison with High-Load Resistance Training

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## Abstract

**Background** While it has been examined whether there are similar magnitudes of muscle strength and hypertrophy adaptations between low-load resistance training combined with blood-flow restriction training (BFR-RT) and high-load resistance training (HL-RT), some important potential moderators (e.g., age, sex, upper and lower limbs, frequency and duration etc.) have yet to be analyzed further. Furthermore, training status, specificity of muscle strength tests (dynamic versus isometric or isokinetic) and specificity of muscle mass assessments (locations of muscle hypertrophy assessments) seem to exhibit different effects on the results of the analysis. The role of these influencing factors, therefore, remains to be elucidated.

**Objectives** The aim of this meta-analysis was to compare the effects of BFR- versus HL-RT on muscle adaptations, when considering the influence of population characteristics (training status, sex and age), protocol characteristics (upper or lower limbs, duration and frequency) and test specificity.

**Methods** Studies were identified through database searches based on the following inclusion criteria: (1) pre- and post-training assessment of muscular strength; (2) pre- and post-training assessment of muscular hypertrophy; (3) comparison of BFR-RT vs. HL-RT; (4) score $\geq 4$ on PEDro scale; (5) means and standard deviations (or standard errors) are reported or allow estimation from graphs. In cases where the fifth criterion was not met, the data were requested directly from the authors.

**Results** The main finding of the present study was that training status was an important influencing factor in the effects of BFR-RT. The trained individuals may gain greater muscle strength and hypertrophy with BFR-RT as compared to HL-RT. However, the results showed that the untrained individuals experienced similar muscle mass gains and superior muscle strength gains in with HL-RT compared to BFR-RT.

**Conclusion** Compared to HL-RT, training status is an important factor influencing the effects of the BFR-RT, in which trained can obtain greater muscle strength and hypertrophy gains in BFR-RT, while untrained individuals can obtain greater strength gains and similar hypertrophy in HL-RT.

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**Key Points**

Training status is an important factor influencing the effects of the BFR-RT.

Trained individuals may obtain greater muscle strength and hypertrophy gains in BFR-RT compared to HL-RT.

Untrained individuals may experience a smaller increase in strength and a similar increase in hypertrophy with BFR-RT compared to HL-RT.

**Keywords** Blood flow restriction training, High-load resistance training, Training effect, Strength, Hypertrophy, Training status, Protocol characteristics, Test specificity, Meta-analysis

## Background

High-load resistance training (HL-RT) has long been considered as the “gold standard” protocol to increase muscle strength and mass. It has been suggested that ≥ 65% one-repetition maximum (1RM) is required to increase strength and hypertrophy [1–3]. However, mounting evidence indicates that the use of low-load resistance training (< 50% 1RM) combined with blood flow restriction (BFR-RT) results in strength and morphological responses [4]. The results of a previous study showed that low load resistance training with and without blood flow resulted in similar adaptations when sets of exercise were taken to failure [5], however the results of multiple studies showed the superiority of BFR-RT in terms of gains in muscle strength and hypertrophy when compared with similar low-load resistance training without blood flow restriction [6–8]. However, the literature is controversial about the magnitude of the adaptations when comparing BFR-RT to HL-RT. For example, some studies have reported greater increases in muscle strength for HL-RT when comparing to BFR-RT [9–13], while others have suggested similar gains between the two exercise protocols [14–17]. Moreover, some studies have reported that BFR-RT has higher muscle strength gains than HL-RT [18, 19]. Some studies compared the effects of BFR-RT and HL-RT through meta-analysis [20, 21]. In the meta-analysis by Lixandrão et al., they observed that BFR-RT and HL-RT have similar gains in muscle hypertrophy, while HL-RT is more effective in increasing muscle strength [20]. However, limited by the number of studies comparing BFR and HL-RT at that time, some important potential moderators (e.g., training frequency, etc.) could not be further explored [20].

The increase in muscle strength is the result of the coordination of nerve and muscle systems [22]. It is believed that neural adaptation dominates early in the training programme; later, as neural adaptations reach a plateau, muscular adaptation (hypertrophy) dominates [23]. At this stage, in intermediate and advanced training, progress is limited to the extent of muscular adaptation that can be achieved [23]. It has been believed that BFR-RT provides a potential time-effective approach to stimulate muscle adaptations [8, 24, 25], and even well-trained athletes may benefit from BFR-RT [26]. Thus, compared to HL-RT, training status and training duration may be a key factor affecting the effectiveness of BFR-RT. Additionally, the results of several studies have showed that compared with HL-RT, BFR-RT induced less hypertrophy in the proximal region [17, 27, 28]. Therefore, this regional specificity may be another influencing factor. Finally, HL-RT implies high-load exercise, which is similar to specific strength assessments (i.e., 1RM test), while during BFR-RT, participants are never exposed to high loads [29]. Thus, non-specific strength assessments (i.e., isometric or isokinetic tests) may more accurately reflect the response to the low-load training protocols [29]. In this regard, test specificity may also affect the results.

In short, the inconsistencies in the literature regarding effects of BFR-RT compared with HL-RT on the muscle strength and hypertrophy justify the need for synthesis and a comprehensive review of the available evidence. Therefore, based on previous studies, the purpose of this study was to conduct a meta-analysis comparing the responses of BFR-RT and HL-RT on muscle strength and hypertrophy. To further explore the effects on muscle strength and hypertrophy of these protocols, we will also consider potential influence factors such as population characteristics (i.e., training status, sex and age), protocol characteristics (i.e., upper or lower limbs, duration and frequency), test specificity (i.e., 1RM and spacing or equal speed testing), and region-specific adaptations in muscle mass.

## Methods

### Search Strategy and Study Selection

The articles were identified through the English databases Web of Knowledge, PubMed, EBSCO-SPORTDiscus from the earliest record up to February 2024, and the Chinese database WANFANG DATA, CNKI from the earliest record up to February 2024. The search strategy combined the English and Chinese terms (see Additional file 1: Table S1). Two reviewers (GY and ZY) evaluated the titles and abstracts of the retrieved articles to assessed their eligibility for the meta-analysis. In cases of differences, a consensus was adopted. If necessary, the third reviewer (WXP) evaluated the article. If the abstract did not provide sufficient information about the inclusion criteria, the reviewers read the full text.

### Eligibility Criteria

Studies were considered for inclusion if they met the following criteria: (1) articles were published in English or Chinese; (2) subjects were healthy people, (3) pre- and post-intervention assessment of muscular strength (i.e., dynamic, isometric or isokinetic test); (4) pre- and post-intervention assessment of muscle hypertrophy (i.e., magnetic resonance imaging, computerized tomography, or ultrasonography); (5) comparisons between HL-RT (i.e., >65%1RM) and BFR-RT (i.e., <50%1RM); (6) score ≥ 4 on the Physiotherapy Evidence Database (PEDro) scale.

### Study Quality

The quality of the study was determined by using the PEDro scale, based on the Delphi list [30]. Studies with a score ≥ 4 were included in this meta-analysis (see Additional file 1: Table S2). For each of the items (2–11) of the PEDro scale, two reviewers (GY and ZY) assessed the studies independently. In cases of disagreement, a consensus was adopted or a third reviewer (WXP) evaluated the study.

### Data Extraction

After screening of the studies, all included studies were assessed for eligibility based on their full texts. Two reviewers (GY and ZY) extracted data from the articles independently; in cases of disagreement, if no consensus could be reached, a third reviewer (WXP) was consulted. The data extracted were recorded relating to (1) population characteristics (i.e., age, sex and training status); (2) intervention protocol characteristics (i.e., duration, frequency, training load, volume, exercises etc.); (3) pre- and post-intervention assessment of muscle strength (i.e., dynamic, isometric, or isokinetic test); (4) pre- and post-intervention assessment of muscle hypertrophy (cross-sectional area [CSA], muscle thickness and muscle mass). The trained individuals were defined as athletes or individuals who participated in regular resistance training protocols before the intervention. The untrained individuals were defined as individuals who were sedentary or did not participate in regular resistance training protocols before the interventions. In cases of incomplete data availability, we extrapolated the data from figures or contacted the corresponding author. The graphical data were extracted using the OriginPro 2021 (Version 2021. OriginLab Corporation, Northampton, MA, USA) graphical digitizing tool. Only the last was included as the post-intervention value for analysis, when intervention effects were assessed at multiple time points. When intervention effects were measured through multiple measurement methods (e.g., CSA and muscle thickness for muscle size), the multiple outcomes were combined (i.e., using the mean of the outcomes) [31]. The combination was performed by Comprehensive Meta-Analysis software (version 3.3, Biostat, Inc., Englewood, NJ, USA). The extracted data of included studies are provided in Tables 1 and 2.

### Statistical Analyses

All analyses were performed using Comprehensive Meta-Analysis software (version 3.3, Biostat, Inc., Englewood, NJ, USA). The comparisons (BFR-RT vs. HL-RT) were calculated as the effect size difference ($ES_{diff}$) using the difference in pre- and post- intervention mean and standard deviation values of muscle strength and mass, sample size and correlation between pre- and post-test for all groups. If the studies included in the meta-analysis did not report correlation between pre- and post-test, the following formula was used for estimation [20, 72]:

$$r = \frac{S_{pre}^2 + S_{post}^2 - SD^2}{2 \times S_{pre} \times S_{post}}$$

where $S_{pre}$ and $S_{post}$ are the standard deviation of pre-test and post-test, respectively. SD is the standard deviation of difference between pre- and post-test calculated using the following formula [1, 20]:

$$SD = \sqrt{\frac{S_{pre}^2}{n} + \frac{S_{post}^2}{n}}$$

Using the correction factor to correct the small sample size bias of all $ES_{diff}$ [20, 31]. The correction factor is given by:

$$\text{Correction factor} = 1 - \frac{3}{4 \times (n_1 + n_2 - 2) - 1}$$

The subjects of the studies included in the present meta-analysis came from different populations. Moreover, different training protocols and various strength and hypertrophy measurements and variables were utilized in these studies. All factors may have an impact on the effect of the intervention. Thus, the random-effects model was used to perform the meta-analysis [73]. The $I^2$ statistics was used to assess heterogeneity. $I^2$ values of 25%, 50% and 75% were set as low, moderate and high levels of heterogeneity, respectively. [74].

The first step was to compare the effects of BFR-RT and HL-RT on muscle strength and muscle mass. Subsequently, subgroup analyses were conducted to examine

**Table 1** Characteristics of studies included in the meta-analysis of muscle strength adaptations

| References | Age | Training Status | N | Exercise | Protocol | Weeks (times/wk) | Exercise load | Occlusion pressure | Muscle strength assessment |
|---|---|---|---|---|---|---|---|---|---|
| Bjornsen et al. [26] | 24 | Trained | 9 | SQ | BFR-RT:30–15-12–8 | 2(5) | 24–30%1RM | 120mmHg | Dynamic SQ<br>Isometric KE |
| | 26 | | 8 | | HL-RT:6–7 × 1–6 | 2(5) | 74–76%1RM | | |
| Buckner et al. [32] | 18–35 | Untrained | 20 | BC | BFR-RT1:4 × failure | 8(2) | 15%1RM | 57mmHg | Dynamic BC<br>Isometric BC<br>Isokinetic BC (60°/s, 180°/s) |
| | 18–35 | | 20 | | BFR-RT2:4 × failure | 8(2) | 15%1RM | 110mmHg | |
| | 18–35 | | 20 | | HL-RT:4 × failure | 8(2) | 70%1RM | | |
| Centner et al. [33] | 27 | Untrained | M11 | CR | BFR-RT:30–15-15–15 | 14(3) | 20–35%1RM | 50%AOP | Isometric CR |
| | 26 | | M14 | | HL-RT:3 × 6–12 | 14(3) | 70–80%1RM | | |
| Centner et al. [28] | 28 | Untrained | M14 | LP, KE, CR | BFR-RT:30–15-15–15 | 14(3) | 20–35%1RM | 50%AOP | Dynamic LP & KE |
| | 28 | | M15 | | HL-RT:3 × 6–12 | 14(3) | 70–85%1RM | | |
| Clark et al. [14] | 24 | Untrained | 9 | KE | BFR-RT:3 × 30–50 | 4(3) | 30%1RM | 170mmHg | Isometric KE |
| | 24 | | 7 | | HL-RT:3 × 8–12 | 4(3) | 80%1RM | | |
| Cook et al. [34] | 77 | Untrained | 12 | KE, KF, LP | BFR-RT: ~ 3 × 30 | 12(2) | 30%1RM | 184 ± 25mmHg | Dynamic KE, KF & LP<br>Isometric KE |
| | 77 | | 12 | | HL-RT: ~ 3 × 15 | 12(2) | 70%1RM | | |
| Cook et al. [35] | 18–22 | Untrained | 6 | KE, LP | BFR-RT:2 × 25,1 × failure | 6(3) | 20%1RM | 180-200mmHg | Dynamic KE<br>Isometric KE |
| | 18–22 | | 6 | | HL-RT:2 × 10,1 × failure | 6(3) | 70%1RM | | |
| Davids et al. [36] | 24 | Trained | 11 | SQ, LP, KE, SSQ | BFR-RT:30 + 2–3 × 15 | 9(3) | 30–40%1RM | 60%AOP | Dynamic SQ<br>Isometric KE & KF |
| | 24 | | 10 | | HL-RT:3–4 × 8 | 9(3) | 75–80%1RM | | |
| de Lemos Muller et al. [37] | 24 | Untrained | M13 | BC, KE | BFR-RT:4 × 22 | 8(3) | 30%1RM | 110-150mmHg | Dynamic BC & KE |
| | 25 | | M13 | | HL-RT:4 × 8 | 8(3) | 80%1RM | | |
| Ellefsen et al. [17] | 23 | Untrained | M12 | KE | BFR-RT:5 × failure | 12(2) | 30%1RM | 90-100mmHg | Dynamic KE |
| | 23 | | M12 | | HL-RT:3 × 6–10 | 12(2) | 75–90%1RM | | |
| Fernandes et al. [38] | 20 | Untrained | F14 | GS | BFR-RT:3 × 15–25 | 4(3) | 45%1RM | 160mmHg | Isometric GS |
| | 20 | | F14 | | HL-RT:3 × 8–12 | 4(3) | 75%1RM | | |
| Jessee et al. [39] | 21 | Untrained | 10 | KE | BFR-RT1:4 × failure | 8(2) | 15%1RM | 40%AOP | Dynamic KE<br>Isometric KE<br>Isokinetic KE (60°/s, 180°/s) |
| | 21 | | 10 | | BFR-RT2:4 × failure | 8(2) | 15%1RM | 80%AOP | |
| | 21 | | 10 | | HL-RT:4 × failure | 8(2) | 70%1RM | | |
| Karabulut et al. [9] | 57 | Untrained | M13 | LP, KE | BFR-RT:30–15-15 | 6(3) | 20%1RM | 205mmHg | Dynamic LP & KE |
| | 57 | | M13 | | HL-RT:3 × 8 | 6(3) | 80%1RM | | |
| Kim et al. [40] | 26 | Untrained | M10 | LP, KE, KF | BFR-RT:2 × 10 | 3(3) | 20%1RM | 178 ± 20mmHg | Dynamic LP, KE & KF |
| | 22 | | M10 | | HL-RT:2 × 10 | 3(3) | 80%1RM | | |
| Kim et al. [41] | 21 | Untrained | M9 | BC | BFR-RT:30–15-15–15 | 8(3) | 30%1RM | 72 ± 11mmHg | Dynamic BC<br>Isometric BC |
| | 21 | | M9 | | HL-RT:3 × 10 | 8(3) | 75%1RM | | |

**Table 1** (continued)

| References | Age | Training Status | N | Exercise | Protocol | Weeks (times/wk) | Exercise load | Occlusion pressure | Muscle strength assessment |
|---|---|---|---|---|---|---|---|---|---|
| Kim et al. [42] | 63 | Untrained | 9 | GS | BFR-RT:3 × failure | 4(3) | 20%1RM | 160mmHg | Isometric GS |
| | 63 | | 10 | | HL-RT:3 × failure | 4(3) | 75%1RM | | |
| Korkmaz et al. [43] | 18 | Trained | M11 | KE | BFR-RT:30–15-15–15 | 6(2) | 30%1RM | 130-150mmHg | Isokinetic KE (60°/s, 80°/s) |
| | 18 | | M12 | | HL-RT:4 × 12 | 6(2) | 80%1RM | | |
| Kubo et al. [10] | 25 | Untrained | M9 | KE | BFR-RT:25–18-15–12 | 12(3) | 20%1RM | 180-240mmHg | Isometric KE |
| | 25 | | M9 | | HL-RT:4 × 10 | 12(3) | 80%1RM | | |
| Laswati et al. [44] | 33 | Untrained | M6 | BC | BFR-RT:30–15-15-15 | 5(2) | 30%1RM | 50mmHg | Isokinetic BC (60°/s) |
| | 33 | | M6 | | HL-RT:3 × 12 | 5(2) | 70%1RM | | |
| Laurentino et al. [15] | 20 | Untrained | M10 | KE | BFR-RT:3–4 × 15 | 8(2) | 20%1RM | 95 ± 10mmHg | Dynamic KE |
| | 24 | | M9 | | HL-RT:3–4 × 8 | 8(2) | 80%1RM | | |
| Letieri et al. [45] | 68 | Untrained | F11 | SQ, LP, KE, KF | BFR-RT1:30–15-15 | 16(3) | 20–30%1RM | 188 ± 5mmHg | Isokinetic KE & KF (60°/s) |
| | 69 | | F10 | | BFR-RT2:30–15-15 | 16(3) | 20–30%1RM | 105 ± 7mmHg | |
| | 67 | | F11 | | HL-RT:3–4 × 6–8 | 16(3) | 70–80%1RM | | |
| Libardi et al. [46] | 64 | Untrained | 10 | LP | BFR-RT:30–15-15–15 | 12(2) | 20–30%1RM | 67 ± 8mmHg | Dynamic LP |
| | 65 | | 8 | | HL-RT:4 × 10 | 12(2) | 70–80%1RM | | |
| Lixandrao et al. [47] | 26 | Untrained | M11 | KE | BFR-RT1:2–3 × 15 | 12(2) | 20%1RM | 56 ± 8mmHg | Dynamic KE |
| | 29 | | M14 | | BFR-RT2:2–3 × 15 | 12(2) | 20%1RM | 110 ± 9mmHg | |
| | 26 | | M8 | | BFR-RT3:2–3 × 15 | 12(2) | 40%1RM | 55 ± 5mmHg | |
| | 29 | | M10 | | BFR-RT4:2–3 × 15 | 12(2) | 40%1RM | 1055 ± 19mmHg | |
| | 29 | | M9 | | HL-RT:2–3 × 10 | 12(2) | 80%1RM | | |
| Luebbers et al. [48] | 16–17 | Trained | M8 | SQ | BFR-RT:30–15-15-15 | 6(2) | 20%1RM | | Dynamic SQ |
| | 16–17 | | M9 | | HL-RT:3 × 10 | 6(2) | 78%1RM | | |
| Martin-Hernandez et al. [12] | 20 | Untrained | M10 | KE | BFR-RT1:30–15-15–15 | 5(2) | 20%1RM | 110mmHg | Dynamic KE<br>Isokinetic KE (60°/s, 80°/s) |
| | 21 | | M10 | | BFR-RT2:2 × (30–15-15–15) | 5(2) | 20%1RM | 110mmHg | |
| | 21 | | M11 | | HL-RT:3 × 8 | 5(2) | 85%1RM | | |
| May et al. [49] | 24 | Untrained | M8 | KE, KF | BFR-RT:30–15-15-15 | 7(3) | 20%1RM | 128mmHg | Dynamic KE & KF |
| | 24 | | M9 | | HL-RT:4 × 8 | 7(3) | 70%1RM | | |
| Mendonca et al. [50] | 22 | Untrained | 15 | CR | BFR-RT:30–15-15-15 | 4(5) | 20%1RM | 60%AOP | Isometric CR |
| | 22 | | 15 | | HL-RT:4 × 10 | 4(5) | 75%1RM | | |
| Morley et al. [51] | 24 | Untrained | 7 | KE | BFR-RT1:3 × 10–12 + 1 × failure | 8(3) | 20%1RM | 100%AOP | Dynamic KE<br>Isometric KE |
| | 21 | | 6 | | BFR-RT2:3 × 10–12 + 1 × failure | 8(3) | 20%1RM | 50%AOP | |
| | 21 | | 7 | | HL-RT:3 × 10–12 + 1 × failure | 8(3) | 70%1RM | | |
| Ozaki et al. [16] | 23 | Untrained | M10 | BP | BFR-RT:30–15-15–15 | 6(3) | 30%1RM | 100-160mmHg | Dynamic BP |
| | 24 | | M9 | | HL-RT:3 × 10 | 6(3) | 75%1RM | | |
| Ramis et al. [52] | 24 | Untrained | M15 | BC, KE | BFR-RT:4 × 23 | 8(3) | 30%1RM | 110-150mmHg | Isometric BC & KE |
| | 25 | | M13 | | HL-RT:4 × 8 | 8(3) | 80%1RM | | Isokinetic BC & KE (60°/s) |

**Table 1** (continued)

| References | Age | Training Status | N | Exercise | Protocol | Weeks (times/wk) | Exercise load | Occlusion pressure | Muscle strength assessment |
|---|---|---|---|---|---|---|---|---|---|
| Sharifi et al. [53] | 21 | Untrained | M8 | LP, KE, KF, CP, BC | BFR-RT:9 × 20 | 6(3) | 20–30%1RM | 110-160mmHg | Dynamic LP & CP |
| | 19 | | M8 | | HL-RT:9 × 10 | 6(3) | 70–80%1RM | | |
| | 21 | | M8 | | BFR-RT:9 × 20 | 6(6) | 20–30%1RM | 110-160mmHg | |
| | 19 | | M8 | | HL-RT:9 × 10 | 6(6) | 70–80%1RM | | |
| Shiromaru et al. [54] | 23 | Untrained | M15 | KE | BFR-RT:3 × 15 | 3(4) | 30%1RM | 80%AOP | Dynamic KE |
| | 23 | | M15 | | HL-RT:3 × 10 | 6(2) | 80%1RM | | |
| Sousa et al. [55] | 24 | Untrained | 10 | KE | BFR-RT:3 × failure | 6(2) | 30%1RM | 142 ± 122mmHg | Isometric KE |
| | 21 | | 11 | | HL-RT:3 × failure | 6(2) | 80%1RM | | |
| Sugiarto et al. [56] | 26–45 | Untrained | M6 | BC | BFR-RT:30–15-15–15 | 5(2) | 30%1RM | 50mmHg | Isokinetic KE (60°/s, 120°/s, 180°/s) |
| | 26–45 | | M6 | | HL-RT:3 × 12 | 5(2) | 75%1RM | | |
| Teixeira et al. [57] | 24 | Untrained | M8 | KE | BFR-RT:3 × 15 | 8(2) | 20%1RM | 80%AOP | Dynamic KE |
| | 24 | | M8 | | HL-RT:3 × 8 | 8(2) | 70%1RM | | |
| Thiebaud et al. [58] | 59 | Untrained | F6 | CP, SR, SHP | BFR-RT:30–15-15 | 8(3) | 10–30%1RM | 80-120mmHg | Dynamic CP, SR & SHP |
| | 62 | | F8 | | HL-RT:3 × 10 | 8(3) | 70–90%1RM | | |
| Vechin et al. [13] | 62 | Untrained | M8 | LP | BFR-RT:30–15-15–15 | 12(2) | 20–30%1RM | 71 ± 9mmHg | Dynamic LP |
| | 65 | | M8 | | HL-RT:4 × 10 | 12(2) | 70–80%1RM | | |
| Yasuda et al. [11] | 22–32 | Untrained | M10 | BP, EE | BFR-RT:30–15-15–15 | 6(3) | 30%1RM | 100-160mmHg | Dynamic BP<br>Isometric EE |
| | 22–32 | | M10 | | HL-RT:3 × 10 | 6(3) | 75%1RM | | |
| Che et al. [19] | 18 | Trained | F8 | SQ | BFR-RT:30–15-15–15 | 6(3) | 30%1RM | 180mmHg | Dynamic SQ<br>Isokinetic KE & KF (60°/s, 180°/s) |
| | 17 | | F8 | | HL-RT:4 × 8–10 | 6(3) | 75%1RM | | |
| Shanghua et al. [59] | 21 | Trained | M12 | LP | BFR-RT:5 × 12 | 8(3) | 40%1RM | 200mmHg | Isokinetic KE & KF (60°/s, 180°/s) |
| | 22 | | M12 | | HL-RT:5 × 12 | 8(3) | 70%1RM | | |
| Li et al. [18] | 22 | Trained | M8 | SQ, SSQ, DF | BFR-RT:30–15-15–15 | 4(3) | 30%1RM | 200mmHg | Dynamic SQ<br>Isokinetic KE & KF (60°/s) |
| | 22 | | M8 | | HL-RT:4 × 8–12 | 4(3) | 70%1RM | | |
| Li et al. [60] | 20 | Trained | M10 | BP, SQ | BFR-RT:30–15-15–15 | 6(2) | 30%1RM | 160-200mmHg | Dynamic SQ & BP |
| | 20 | | M10 | | HL-RT:4 × 12 | 6(2) | 70%1RM | | |
| Wang et al. [61] | 24 | Trained | M9 | SQ, SSQ, DF | BFR-RT:4 × 20–30 | 8(3) | 30%1RM | 200-220mmHg | Isokinetic KE & KF (60°/s) |
| | 24 | | M9 | | HL-RT:4 × 12 | 8(3) | 70%1RM | | |
| Zhang et al. [62] | 23 | Trained | M8 | SQ | BFR-RT1:5 × 10 | 5(2) | 20%1RM | 252mmHg | Dynamic SQ |
| | 24 | | M8 | | BFR-RT2:5 × 11 | 5(2) | 40%1RM | 252mmHg | |
| | 23 | | M8 | | HL-RT:5 × 12 | 5(2) | 75%1RM | | |
| Centner et al. [65] | 28 | Untrained | M14 | CR | BFR-RT:30–15-15–15 | 14(3) | 20–35%1RM | 50%AOP | Dynamic CR |
| | 28 | | M15 | | HL-RT:3 × 6–12 | 14(30 | 70–80%1RM | | |
| De Araujo et al. [66] | 23 | Untrained | M10 | BC | BFR-RT:30–15-15–15 | 6(2) | 30%1RM | 50%AOP | Dynamic BC |
| | 23 | | M10 | | HL-RT:3 × 10–12 | 6(2) | 70%1RM | | |

**Table 1** (continued)

| References | Age | Training Status | N | Exercise | Protocol | Weeks (times/wk) | Exercise load | Occlusion pressure | Muscle strength assessment |
|---|---|---|---|---|---|---|---|---|---|
| Horiuchi et al. [67] | 18–30 | Untrained | M12 | LP, KE | BFR-RT:4 × 20 | 4(4) | 30%1RM | 130%AOP | Dynamic LP & KE |
| | 18–30 | | M12 | | HL-RT:3 × 10 | 4(4) | 75%1RM | | |
| Judd et al. [68] | 20 | Trained | M4 | BC | BFR-RT: 4 × 5 | 6(2) | 30%1RM | 40%AOP | Dynamic BC |
| | 20 | | M4 | | HL-RT: 4 × 5 | 6(2) | 80%1RM | | |
| | 20 | | F4 | | BFR-RT: 4 × 5 | 3(2) | 30%1RM | 40%AOP | |
| | 20 | | F5 | | HL-RT: 4 × 5 | 3(2) | 80%1RM | | |
| Reece et al. [69] | 21 | Untrained | 15 | KE | BFR-RT: 3 × failure | 6(3) | 30%1RM | 50%AOP | Dynamic KE |
| | 22 | | 15 | | HL-RT:3 × failure | 6(3) | 80%1RM | | |
| Sousa-Silva et al. [70] | 21 | Untrained | M9 | BC | BFR-RT:1 × 30 + 2–3 × 15 | 8(2) | 30%1RM | 50%AOP | Dynamic BC |
| | 21 | | M9 | | HL-RT:3–4 × 10–12 | 8(2) | 70%1RM | | |
| Wang et al. [71] | 20 | Trained | M8 | SQ | BFR-RT: 30–15-15–15 | 4(3) | 30%1RM | 200mmHg | Dynamic SQ |
| | 20 | | M8 | | HL-RT;4 × 8–12 | 4(3) | 70%1RM | | |

*M* male, *F* female

*BC* biceps curls, *BP* bench press, *CP* chest press, *DF* deadlift, *EE* elbow extension, *GS* grip strength, *KE* knee extension, *KF* knee flexion, *LP* leg press, *SHP* seated shoulder press, *CR* calf raises, *SQ* squat, *SSQ* split squat, *SR* Seated Rowing

the effects of training status (trained vs. untrained individuals), sex, age, upper and lower limbs, test specificity (i.e. 1RM test vs. isometric or isokinetic tests) and region-specific adaptations of muscle hypertrophy. Based on the average age reported by the included studies, the age subgroups were divided into young ($\leq 33$ year) and old ($\geq 57$ year). Finally, according to the measured position reported by the studies, the results for muscle hypertrophy were categorized into three subgroups: proximal, middle and distal, which were $< 50\%$, $= 50\%$ and $> 50\%$ of the length of the femur or humerus, respectively.

To identify the presence of highly influential studies that might bias the analyses, a sensitivity analysis was performed. The analysis was therefore conducted by removing one study at a time and then examining its effect on comparisons. If removal changed the significance level of $ES_{diff}$ (i.e., from $P \leq 0.05$ to $P > 0.05$, or vice versa), the study was considered as influential. This method has been used elsewhere [75]. The funnel plot, and Begg and Egger's test were used to consider and assess publication bias, respectively. All data are presented as mean ± standard error. The significance level was set at $P \leq 0.05$.

## Results

The initial search retrieved 2801 English studies and Chinese 361studies. Afterwards, 723 duplicated studies were excluded. After evaluation of titles and abstracts, 2376 studies were removed, while the remaining 63 studies were assessed through full texts. Finally, 53 studies were considered to meet the inclusion criteria (Fig. 1), 51 of which were included in the muscle strength analysis (Table 1) and 28 in the muscle hypertrophy analysis (Table 2). In addition, by contacting the authors, the muscle hypertrophy data of one study were obtained [28]. However, after multiple attempts to contact the author, the muscle strength and hypertrophy data for another study were not included as the author did not respond [76].

### Muscle Strength

Fifty-one studies involving 1164 participants were included in the present meta-analysis to compare muscle strength gains. In the studies that investigated the trained population, only one study adopted 9 weeks of training duration and one study adopted a training frequency of 5 sessions per week (Fig. 2).

The overall $ES_{diff}$ demonstrated significantly lower gains in muscle strength for BFR-RT compared with HL-RT ($ES_{diff} = -0.335 \pm 0.092$, 95% confidence interval [CI] −0.515 to −0.156) (Fig. 2 and Table 3). However, when considering training status, the differences between trained and untrained subgroups were significant ($Q = 29.39$, $P < 0.01$) (Table 3). Significantly higher strength gains for BFR-RT were observed compared with HL-RT in the trained group ($ES_{diff} = 0.491 \pm 0.172$, 95% CI 0.154 to 0.827) (Fig. 3 and Table 3). In contrast, the strength gains of HL-RT were significantly higher than that of BFR-RT in the untrained group ($ES_{diff} = -0.552 \pm 0.087$, 95%CL −0.722 to −0.382) (Fig. 3 and Table 3). In trained individuals, there were no significant differences between the different sexes, limbs, durations, frequency and test types (Table 3 and Additional

**Table 2** Characteristics of studies included in the meta-analysis of muscle hypertrophy adaptations

| References | Age | Training Status | N | Exercise | Protocol | Weeks (times/wk) | Exercise load | Occlusion pressure | Muscle mass assessment | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | Method | Muscle groups | Test site |
| Bjornsen et al. [26] | 24 | Trained | 9 | SQ | BFR-RT:30–15-12–8 | 2(5) | 24–30%1RM | 120 mmHg | US | Rectus femoris<br>Vastus lateralis<br>Vastus medialis<br>Vastus intermedius | Distal |
| | 26 | | 8 | | HL-RT: 6–7 × 1–6 | 2(5) | 74–76%1RM | | | | |
| Buckner et al. [32] | 18–35 | Untrained | 20 | BC | BFR-RT1: 4 × failure | 8(2) | 15%1RM | 57 mmHg | US | Upper arm | Mid<br>Distal |
| | 18–35 | | 20 | | BFR-RT2: 4 × failure | 8(2) | 15%1RM | 110 mmHg | | | |
| | 18–35 | | 20 | | HL-RT: 4 × failure | 8(2) | 70%1RM | | | | |
| Centner et al. [33] | 27 | Untrained | M11 | CR | BFR-RT:30–15-15–15 | 14(3) | 20–35%1RM | 50%AOP | US | Gastrocnemius | |
| | 26 | | M14 | | HL-RT:3 × 6–12 | 14(3) | 70–80%1RM | | | | |
| Centner et al. [28] | 28 | Untrained | M14 | LP,KE,CR | BFR-RT:30–15-15–15 | 14(3) | 20–35%1RM | 50%AOP | MRI | Rectus femoris, | Proximal Mid<br>Distal |
| | 27 | | M15 | | HL-RT:3 × 6–12 | 14(3) | 70–85%1RM | | | | |
| Cook et al. [34] | 76 | Untrained | 12 | KE,KF,LP | BFR-RT: ~ 3 × 30 | 12(2) | 30%1RM | 184 ± 25 mmHg | MRI | Quadriceps | |
| | 77 | | 12 | | HL-RT: ~ 3 × 15 | 12(2) | 70%1RM | | | | |
| Cook et al. [35] | 18–22 | Untrained | 6 | KE,LP | BFR-RT:2 × 25, 1 × failure | 6(3) | 20%1RM | 180-200 mmHg | MRI | Quadriceps | |
| | 18–22 | | 6 | | HL-RT:2 × 10, 1 × failure | 6(3) | 70%1RM | | | | |
| Davids et al. [36] | 24 | Trained | 11 | SQ,LP,KE,SSQ | BFR-RT:30 + 2–3 × 15 | 9(3) | 30–40%1RM | 60%AOP | MRI | Quadriceps | |
| | 24 | | 10 | | HL-RT:3–4 × 8 | 9(3) | 75–80%1RM | | | | |
| Ellefsen et al. [18] | 23 | Untrained | M12 | KE | BFR-RT: 5 × failure | 12(2) | 30%1RM | 90-100 mmHg | MRI | Quadriceps | Proximal<br>Distal |
| | 23 | | M12 | | HL-RT:3 × 6–10 | 12(2) | 75–90%1RM | | | | |
| Jessee et al. [41] | 21 | Untrained | 10 | KE | BFR-RT1: 4 × failure | 8(2) | 15%1RM | 40%AOP | US | Quadriceps | Proximal<br>Mid<br>Distal |
| | 21 | | 10 | | BFR-RT2: 4 × failure | 8(2) | 15%1RM | 80%AOP | | | |
| | 21 | | 10 | | HL-RT: 4 × failure | 8(2) | 70%1RM | | | | |
| Kataoka et al. [65] | 23 | Untrained | 27 | CR | BFR-RT:4 × 16–39 | 6(3) | 30%1RM | 40%AOP | US | Gastrocnemius<br>Soleus | |
| | 23 | | 27 | | HL-RT:4 × 12–19 | 6(3) | 70%1RM | | | | |
| Kim et al. [66] | 26 | Untrained | M10 | LP,KE,KF | BFR-RT:2 × 10 | 3(3) | 20%1RM | 178 ± 20 mmHg | CT | Thigh | Mid |
| | 22 | | M10 | | HL-RT:2 × 10 | 3(3) | 80%1RM | | | | |

**Table 2** (continued)

| References | Age | Training Status | N | Exercise | Protocol | Weeks (times/wk) | Exercise load | Occlusion pressure | Muscle mass assessment | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | Method | Muscle groups | Test site |
| Kim et al. [41] | 21 | Untrained | M9 | BC | BFR-RT:30–15-15–15 | 8(3) | 30%1RM | 72 ± 11 mmHg | US | Upper arm | Mid<br>Distal |
| | 21 | | M9 | | HL-RT:3 × 10 | 8(3) | 75%1RM | | | | |
| Korkmaz et al. [43] | 18 | Trained | M11 | KE | BFR-RT:30–15-15–15 | 6(2) | 30%1RM | 130-150 mmHg | US | Rectus femoris<br>Vastus lateralis | Mid |
| | 18 | | M12 | | HL-RT:4 × 12 | 6(2) | 80%1RM | | | | |
| Kubo et al. [10] | 25 | Untrained | M9 | KE | BFR-RT:25–18-15–12 | 12(3) | 20%1RM | 180-240 mmHg | MRI | Quadriceps | |
| | 25 | | M9 | | HL-RT:4 × 10 | 12(3) | 80%1RM | | | | |
| Laurentino et al. [15] | 20 | Untrained | M10 | KE | BFR-RT:3–4 × 15 | 8(2) | 20%1RM | 95 ± 10 mmHg | MRI | Quadriceps | Mid |
| | 23 | | M9 | | HL-RT:3–4 × 8 | 8(2) | 80%1RM | | | | |
| Libardi et al. [46] | 64 | Untrained | 10 | LP | BFR-RT:30–15-15–15 | 12(2) | 20–30%1RM | 67 ± 8 mmHg | MRI | Quadriceps | Mid |
| | 65 | | 8 | | HL-RT:4 × 10 | 12(2) | 70–80%1RM | | | | |
| Lixandrao et al. [47] | 26 | Untrained | M11 | KE | BFR-RT1:2–3 × 15 | 12(2) | 20%1RM | 55.5 ± 8 mmHg | MRI | Quadriceps | Mid |
| | 28 | | M14 | | BFR-RT2:2–3 × 15 | 12(2) | 20%1RM | 109 ± 9 mmHg | | | |
| | 26 | | M8 | | BFR-RT3:2–3 × 15 | 12(2) | 40%1RM | 54 ± 5 mmHg | | | |
| | 28 | | M10 | | BFR-RT4:2–3 × 15 | 12(2) | 40%1RM | 105 ± 19 mmHg | | | |
| | 29 | | M9 | | HL-RT:2–3 × 10 | 12(2) | 80%1RM | | | | |
| Martin-Hernandez et al. [12] | 20 | Untrained | M10 | KE | BFR-RT1:30–15-15–15 | 5(2) | 20%1RM | 110 mmHg | US | Rectus femoris<br>Vastus lateralis | Mid |
| | 21 | | M10 | | BFR-RT2:2 × (30–15-15–15) | 5(2) | 20%1RM | 110 mmHg | | | |
| | 20 | | M11 | | HL-RT:3 × 8 | 5(2) | 85%1RM | | | | |
| May et al. [49] | 24 | Untrained | M8 | KE,KF | BFR-RT:30–15-15–15 | 7(3) | 20%1RM | 128 mmHg | CT | Quadriceps<br>Hamstrings | Mid<br>Distal |
| | 24 | | M9 | | HL-RT:4 × 8 | 7(3) | 70%1RM | | | | |
| Mendonca et al. [50] | 22 | Untrained | 15 | CR | BFR-RT:30–15-15–15 | 4(5) | 20%1RM | 60%AOP | US | Soleus | |
| | 21 | | 15 | | HL-RT:4 × 10 | 4(5) | 75%1RM | | | | |
| Ozaki et al. [16] | 23 | Untrained | M10 | BP | BFR-RT:30–15-15–15 | 6(3) | 30%1RM | 100-160 mmHg | MRI | Triceps brachii<br>Pectoralis major | |
| | 24 | | M9 | | HL-RT:3 × 10 | 6(3) | 75%1RM | | | | |
| Ramis et al. [52] | 23 | Untrained | M15 | BC,KE | BFR-RT:4 × 23 | 8(3) | 30%1RM | 110-150 mmHg | US | Biceps brachii<br>Quadriceps | |
| | 24 | | M13 | | HL-RT:4 × 8 | 8(3) | 80%1RM | | | | |

**Table 2** (continued)

| References | Age | Training Status | N | Exercise | Protocol | Weeks (times/wk) | Exercise load | Occlusion pressure | Muscle mass assessment | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | Method | Muscle groups | Test site |
| Shiromaru et al. [54] | 22 | Untrained | M15 | KE | BFR-RT:3 × 15 | 3(4) | 30%1RM | 80%AOP | MRI | Quadriceps | Mid |
| | 22 | | M15 | | HL-RT:3 × 10 | 6(2) | 80%1RM | | | | |
| Teixeira et al. [57] | 24 | Untrained | M8 | KE | BFR-RT:3 × 15 | 8(2) | 20%1RM | 80%AOP | MRI | Quadriceps | Mid |
| | 24 | | M8 | | HL-RT:3 × 8 | 8(2) | 70%1RM | | | | |
| Thiebaud et al. [58] | 59 | Untrained | F6 | CP,SR,SHP | BFR-RT:30–15-15 | 8(3) | 10–30%1RM | 80-120 mmHg | US | Biceps brachii<br>Triceps brachii | Distal |
| | 62 | | F8 | | HL-RT:3 × 10 | 8(3) | 70–90%1RM | | | | |
| Vechin et al. [13] | 62 | Untrained | M8 | LP | BFR-RT:30–15-15–15 | 12(2) | 20–30%1RM | 71 ± 9 mmHg | MRI | Quadriceps | Mid |
| | 65 | | M8 | | HL-RT:4 × 10 | 12(2) | 70–80%1RM | | | | |
| Yasuda et al. [11] | 22–32 | Untrained | M10 | BP,EE | BFR-RT:30–15-15–15 | 6(3) | 30%1RM | 100-160 mmHg | MRI | Triceps brachii | Mid |
| | 22–32 | | M10 | | HL-RT:3 × 10 | 6(3) | 75%1RM | | | | |
| Sousa-Silva et al. [70] | 21 | Untrained | M9 | BC | BFR-RT: 1 × 30 + 2–3 × 15 | 8(2) | 30%1RM | 50%AOP | US | Biceps brachii | Distal |
| | 21 | | M9 | BC | HL-RT:3–4 × 10–12 | 8(2) | 70%1RM | | | | |

*M* male, *F* female

*1RM* one-repetition maximum, *AOP* arterial occlusion pressure, *CT* Computed Tomography, *MRI* magnetic resonance imaging, *US* ultrasonography,

*Distal* > 50% of the thigh or upper arm length, *Mid* = 50% of the thigh or upper arm length, *Proximal* < 50% of the thigh or upper arm length

*BC* biceps curls, *BP* bench press, *CP* chest press, *DF* deadlift, *EE* elbow extension, *GS* grip strength, *KE* knee extension, *KF* knee flexion, *LP* leg press, *SHP* seated shoulder press, *CR* calf raises, *SQ* squat, *SSQ* split squat, *SR* Seated Rowing

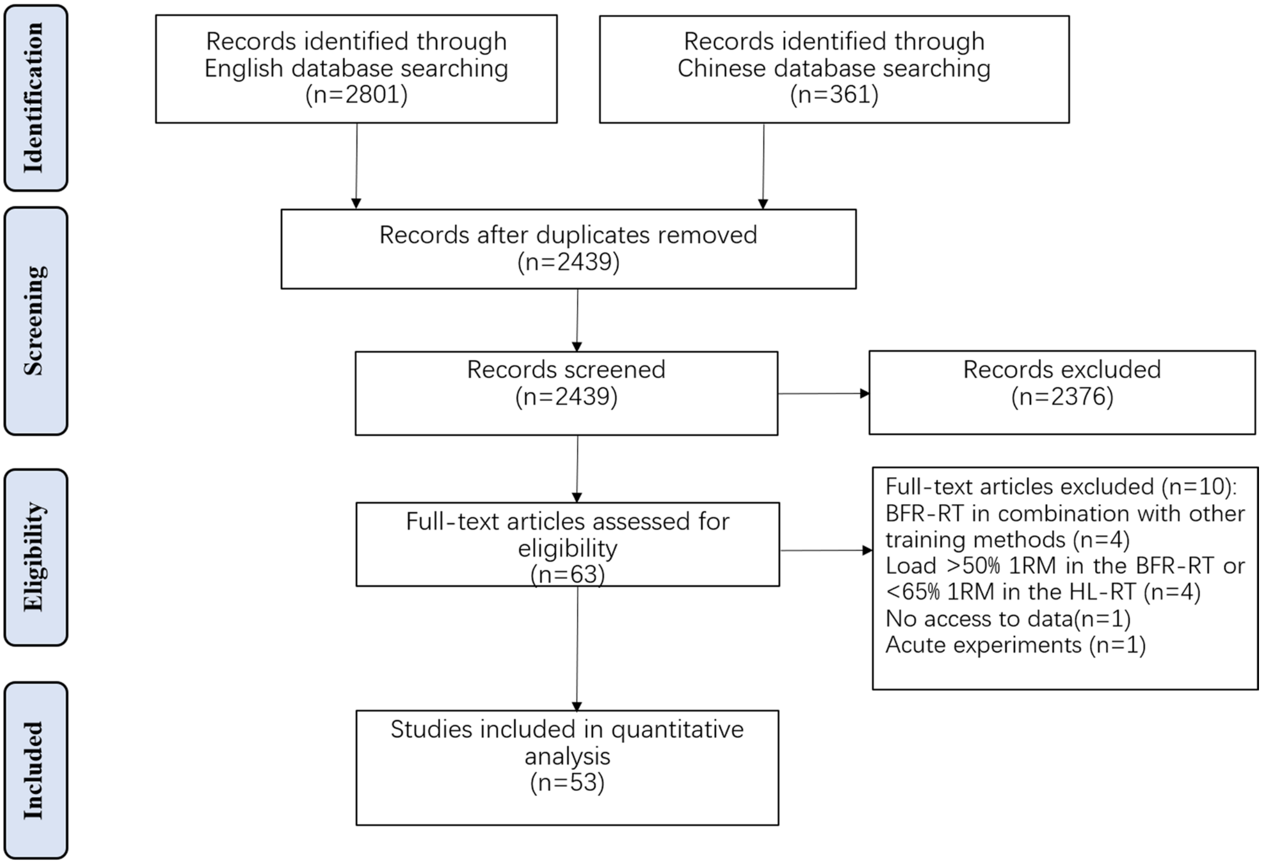


**Fig. 1** Flow diagram of the search and review process

file 1: Figs. S1–S5). In untrained individuals, there were also no significant differences between the different sexes, age, limbs, training duration and frequency (Table 3 and Additional file 1: Figs. S6–S11).

The sensitivity analysis conducted by deleting one study at a time and re-analyzing the data showed that none of the studies had a significant impact on muscle strength results. Inspection of the funnel plots indicated no evidence of publication bias (Additional file 1: Fig. S12). The results of the Begg test showed that Kendall's tau with continuity correction was equal to $-0.02$ ($P = 0.84$), and Egger's regression intercept was equal to 1.09 ($P = 0.41$).

### Muscle Hypertrophy

Twenty-eight studies involving 703 participants were included in the present meta-analysis to compare muscle hypertrophy gains. However, only three studies investigated the trained population. In addition, of the studies that investigated the untrained population, only one included female subjects, and only one adopted a training frequency of 4 sessions per week.

The overall $\text{ES}_{\text{diff}}$ suggested similar gains in muscle mass between BFR-RT and HL-RT ($\text{ES}_{\text{diff}} = -0.067 \pm 0.070$, 95% CI $-0.205$ to 0.071) (Fig. 4 and Table 4). However, when considering training status, the differences between trained and untrained subgroups were significant ($Q = 9.41$, $P < 0.01$) (Table 4). Significantly higher muscle hypertrophy gains for BFR-RT were observed compared with HL-RT in the trained subgroup ($\text{ES}_{\text{diff}} = 0.695 \pm 0.258$, 95% CI 0.189–1.200). In contrast, the muscle mass gains with BFR-RT were similar to those with HL-RT in the untrained subgroup ($\text{ES}_{\text{diff}} = -0.128 \pm 0.073$, 95% CI $-0.272$ to 0.015) (Fig. 5 and Table 4). However, in untrained individuals, there were no significant differences between the different age, limbs, duration and frequency, and region-specific adaptations in muscle mass (Additional file 1: Figs. S13–S18 and Table 4).

The sensitivity analysis showed that muscle hypertrophic adaptation was not affected by any particular study. Inspection of the funnel plots indicated no evidence of publication bias (Additional file 1: Fig. S19). The results of the Begg test show that Kendall's tau with continuity correction was equal to 0.17 ($P = 0.16$), and Egger's regression intercept was equal to 0.52 ($P = 0.65$).

| Study name | Outcome | Statistics for each study | | | |
|---|---|---|---|---|---|
| | | Hedges'g | Standard error | Lower limit | Upper limit |
| Bjornsen et al.[26] | Combined | 0.188 | 0.470 | -0.732 | 1.109 |
| Buckner et al.[32]A | Combined | -0.534 | 0.319 | -1.159 | 0.090 |
| Buckner et al.[32]B | Combined | -0.377 | 0.317 | -0.997 | 0.243 |
| Cook et al.[34] | Combined | -0.629 | 0.407 | -1.426 | 0.168 |
| Jessee et al.[39]A | Combined | -0.709 | 0.453 | -1.598 | 0.180 |
| Jessee et al.[39]B | Combined | -0.668 | 0.447 | -1.543 | 0.208 |
| Kim et al.[41] | Combined | -0.366 | 0.454 | -1.256 | 0.524 |
| Sugiarto et al.[56] | Combined | 0.877 | 0.563 | -0.228 | 1.981 |
| Wang et al.[71] | 1rm | 0.509 | 0.481 | -0.434 | 1.452 |
| Centner et al.[28] | Combined | 0.945 | 0.421 | 0.119 | 1.771 |
| Centner et al.[33] | mvc | -0.189 | 0.391 | -0.955 | 0.576 |
| Clark et al.[14] | mvc | -0.487 | 0.484 | -1.436 | 0.462 |
| Cook et al.[35] | Combined | -0.806 | 0.558 | -1.900 | 0.287 |
| Davids et al.[36] | Combined | -0.322 | 0.423 | -1.150 | 0.506 |
| de Lemos Muller et al.[37] | Combined | -1.894 | 0.479 | -2.834 | -0.955 |
| Ellefsen et al.[17] | 1rm | -0.327 | 0.397 | -1.106 | 0.451 |
| Fernandes et al.[38] | Combined | -0.258 | 0.369 | -0.980 | 0.465 |
| Karabulut et al.[9] | Combined | -0.263 | 0.396 | -1.040 | 0.514 |
| Kim et al.[40] | Combined | -0.618 | 0.442 | -1.485 | 0.248 |
| Kim et al.[42] | mvc | -1.324 | 0.489 | -2.282 | -0.366 |
| Korkmaz et al.[43] | Combined | 1.401 | 0.453 | 0.513 | 2.289 |
| Kubo et al.[10] | mvc | -0.601 | 0.460 | -1.503 | 0.300 |
| Laswati et al.[44] | mvc | 0.735 | 0.554 | -0.350 | 1.820 |
| Laurentino et al.[15] | 1rm | 0.840 | 0.460 | -0.061 | 1.741 |
| Letieri et al.[45]A | Combined | -0.226 | 0.415 | -1.038 | 0.587 |
| Letieri et al.[45]B | Combined | -1.485 | 0.478 | -2.422 | -0.548 |
| Libardi et al.[46] | 1rm | -0.832 | 0.473 | -1.758 | 0.094 |
| Lixandrao et al.[47]A | 1rm | -1.087 | 0.464 | -1.995 | -0.178 |
| Lixandrao et al.[47]B | 1rm | -0.982 | 0.437 | -1.837 | -0.126 |
| Lixandrao et al.[47]C | 1rm | -0.871 | 0.485 | -1.821 | 0.079 |
| Lixandrao et al.[47]D | 1rm | -0.852 | 0.460 | -1.753 | 0.050 |
| Luebbers et al.[48] | 1rm | 0.724 | 0.478 | -0.212 | 1.660 |
| Martin-Hernandez et al.[12]A | Combined | -0.978 | 0.450 | -1.859 | -0.096 |
| Martin-Hernandez et al.[12]B | Combined | -0.705 | 0.442 | -1.571 | 0.161 |
| May et al.[49] | Combined | -0.186 | 0.463 | -1.093 | 0.721 |
| Mendonca et al.[50] | mvc | -0.023 | 0.355 | -0.719 | 0.674 |
| Morley et al.[51]A | Combined | -0.377 | 0.521 | -1.398 | 0.644 |
| Morley et al.[51]B | Combined | -0.097 | 0.522 | -1.119 | 0.925 |
| Ozaki et al.[16] | 1rm | -0.868 | 0.461 | -1.772 | 0.035 |
| Ramis et al.[52] | Combined | -1.071 | 0.400 | -1.856 | -0.287 |
| Sharifi et al.[53]A | Combined | -0.285 | 0.475 | -1.216 | 0.647 |
| Sharifi et al.[53]B | Combined | -0.086 | 0.541 | -1.147 | 0.974 |
| Shiromaru et al.[54] | 1rm | -0.524 | 0.362 | -1.233 | 0.185 |
| Sousa et al.[55] | mvc | -1.355 | 0.469 | -2.274 | -0.437 |
| Teixeira et al.[57] | 1rm | -0.501 | 0.481 | -1.444 | 0.441 |
| Thiebaud et al.[58] | Combined | -0.469 | 0.523 | -1.494 | 0.556 |
| Vechin et al.[13] | 1rm | -0.692 | 0.488 | -1.649 | 0.265 |
| Yasuda et al.[11] | Combined | -1.034 | 0.459 | -1.932 | -0.135 |
| Che Tongtong et al.[19] | Combined | 0.007 | 0.480 | -0.935 | 0.948 |
| Li Shanghua et al.[59] | Combined | 0.599 | 0.415 | -0.213 | 1.412 |
| Li Zhiyuan et al.[18] | Combined | 0.865 | 0.505 | -0.125 | 1.854 |
| Li Zhiyuan et al.[60] | Combined | 0.268 | 0.433 | -0.580 | 1.116 |
| Wang Mingbo et al.[61] | Combined | 0.910 | 0.485 | -0.042 | 1.861 |
| Zhang Junjie et al.[62]A | 1rm | -0.870 | 0.497 | -1.845 | 0.104 |
| Zhang Junjie et al.[62]B | 1rm | 0.112 | 0.473 | -0.816 | 1.039 |
| Centner et al.[65] | 1rm | 0.208 | 0.362 | -0.502 | 0.918 |
| De Araujo et al.[66] | 1rm | -1.895 | 0.523 | -2.920 | -0.871 |
| Horiuchi et al.[67] | Combined | -0.465 | 0.401 | -1.250 | 0.320 |
| Judd et al.[68]A | 1rm | 2.437 | 0.866 | 0.740 | 4.133 |
| Judd et al.[68]B | 1rm | 1.716 | 0.721 | 0.304 | 3.128 |
| Reece et al.[69]A | 1rm | -1.883 | 0.614 | -3.087 | -0.680 |
| Reece et al.[69]B | 1rm | -0.899 | 0.499 | -1.876 | 0.079 |
| Sousa-Silva et al.[70] | 1rm | -0.734 | 0.465 | -1.646 | 0.178 |
| | | -0.335 | 0.092 | -0.515 | -0.156 |

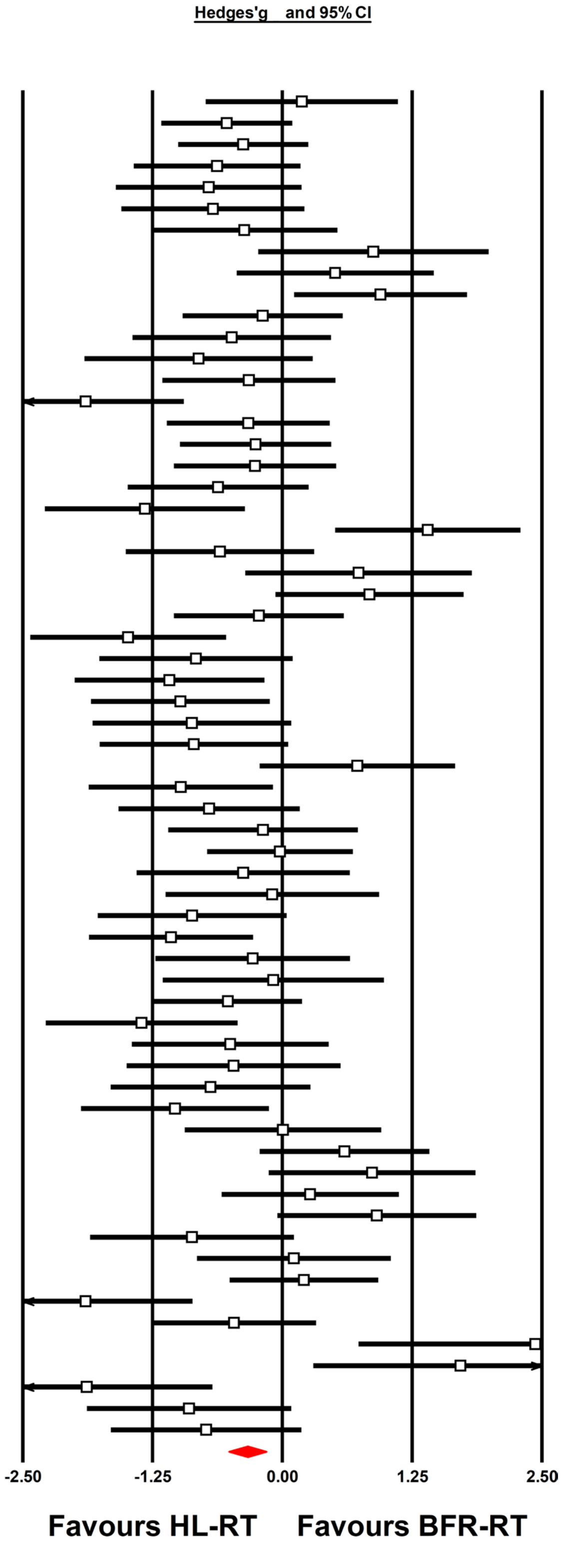


**Fig. 2** Forest plot of the effect size difference between BFR-RT versus HL-RT for muscle strength. The different capital letters (i.e. A, B, C, D) after the reference number are used to represent different training protocols for the same study. Hedges'g represents effect size difference. Red diamond represents overall Hedges'g. *1rm* 1RM test, *BFR-RT* blood-flow restriction low-load resistance training, *CI* confidence interval, *Combined* mean of multiple outcomes from the same training protocol, *HL-RT* high-load resistance training, *mvc* isometric or isokinetic tests

**Table 3** Summary of meta-analysis results for muscle strength

| | Subgroups | N | $ES_{diff}$ | Standard error | 95% Confidence interval | | *P* value | Between group | | Heterogeneity | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Lower limit | Upper limit | | Q-value | *P* value | Q-value | *P* value | $I^2$ |
| Overall effect | | | | | | | | | | | | |
| | | 63 | −0.335 | 0.092 | −0.515 | −0.156 | < 0.01 | | | 157.542 | < 0.01 | 60.65 |
| Training status | | | | | | | | | | | | |
| | Trained | 14 | 0.491 | 0.172 | 0.154 | 0.827 | < 0.01 | 29.392 | < 0.01 | 27.047 | 0.01 | 51.94 |
| | Untrained | 49 | −0.552 | 0.087 | −0.722 | −0.382 | < 0.01 | | | 83.634 | < 0.01 | 42.61 |
| Trained | | | | | | | | | | | | |
| Sex | Female | 2 | 0.682 | 0.572 | −0.440 | 1.804 | 0.23 | 0.014 | 0.91 | 3.896 | 0.05 | 74.33 |
| | Male | 10 | 0.609 | 0.236 | 0.146 | 1.072 | 0.01 | | | 18.791 | 0.03 | 52.11 |
| Limbs | Lower limb | 12 | 0.391 | 0.198 | 0.003 | 0.779 | 0.05 | 1.495 | 0.22 | 18.374 | 0.07 | 40.13 |
| | Upper limb | 3 | 1.011 | 0.467 | 0.095 | 1.926 | 0.03 | | | 8.736 | 0.01 | 77.11 |
| Duration | ≤ 4wk | 4 | 0.724 | 0.371 | −0.004 | 1.452 | 0.05 | 0.214 | 0.64 | 3.420 | 0.33 | 12.28 |
| | = 5–8wk | 9 | 0.520 | 0.238 | 0.053 | 0.987 | 0.03 | | | 19.563 | 0.01 | 59.11 |
| Frequency | 2/wk | 7 | 0.660 | 0.300 | 0.072 | 1.248 | 0.03 | 0.330 | 0.57 | 20.471 | < 0.01 | 70.69 |
| | 3/wk | 6 | 0.415 | 0.303 | −0.179 | 1.010 | 0.17 | | | 5.821 | 0.32 | 14.10 |
| Test type | Non-specific test | 6 | 0.541 | 0.282 | −0.011 | 1.094 | 0.05 | 0.352 | 0.55 | 11.211 | 0.05 | 55.40 |
| | Specific test | 11 | 0.330 | 0.218 | −0.098 | 0.758 | 0.13 | | | 20.499 | 0.02 | 51.22 |
| Untrained | | | | | | | | | | | | |
| Sex | Female | 5 | −0.638 | 0.297 | −1.220 | −0.055 | 0.03 | 0.143 | 0.71 | 5.529 | 0.24 | 27.66 |
| | Male | 31 | −0.516 | 0.120 | −0.751 | −0.282 | < 0.01 | | | 68.109 | < 0.01 | 55.95 |
| Age | Old | 8 | −0.714 | 0.205 | −1.115 | −0.312 | < 0.01 | 0.573 | 0.45 | 7.159 | 0.41 | 2.22 |
| | Young | 40 | −0.544 | 0.091 | −0.721 | −0.367 | < 0.01 | | | 69.180 | < 0.01 | 43.63 |
| Limbs | Lower limb | 36 | −0.618 | 0.111 | −0.836 | −0.400 | < 0.01 | 0.514 | 0.47 | 73.921 | < 0.01 | 52.65 |
| | Upper limb | 17 | −0.477 | 0.162 | −0.794 | −0.160 | < 0.01 | | | 38.871 | < 0.01 | 58.84 |
| Duration | ≤ 4wk | 7 | −0.493 | 0.216 | −0.916 | −0.070 | 0.02 | 0.278 | 0.87 | 5.107 | 0.53 | 0.00 |
| | = 5–8wk | 28 | −0.593 | 0.116 | −0.820 | −0.365 | < 0.01 | | | 51.803 | < 0.01 | 47.88 |
| | ≥ 9wk | 14 | −0.507 | 0.158 | −0.816 | −0.198 | < 0.01 | | | 25.833 | 0.02 | 49.68 |
| Frequency | 2/wk | 21 | −0.596 | 0.131 | −0.853 | −0.339 | < 0.01 | 0.795 | 0.67 | 35.971 | 0.02 | 44.40 |
| | 3/wk | 25 | −0.560 | 0.121 | −0.797 | −0.323 | < 0.01 | | | 44.477 | 0.01 | 46.04 |
| | 4/wk | 2 | −0.231 | 0.388 | −0.991 | 0.528 | 0.55 | | | 0.683 | 0.41 | 0.00 |
| Test specificity | Non-specific test | 24 | −0.422 | 0.120 | −0.657 | −0.188 | < 0.01 | 3.573 | 0.06 | 33.745 | 0.07 | 31.84 |
| | Specific test | 37 | −0.715 | 0.099 | −0.909 | −0.522 | < 0.01 | | | 70.945 | < 0.01 | 49.26 |

$ES_{diff}$ effect size difference

| Group by<br>TRAINING STATUS | Study name | Outcome | Statistics for each study<br>Hedges'g | Standard error | Lower limit | Upper limit |
|---|---|---|---|---|---|---|
| Trained | Bjornsen et al.[26] | Combined | 0.188 | 0.470 | -0.732 | 1.109 |
| Trained | Che Tongtong et al.[19] | Combined | 0.007 | 0.480 | -0.935 | 0.948 |
| Trained | Davids et al.[36] | Combined | -0.322 | 0.423 | -1.150 | 0.506 |
| Trained | Judd et al.[68]A | 1rm | 2.437 | 0.866 | 0.740 | 4.133 |
| Trained | Judd et al.[68]B | 1rm | 1.716 | 0.721 | 0.304 | 3.128 |
| Trained | Korkmaz et al.[43] | Combined | 1.401 | 0.453 | 0.513 | 2.289 |
| Trained | Li Shanghua et al.[59] | Combined | 0.599 | 0.415 | -0.213 | 1.412 |
| Trained | Li Zhiyuan et al.[18] | Combined | 0.865 | 0.505 | -0.125 | 1.854 |
| Trained | Li Zhiyuan et al.[60] | Combined | 0.268 | 0.433 | -0.580 | 1.116 |
| Trained | Luebbers et al.[48] | 1rm | 0.724 | 0.478 | -0.212 | 1.660 |
| Trained | Wang et al.[71] | 1rm | 0.509 | 0.481 | -0.434 | 1.452 |
| Trained | Wang Mingbo et al.[61] | Combined | 0.910 | 0.485 | -0.042 | 1.861 |
| Trained | Zhang Junjie et al.[62]A | 1rm | -0.870 | 0.497 | -1.845 | 0.104 |
| Trained | Zhang Junjie et al.[62]B | 1rm | 0.112 | 0.473 | -0.816 | 1.039 |
| Trained | | | 0.491 | 0.172 | 0.154 | 0.827 |
| Untrained | Buckner et al.[32]A | Combined | -0.534 | 0.319 | -1.159 | 0.090 |
| Untrained | Buckner et al.[32]B | Combined | -0.377 | 0.317 | -0.997 | 0.243 |
| Untrained | Centner et al.[28] | Combined | 0.945 | 0.421 | 0.119 | 1.771 |
| Untrained | Centner et al.[33] | mvc | -0.189 | 0.391 | -0.955 | 0.576 |
| Untrained | Centner et al.[65] | 1rm | 0.208 | 0.362 | -0.502 | 0.918 |
| Untrained | Clark et al.[14] | mvc | -0.487 | 0.484 | -1.436 | 0.462 |
| Untrained | Cook et al.[34] | Combined | -0.629 | 0.407 | -1.426 | 0.168 |
| Untrained | Cook et al.[35] | Combined | -0.806 | 0.558 | -1.900 | 0.287 |
| Untrained | De Araujo et al.[66] | 1rm | -1.895 | 0.523 | -2.920 | -0.871 |
| Untrained | de Lemos Muller et al.[37] | Combined | -1.894 | 0.479 | -2.834 | -0.955 |
| Untrained | Ellefsen et al.[17] | 1rm | -0.327 | 0.397 | -1.106 | 0.451 |
| Untrained | Fernandes et al.[38] | Combined | -0.258 | 0.369 | -0.980 | 0.465 |
| Untrained | Horiuchi et al.[67] | Combined | -0.465 | 0.401 | -1.250 | 0.320 |
| Untrained | Jessee et al.[39]A | Combined | -0.709 | 0.453 | -1.598 | 0.180 |
| Untrained | Jessee et al.[39]B | Combined | -0.668 | 0.447 | -1.543 | 0.208 |
| Untrained | Karabulut et al.[9] | Combined | -0.263 | 0.396 | -1.040 | 0.514 |
| Untrained | Kim et al.[40] | Combined | -0.618 | 0.442 | -1.485 | 0.248 |
| Untrained | Kim et al.[41] | Combined | -0.366 | 0.454 | -1.256 | 0.524 |
| Untrained | Kim et al.[42] | mvc | -1.324 | 0.489 | -2.282 | -0.366 |
| Untrained | Kubo et al.[10] | mvc | -0.601 | 0.460 | -1.503 | 0.300 |
| Untrained | Laswati et al.[44] | mvc | 0.735 | 0.554 | -0.350 | 1.820 |
| Untrained | Laurentino et al.[15] | 1rm | 0.840 | 0.460 | -0.061 | 1.741 |
| Untrained | Letieri et al.[45]A | Combined | -0.226 | 0.415 | -1.038 | 0.587 |
| Untrained | Letieri et al.[45]B | Combined | -1.485 | 0.478 | -2.422 | -0.548 |
| Untrained | Libardi et al.[46] | 1rm | -0.832 | 0.473 | -1.758 | 0.094 |
| Untrained | Lixandrao et al.[47]A | 1rm | -1.087 | 0.464 | -1.995 | -0.178 |
| Untrained | Lixandrao et al.[47]B | 1rm | -0.982 | 0.437 | -1.837 | -0.126 |
| Untrained | Lixandrao et al.[47]C | 1rm | -0.871 | 0.485 | -1.821 | 0.079 |
| Untrained | Lixandrao et al.[47]D | 1rm | -0.852 | 0.460 | -1.753 | 0.050 |
| Untrained | Martin-Hernandez et al.[12]A | Combined | -0.978 | 0.450 | -1.859 | -0.096 |
| Untrained | Martin-Hernandez et al.[12]B | Combined | -0.705 | 0.442 | -1.571 | 0.161 |
| Untrained | May et al.[49] | Combined | -0.186 | 0.463 | -1.093 | 0.721 |
| Untrained | Mendonca et al.[50] | mvc | -0.023 | 0.355 | -0.719 | 0.674 |
| Untrained | Morley et al.[51]A | Combined | -0.377 | 0.521 | -1.398 | 0.644 |
| Untrained | Morley et al.[51]B | Combined | -0.097 | 0.522 | -1.119 | 0.925 |
| Untrained | Ozaki et al.[16] | 1rm | -0.868 | 0.461 | -1.772 | 0.035 |
| Untrained | Ramis et al.[52] | Combined | -1.071 | 0.400 | -1.856 | -0.287 |
| Untrained | Reece et al.[69]A | 1rm | -1.883 | 0.614 | -3.087 | -0.680 |
| Untrained | Reece et al.[69]B | 1rm | -0.899 | 0.499 | -1.876 | 0.079 |
| Untrained | Sharifi et al.[53]A | Combined | -0.285 | 0.475 | -1.216 | 0.647 |
| Untrained | Sharifi et al.[53]B | Combined | -0.086 | 0.541 | -1.147 | 0.974 |
| Untrained | Shiromaru et al.[54] | 1rm | -0.524 | 0.362 | -1.233 | 0.185 |
| Untrained | Sousa et al.[55] | mvc | -1.355 | 0.469 | -2.274 | -0.437 |
| Untrained | Sousa-Silva et al.[70] | 1rm | -0.734 | 0.465 | -1.646 | 0.178 |
| Untrained | Sugiarto et al.[56] | Combined | 0.877 | 0.563 | -0.228 | 1.981 |
| Untrained | Teixeira et al.[57] | 1rm | -0.501 | 0.481 | -1.444 | 0.441 |
| Untrained | Thiebaud et al.[58] | Combined | -0.469 | 0.523 | -1.494 | 0.556 |
| Untrained | Vechin et al.[13] | 1rm | -0.692 | 0.488 | -1.649 | 0.265 |
| Untrained | Yasuda et al.[11] | Combined | -1.034 | 0.459 | -1.932 | -0.135 |
| Untrained | | | -0.552 | 0.087 | -0.722 | -0.382 |

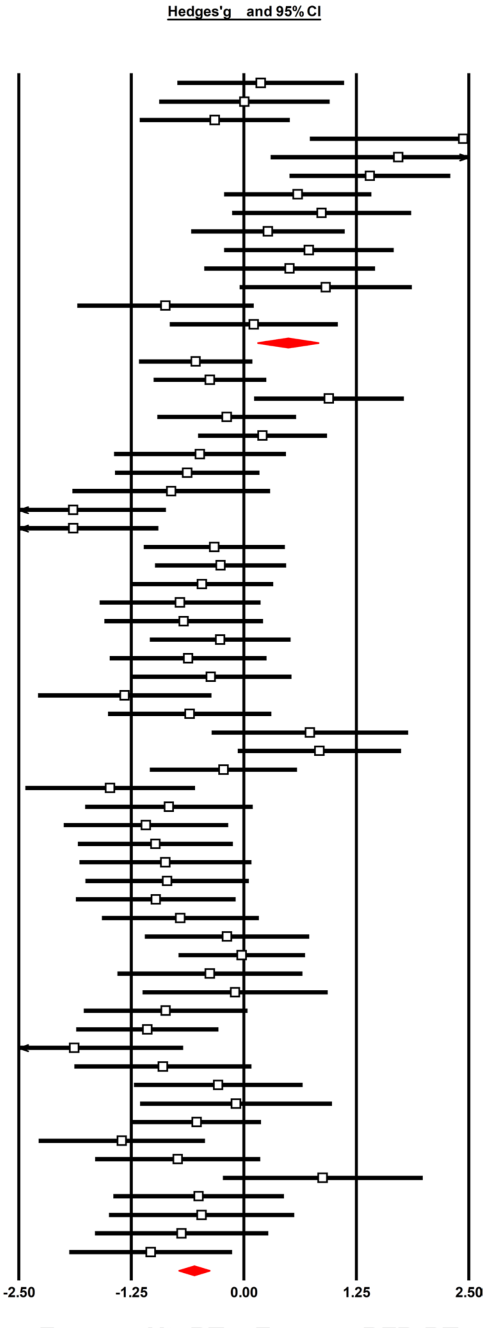
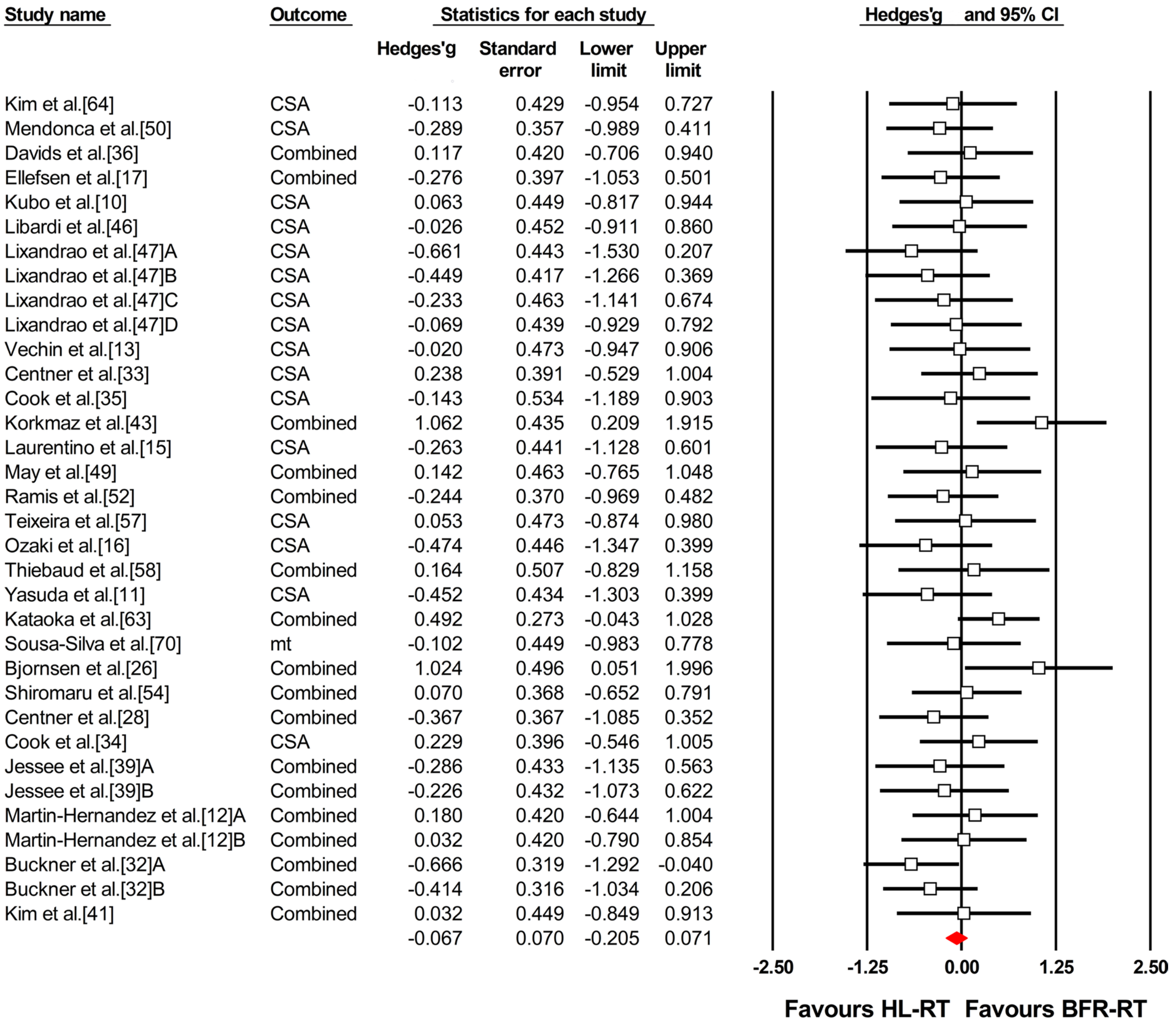


**Fig. 3** Forest plot of the effect size difference between BFR-RT versus HL-RT for muscle strength according to training status. The different capital letters (i.e. A, B, C, D) after the reference number are used to represent different training protocols for the same study. Hedges'g represents effect size difference. Red diamonds represent overall Hedges'g of subgroups. *1rm* 1RM test, *BFR-RT* blood-flow restriction low-load resistance training, *CI* confidence interval, *Combined* mean of multiple outcomes from the same training protocol, *HL-RT* high-load resistance training, *mvc* isometric or isokinetic tests



| Study name | Outcome | Hedges's g | Standard error | Lower limit | Upper limit |
|---|---|---|---|---|---|
| Kim et al.[64] | CSA | -0.113 | 0.429 | -0.954 | 0.727 |
| Mendonca et al.[50] | CSA | -0.289 | 0.357 | -0.989 | 0.411 |
| Davids et al.[36] | Combined | 0.117 | 0.420 | -0.706 | 0.940 |
| Ellefsen et al.[17] | Combined | -0.276 | 0.397 | -1.053 | 0.501 |
| Kubo et al.[10] | CSA | 0.063 | 0.449 | -0.817 | 0.944 |
| Libardi et al.[46] | CSA | -0.026 | 0.452 | -0.911 | 0.860 |
| Lixandrao et al.[47]A | CSA | -0.661 | 0.443 | -1.530 | 0.207 |
| Lixandrao et al.[47]B | CSA | -0.449 | 0.417 | -1.266 | 0.369 |
| Lixandrao et al.[47]C | CSA | -0.233 | 0.463 | -1.141 | 0.674 |
| Lixandrao et al.[47]D | CSA | -0.069 | 0.439 | -0.929 | 0.792 |
| Vechin et al.[13] | CSA | -0.020 | 0.473 | -0.947 | 0.906 |
| Centner et al.[33] | CSA | 0.238 | 0.391 | -0.529 | 1.004 |
| Cook et al.[35] | CSA | -0.143 | 0.534 | -1.189 | 0.903 |
| Korkmaz et al.[43] | Combined | 1.062 | 0.435 | 0.209 | 1.915 |
| Laurentino et al.[15] | CSA | -0.263 | 0.441 | -1.128 | 0.601 |
| May et al.[49] | Combined | 0.142 | 0.463 | -0.765 | 1.048 |
| Ramis et al.[52] | Combined | -0.244 | 0.370 | -0.969 | 0.482 |
| Teixeira et al.[57] | CSA | 0.053 | 0.473 | -0.874 | 0.980 |
| Ozaki et al.[16] | CSA | -0.474 | 0.446 | -1.347 | 0.399 |
| Thiebaud et al.[58] | Combined | 0.164 | 0.507 | -0.829 | 1.158 |
| Yasuda et al.[11] | CSA | -0.452 | 0.434 | -1.303 | 0.399 |
| Kataoka et al.[63] | Combined | 0.492 | 0.273 | -0.043 | 1.028 |
| Sousa-Silva et al.[70] | mt | -0.102 | 0.449 | -0.983 | 0.778 |
| Bjornsen et al.[26] | Combined | 1.024 | 0.496 | 0.051 | 1.996 |
| Shiromaru et al.[54] | Combined | 0.070 | 0.368 | -0.652 | 0.791 |
| Centner et al.[28] | Combined | -0.367 | 0.367 | -1.085 | 0.352 |
| Cook et al.[34] | CSA | 0.229 | 0.396 | -0.546 | 1.005 |
| Jessee et al.[39]A | Combined | -0.286 | 0.433 | -1.135 | 0.563 |
| Jessee et al.[39]B | Combined | -0.226 | 0.432 | -1.073 | 0.622 |
| Martin-Hernandez et al.[12]A | Combined | 0.180 | 0.420 | -0.644 | 1.004 |
| Martin-Hernandez et al.[12]B | Combined | 0.032 | 0.420 | -0.790 | 0.854 |
| Buckner et al.[32]A | Combined | -0.666 | 0.319 | -1.292 | -0.040 |
| Buckner et al.[32]B | Combined | -0.414 | 0.316 | -1.034 | 0.206 |
| Kim et al.[41] | Combined | 0.032 | 0.449 | -0.849 | 0.913 |
| | | -0.067 | 0.070 | -0.205 | 0.071 |

**Fig. 4** Forest plot of the effect size difference between BFR-RT versus HL-RT for muscle hypertrophy. The different capital letters (i.e. A, B, C, D) after the reference number are used to represent different training protocols for the same study. Hedges'g represents effect size difference. Red diamond represents overall Hedges'g. *BFR-RT* blood-flow restriction low-load resistance training, *CI* confidence interval, *Combined* mean of multiple outcomes from the same training protocol, *CSA* cross-sectional area, *HL-RT* high-load resistance training, *mt* muscle thickness

## Discussion

The purpose of the current study was to compare the effects of BFR-RT and HL-RT on the muscle strength and hypertrophy, using HL-RT as a control to evaluate the effects and characteristics of BFR-RT. The main finding of the present study was that training status was an important influencing factor in the effects of BFR-RT. The trained individuals will get greater muscle strength and hypertrophy gains from BFR-RT as compared with HL-RT. However, in the untrained individuals, the results demonstrated that superior gains in muscle strength and similar muscle mass for HL-RT as compared with BFR-RT.

### Effect of BFR-RT on Trained Individuals

The analysis results of trained individuals ($ES_{diff}=0.491$) suggested that in the comparison of these two training modalities, 69% of trained individuals may obtain greater gains in muscle strength with BFR-RT [77].

Training is initially characterized by neural adaptations, however, later as neural adaptations reach a plateau, muscular adaptation (i.e., hypertrophy) dominates

**Table 4** Summary of meta-analysis results for muscle hypertrophy

| | | N | $ES_{diff}$ | Standard error | 95% CI | | Between Group | | | Heterogeneity | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Lower limit | Upper limit | *P* value | Q-value | *P* value | Q-value | *P* value | $I^2$(%) |
| Overall effect | | | | | | | | | | | | |
| | | 34 | −0.067 | 0.070 | −0.205 | 0.071 | 0.34 | | | 29.578 | 0.64 | 0.00 |
| Training status | | | | | | | | | | | | |
| | Trained | 3 | 0.695 | 0.258 | 0.189 | 1.200 | 0.01 | 9.413 | < 0.01 | 3.048 | 0.22 | 34.39 |
| | Untrained | 31 | −0.128 | 0.073 | −0.272 | 0.015 | 0.08 | | | 17.116 | 0.97 | 0.00 |
| Untrained | | | | | | | | | | | | |
| Age | Old | 4 | 0.096 | 0.226 | −0.346 | 0.538 | 0.67 | 1.106 | 0.29 | 0.265 | 0.97 | 0.00 |
| | Young | 27 | −0.155 | 0.077 | −0.306 | −0.003 | 0.05 | | | 15.746 | 0.94 | 0.00 |
| Limbs | Lower limbs | 24 | −0.053 | 0.084 | −0.217 | 0.111 | 0.52 | 3.398 | 0.07 | 10.961 | 0.98 | 0.00 |
| | Upper limbs | 8 | −0.354 | 0.140 | −0.628 | −0.080 | 0.01 | | | 3.231 | 0.86 | 0.00 |
| Duration | ≤ 4 wk | 3 | −0.115 | 0.220 | −0.546 | 0.317 | 0.60 | 0.254 | 0.88 | 0.489 | 0.78 | 0.00 |
| | = 5–8 wk | 18 | −0.102 | 0.095 | −0.289 | 0.084 | 0.28 | | | 12.718 | 0.75 | 0.00 |
| | ≥ 9 wk | 10 | −0.185 | 0.134 | −0.448 | 0.079 | 0.17 | | | 3.656 | 0.93 | 0.00 |
| Frequency | 2/wk | 17 | −0.219 | 0.100 | −0.416 | −0.022 | 0.03 | 2.128 | 0.15 | 7.113 | 0.97 | 0.00 |
| | 3/wk | 13 | 0.000 | 0.112 | −0.219 | 0.220 | 0.99 | | | 7.663 | 0.81 | 0.00 |
| Assessment region (Thigh) | Distal | 5 | −0.069 | 0.184 | −0.430 | 0.291 | 0.71 | 1.805 | 0.41 | 0.478 | 0.98 | 0.00 |
| | Mid | 16 | −0.149 | 0.107 | −0.359 | 0.062 | 0.17 | | | 4.550 | 0.99 | 0.00 |
| | Proximal | 4 | −0.417 | 0.203 | −0.816 | −0.018 | 0.04 | | | 0.470 | 0.93 | 0.00 |
| Assessment region (Upper-arm) | Distal | 5 | −0.242 | 0.172 | −0.579 | 0.094 | 0.16 | 1.762 | 0.18 | 1.912 | 0.75 | 0.00 |
| | Mid | 4 | −0.577 | 0.184 | −0.938 | −0.216 | < 0.01 | | | 3.881 | 0.28 | 22.70 |

*2/wk* 2 sessions per week, *3/w* 3 sessions per week, $ES_{diff}$ effect size difference

| Group by TRAINING STATUS | Study name | Outcome | Statistics for each study | | | |
|---|---|---|---|---|---|---|
| | | | Hedges'g | Standard error | Lower limit | Upper limit |
| Trained | Bjornsen et al.[26] | Combined | 1.024 | 0.496 | 0.051 | 1.996 |
| Trained | Davids et al.[36] | Combined | 0.117 | 0.420 | -0.706 | 0.940 |
| Trained | Korkmaz et al.[43] | Combined | 1.062 | 0.435 | 0.209 | 1.915 |
| Trained | | | 0.695 | 0.258 | 0.189 | 1.200 |
| Untrained | Buckner et al.[32]A | Combined | -0.666 | 0.319 | -1.292 | -0.040 |
| Untrained | Buckner et al.[32]B | Combined | -0.414 | 0.316 | -1.034 | 0.206 |
| Untrained | Centner et al.[28] | Combined | -0.367 | 0.367 | -1.085 | 0.352 |
| Untrained | Centner et al.[33] | CSA | 0.238 | 0.391 | -0.529 | 1.004 |
| Untrained | Cook et al.[34] | CSA | 0.229 | 0.396 | -0.546 | 1.005 |
| Untrained | Cook et al.[35] | CSA | -0.143 | 0.534 | -1.189 | 0.903 |
| Untrained | Ellefsen et al.[17] | Combined | -0.276 | 0.397 | -1.053 | 0.501 |
| Untrained | Jessee et al.[39]A | Combined | -0.286 | 0.433 | -1.135 | 0.563 |
| Untrained | Jessee et al.[39]B | Combined | -0.226 | 0.432 | -1.073 | 0.622 |
| Untrained | Kataoka et al.[63] | Combined | 0.492 | 0.273 | -0.043 | 1.028 |
| Untrained | Kim et al.[41] | Combined | 0.032 | 0.449 | -0.849 | 0.913 |
| Untrained | Kim et al.[64] | CSA | -0.113 | 0.429 | -0.954 | 0.727 |
| Untrained | Kubo et al.[10] | CSA | 0.063 | 0.449 | -0.817 | 0.944 |
| Untrained | Laurentino et al.[15] | CSA | -0.263 | 0.441 | -1.128 | 0.601 |
| Untrained | Libardi et al.[46] | CSA | -0.026 | 0.452 | -0.911 | 0.860 |
| Untrained | Lixandrao et al.[47]A | CSA | -0.661 | 0.443 | -1.530 | 0.207 |
| Untrained | Lixandrao et al.[47]B | CSA | -0.449 | 0.417 | -1.266 | 0.369 |
| Untrained | Lixandrao et al.[47]C | CSA | -0.233 | 0.463 | -1.141 | 0.674 |
| Untrained | Lixandrao et al.[47]D | CSA | -0.069 | 0.439 | -0.929 | 0.792 |
| Untrained | Martin-Hernandez et al.[12]A | Combined | 0.180 | 0.420 | -0.644 | 1.004 |
| Untrained | Martin-Hernandez et al.[12]B | Combined | 0.032 | 0.420 | -0.790 | 0.854 |
| Untrained | May et al.[49] | Combined | 0.142 | 0.463 | -0.765 | 1.048 |
| Untrained | Mendonca et al.[50] | CSA | -0.289 | 0.357 | -0.989 | 0.411 |
| Untrained | Ozaki et al.[16] | CSA | -0.474 | 0.446 | -1.347 | 0.399 |
| Untrained | Ramis et al.[52] | Combined | -0.244 | 0.370 | -0.969 | 0.482 |
| Untrained | Shiromaru et al.[54] | Combined | 0.070 | 0.368 | -0.652 | 0.791 |
| Untrained | Sousa-Silva et al.[70] | mt | -0.102 | 0.449 | -0.983 | 0.778 |
| Untrained | Teixeira et al.[57] | CSA | 0.053 | 0.473 | -0.874 | 0.980 |
| Untrained | Thiebaud et al.[58] | Combined | 0.164 | 0.507 | -0.829 | 1.158 |
| Untrained | Vechin et al.[13] | CSA | -0.020 | 0.473 | -0.947 | 0.906 |
| Untrained | Yasuda et al.[11] | CSA | -0.452 | 0.434 | -1.303 | 0.399 |
| Untrained | | | -0.128 | 0.073 | -0.272 | 0.015 |

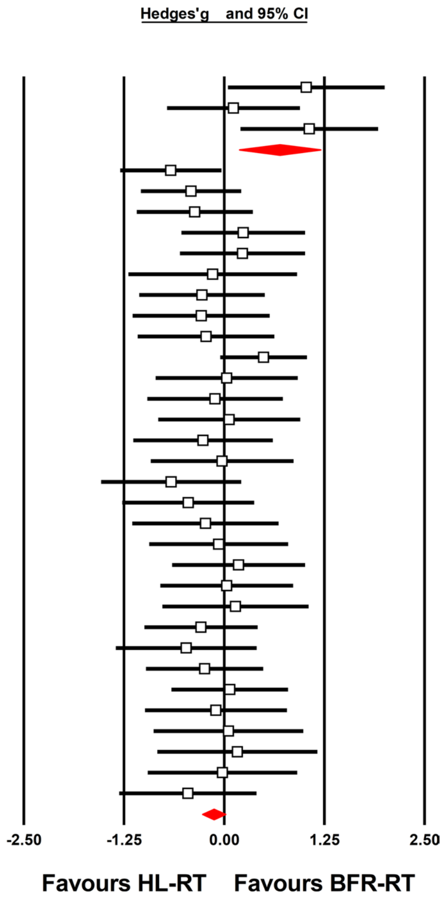


**Fig. 5** Forest plot of the effect size difference between BFR-RT versus HL-RT for muscle hypertrophy according to training status. The different capital letters (i.e. A, B, C, D) after the reference number are used to represent different training protocols for the same study. Hedges'g represents effect size difference. Red diamonds represent overall Hedges'g of subgroups. *BFR-RT* blood-flow restriction low-load resistance training, *CI* confidence interval, *Combined* mean of multiple outcomes from the same training protocol, *CSA* cross-sectional area, *HL-RT* high-load resistance training, *mt* muscle thickness

[23, 78]. In intermediate and advanced training, the progress of strength training is limited to the degree of muscle adaptation that can be achieved [23]. Hakkinen et al. reported that during one-year traditional strength training, advanced weight-lifters show limited potential for further neural adaptations, and the total mean muscle fiber area did not increase significantly [79]. However, mounting research indicates that BFR-RT can promote muscle hypertrophy in athletes [18, 26, 43, 80, 81], and even in elite powerlifters the muscle fiber CSA increased more with BFR-RT than with HL-RT [26].

Metabolic stress was believed to be one of the factors promoting muscle hypertrophy [82]. Compared with other strength training protocols, BFR-RT was believed to produce a higher level of metabolic stress [83]. Studies suggested that compared with normoxic conditions, resistance training under the hypoxic condition caused greater metabolic and hormonal responses [84, 85], whereas it was believed that blood flow restriction could cause similar muscle hypoxia as compared with systemic hypoxia [86]. In this study, the results (Table 4) showed that in the trained individuals, superior muscle hypertrophy gains were observed for BFR-RT as compared with HL-RT. Put another way, 76% of the trained population may obtain greater gains in muscle hypertrophy with BFR-RT [77]. In fact, our results showed that the average relative strength change [(pre-training − post-training)/pre-training × 100] with BFR-RT (8.4% ± 1.09) was twice that of HL-RT (3.96% ± 0.66) in the trained individuals.

### Effect of BFR-RT on Untrained Individuals

Being different from the trained subjects, the analysis results for untrained individuals ($ES_{diff} = -0.552$) suggested that about 70% of untrained individuals may experience greater gains in muscle strength with HL-RT [77].

However, previous studies have found that the muscle activation level of BFR-RT was higher than that of the same intensity (low load) resistance exercise [87–90], its muscle activation level is still low as compared with HL-RT [91–93]. For example, Cook et al. [92] reported that muscle activation level (according to surface electromyography) was greater in the HL-RT at the beginning and end of exercise compared with the BFR-RT. It has been suggested that increasing the occlusion pressure (from 40 to 60% occlusive pressure) could increase the activation level of muscle [94], but recent research showed that even with higher occlusive pressure (80%), the activation level of BFR-RT on muscle was also significantly lower than HL-RT [91]. While these findings were based on surface electromyography, BFR-RT may not achieve the same level of muscle activation and produce the same neural stimulation as HL-RT [83, 95].

### Limitations

The current meta-analysis has some limitations. The lack of studies including females limited generalizability of the findings. Because of the sparse number of studies, the results comparing muscle hypertrophy in trained individuals should be interpreted with caution. In addition, the data from one study were not included [76]. However, the sensitivity analysis revealed that no single study had a significant impact on the analysis results. Therefore, the absence of these data would unlikely to have affected the current results and their interpretation.

## Conclusion

The present meta-analysis indicates that training status is an important factor influencing the effects of BFR-RT. Compared to HL-RT, trained individuals can obtain greater strength and hypertrophy gains from BFR-RT. However, in untrained individuals, the results demonstrate that superior muscle strength and similar mass gains for HL-RT.

From a practical standpoint, BFR-RT could be a beneficial supplemental training protocol for trained population. It has been demonstrated that the combination of BFR- and HL-RT was more beneficial for the increase of muscle strength [97]. Thus, healthy individuals or athletes are likely to maximize their training adaptations by combining these two training methods [4, 98]. Finally, it is important to highlight that BFR-RT remains a valid and effective alternative for people who cannot perform high-load resistance training.

### Abbreviations

| | |
|---|---|
| 1RM | One repetition maximum |
| BFR-RT | Low-load resistance training (< 50% 1RM) combined with blood flow restriction |
| CI | Confidence interval |
| CSA | Cross-sectional area |
| $ES_{diff}$ | Effect size difference |
| HL-RT | High-load resistance training |
| PEDro | Physiotherapy Evidence Database |

## Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40798-024-00719-3.

**Additional file 1**

### Acknowledgements

Not applicable.

### Author contributions

YG and XPW contributed to the study concept and design. YG, XPW and YZ performed the literature search. YG and YZ performed the data extraction and quality assessment. YG wrote the first draft of the manuscript. XPW, Y Z and MZ critically revised the draft of the manuscript. All authors read and approved the final manuscript.

### Funding

No funding was received for this project.

### Availability of Data and Materials

The datasets analysed during the current study are available from the corresponding author on reasonable request.

## Declarations

### Ethics Approval and Consent to participate

Not applicable.

### Consent for Publication

Not applicable.

### Competing interests

Yu Geng, Xueping Wu, Yong Zhang and Meng Zhang declare that they have no conflict of interests relevant to the content of this review.

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Received: 29 May 2023 Accepted: 21 April 2024

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## Publisher's Note