MASTER´S THESIS

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Effects of low-load blood-flow-restricted resistance training on enhancing skeletal muscle hypertrophy and strength: – a systematic review and meta-analysis

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Abstract

Background

Blood-flow restriction in combination with low-loads resistance training can increase muscle mass and strength, but it remains uncertain to what degree these adaptations can measure up to conventional high-load strength training. The objective of the study was to conduct a systematic review and meta-analysis on the literature comparing the longitudinal effects of low-load blood-flow-restricted resistance training with high load resistance training on skeletal muscle hypertrophy and strength.

Methods

Scopus, SPORTSDiscus & MEDLINE/PubMed databases were searched for studies based on the following inclusion criteria: (1) had an experimental design; (2) was published in a peer reviewed, English-language journal; (3) compare low-load (<40% of 1RM) resistance training with blood-flow-restriction training and high-load (>60% of 1RM) resistance training regarding estimated changes in muscle mass and/or muscular strength; (4) had a minimum duration of four weeks for strength measures, and six weeks for hypertrophy measures; (5) only included healthy individuals above 18 years of age; and (6) had a Testex-score above 6.

Results

25 studies were included in the analysis. The main findings were that there were no significant differences between the two training methods regarding changes in muscle hypertrophy, but for strength there were significantly differences favoring high loads. When only including upper-body outcomes, there were no significant differences in strength improvements between groups. These results did not differ when grouping by age-groups, but the occlusion pressure seems to affect the strength-results, with narrower cuffs favoring high loads, while wider cuff widths showed no significant differences between protocols.

Conclusion

Our findings indicate that both blood flow restriction and high load-training are equally effective in enhancing skeletal muscle hypertrophy. However, our results suggest that high load-training may be more effective than blood flow restriction in increasing overall and lower-body strength, whereas blood flow restriction are equally effective as high load training in enhancing upper-body strength.

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Introduction

Maintaining and improving skeletal muscle mass is vital for quality of life, enabling individuals to carry out daily activities and enhancing sport performance, strength, power, caloric expenditure, and basal metabolic rate (Schoenfeld, 2020). Inactivity and disuse of the skeletal muscle may lead to atrophy, reducing the capacity of normal movement. While a typical hypertrophy and strength resistance training program for untrained to intermediately trained, healthy, adults usually involve carrying out sets with 3-10 repetitions at >60% of maximal capacity with 2-5 minutes rest between sets (Garber et al., 2011; Ratamess et al., 2009). heavy load resistance training can sometimes be challenging or harmful to certain individuals, such as elderly, individuals with chronic disease or individuals undertaking rehabilitation. Therefore, in the recent years, studies examining blood flow restriction (BFR) is intriguing, as it has shown potential to stimulate to muscular adaptions at even as low loads as <25% of maximal capacity (Lixandrao et al., 2018).

BFR is accomplished by the application of external pressure over the proximal portion of the lower or upper extremities. Usually using blood pressure cuffs, tourniquets, or elastic bands. This is sufficient to maintain arterial inflow, while resisting venous outflow of blood distal to the occlusion site. This reduces intramuscular oxygen delivery and decreases venous ability to clear out metabolites, which usually leads to an earlier onset of fatigue, practically demonstrated by a reduction in repetitions during resistance training sets. (Pope et al., 2013).

The underlaying mechanisms that may make BFR an effective strategy remains somewhat controversial and may involve metabolic stress, muscle fiber recruitment and mechanic tension. BFR causes hypoxia in the working muscles as they are depleted of oxygen, which leads to an accumulation of metabolites, and thereby may contribute to an increase in muscle mass (Hwang & Willoughby, 2019; Vanwye et al., 2017).

Furthermore, BFR increases muscle fiber recruitment, probably by the hypoxia conditions in the muscles causing a deficit in overall force development due to fatigue, in which the additional motor-units may be recruited to compensate. Thereby, the fast-twitch muscle fibers may be recruited more quickly even if the absolute intensities are low (Hwang & Willoughby, 2019).

Several previous reviews regarding BFR training have been conducted (Centner et al., 2019; Grønfeldt et al., 2020; Hughes et al., 2017; Lixandrao et al., 2018; Pope et al., 2013; Wortman et al., 2021). However, the reviews examining the training effect of high-load tradition training vs. low-load BFR on strength and skeletal muscle hypertrophy are several years old (Grønfeldt et al., 2020; Lixandrao et al., 2018), and there has been a growing number of studies comparing BFR training vs high load (HL) training. As a result, there is need for an up-to-date systematic review and meta-analysis, to provide a more currently understanding of the effect of BFR training on muscle strength and hypertrophic adaptations.

Therefore, the aim of the study was to conduct a systematic review and meta-analysis on the literature comparing the longitudinal effects of low load BFR resistance training with high load resistance training on skeletal muscle hypertrophy and strength. The secondary objective was to explore the results, by taking different potential moderators into account, such as age-group, different body-parts, occlusion pressure prescription and different types of strength tests.

Materials and methods

The systematic review follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines, PRISMA (Page et al., 2021).

Eligibility criteria

The review includes studies that (1) had an experimental design; (2) is published in a peer reviewed, English-language journal; (3) compared low-load (<40% of 1RM) resistance training with blood-flow-restriction training and high-load (>60% of 1RM) resistance training regarding estimated changes in muscle mass and/or muscular strength; (4) had a minimum duration of four weeks for strength measures, and six weeks for hypertrophy measures; (5) only included healthy individuals, free of injury, above 18 years of age; and (6) had a Testex-score above 6, which is considered “fair quality”.

Literature search

Scopus, SPORTSDiscus & MEDLINE/PubMed databases were searched for all studies investigating the effects of blood flow restricted resistance training on muscle hypertrophy and/or strength up to 28. January 2023. The search process was conducted using the following search syntax: “blood flow restriction” OR “occlusion training” OR “KAATSU” OR “ischemi training” OR “vascular occlusion” AND “hypertrophy” OR “muscle mass” OR “muscle strength” OR “muscle force”. Secondary searches were performed by screening reference lists of the identified studies. The identified studies were exported to Rayyan (https://www.rayyan.ai/), where duplicates were removed. Title and abstract of the remaining studies were screened for the predefined inclusion. Where a decision based on title or abstract was not possible, a full text search was performed.

Data extraction

First authors name and year of publication, number of participants (N), mean age of participants, training status, duration of the intervention (in weeks), exercises prescribed, an overview of the training-intervention, methods of measurements, assessment of hypertrophy and/or strength (pre-post means ± standard deviations) was extracted and tabulated on a predefined Microsoft excel coding sheet.

Methodological quality

The 12-point TESTEX scale was used to assess the methodological quality of the identified studies, as it is shown to be specific to exercise studies (Smart et al., 2015). The TESTEX scale contains 12 questions, but due to some of the questions having a, b and c questions, a total of 15 points can be received. 5 of the points can be given for study quality, and 10 of the points addresses how and what results is reported. The questions have one or more criteria, which must be fulfilled to receive a point, if not 0 is given. The studies are classified based on sum of scores; “excellent quality” (12-15 points), “good quality” (9-11 points), “fair quality” (6-8 points), or “poor quality” (<6 points).

Statistical analysis

Comprehensive Meta-Analysis version 3 software (Biostat Inc., Englewood, NJ, USA) was used to run the statistical analysis. The core analysis contains a between group comparison of the effect on hypertrophy and on strength.

Hedge`s g was used as effect size, as it corrects for bias regarding small sample sizes (Borenstein et al., 2021). Where only confidence-interval`s (CI) were stated, standard deviations were obtained by dividing the confidence intervals length by 3.92 and then multiplying it by the square root of the sample size, as described in Higgins et al. (2019). Since none of the included studies reported the correlation coefficient, which was required to perform the analysis, similar studies with open datasets were examined for the correlation coefficients as proposed by Borenstein et al. (2021). Both of these studies showed correlations of >0.88, which is considered very high (Higgins et al., 2019). Therefore, a more conservative estimate of 0.8 was set across all studies, and sensitivity-analysis of more conservative correlation coefficients (r=0.6) is carried out on the primary analysis to determine if the results were robust (Higgins et al., 2019).

For the studies with multiple time points for hypertrophy/strength measuring, only pre and post data were used in the analysis. For the studies with more than one type of measurement, they were inserted as multiple outcomes and then pooled in the analysis by the mean of outcomes into one effect size per study to prevent for unit-of-analysis errors (Higgins et al. (2019). As some of the studies (Lixandrão et al., 2015; Jessee et al., 2018; Letieri et al., 2018) had more than one BFR-group that was eligible to participate in the study, they were inserted as different parts of the study, using a, b & c to tell them apart.

Forest plots were made using the random effect modelling to present the results, as the studies in the analysis are assumed to be a random sample from a universe of potential studies, showing hedge`s g, 95% CI, p-value and prediction intervals, provided the data shows a dispersion of true effects. The alpha level of the meta-analysis was set to 0.05 to function as a criterion for statistical significance. Effect sizes were considered very large >0.8, large from 0.5-0.8, moderate from 0.2-0.5 and small from 0-0.2 (Cohen, 1988).

Sensitivity analysis was performed, by the one-study removal test, to check if any of the individual studies have a large impact on the results, that could bias the analysis. Study heterogeneity was assessed using Cochran`s Q (with an alpha level of 0.10), T^2, T & I^2. I^2 values of ≤30, 31-70 and ≥71 was considered low, moderate and considerable. Regardless of heterogeneity, pooled-group analysis was performed, examining how different potential moderators (such as age-groups, upper- vs. lower-body, specific vs non-specific tests and different occlusion pressure grouped as ≤110 mmHg/cuff width of ≥140mm and ≥111 mmHg/cuff width ≤139mm as done in an earlier meta-analysis (Lixandrao et al., 2018) affected the results.

Publication bias was assessed visual through the funnel plots for asymmetry (Higgins et al. (2019). If publication bias were suspected, the fill-and-trim method was applied to better understand how the effect could differ if the missing studies were present.

Results

Delimination of literature

A total of 17602 studies were initially identified, then reduced to 16809 after the duplicates were removed by Rayan software and the author. 16773 studies were removed when title and abstract were screened. The remaining 36 articles were fully read, 10 studies were removed because of inappropriate study-design, one study was removed because of inappropriate population, and 25 articles were considered eligible according to the eligibility criterion. The search process is summarized in figure 1.

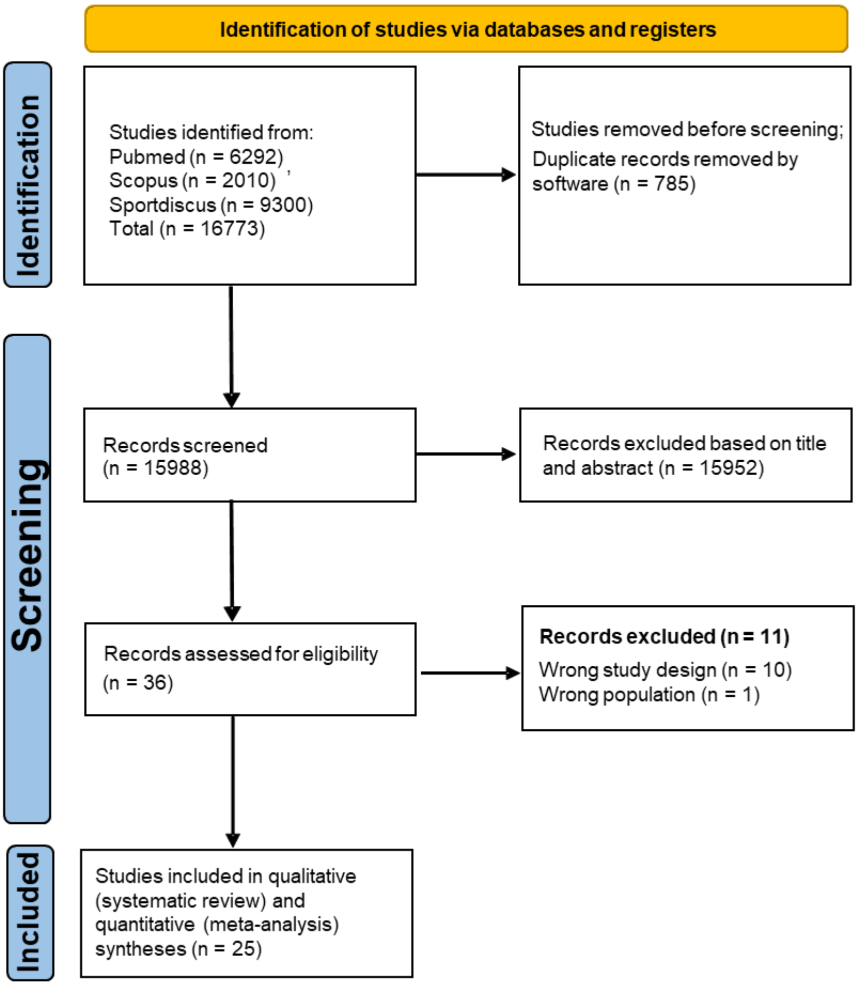


Figure 1 PRISMA flowchart presenting the searching process.

Subjects

The total number of participants in the included studies was 712, with an average sample size of 28.5 ± 10.6 (range 15 – 56). Three studies included elderly participants (mean age >59), while the rest of the studies included younger participants (age range 18-59). Eleven studies included only males, two studies included only females and the rest of the studies included both genders. Two studies examined athletes, one study examined resistance trained participants, one included trained participants, three studies examined recreationally active participants, and 18 studies only included untrained participants. The duration of the studies ranged from 4 to 16 weeks with an average duration of 8.2 weeks. 24 studies assessed changes in muscle strength; eighteen used specific strength tests (17 studies used 1 repetition maximum (RM) tests, one study used as many reps as possible (AMRAP) at 60% of 1RM test), 14 used non-specific strength measurements (isometric and isokinetic strength tests). 16 studies assessed changes in muscle mass; ten studies used magnetic resonance imaging (MRI), four studies used ultrasound (US), one study used computerised tomography (CT) and one study used peripheral quantitative computed tomography (pQCT). Martín-Hernández et al. (2013) had two different BFR groups, but as their high-volume-BFR-group had double the volume of HL, and any other BFR-group, only the low-volume-BFR-group were included, as it is more comparable to the HL group and training volume has been reported to be a key driver for muscle hypertrophy (Figueiredo et al., 2018). The characteristics for the studies examining changes in muscle mass were summarised in table 1, and those examining changes in strength were summarised in table 2.

- **Table 1.** Overview of the intervention studies assessing BFR and the effect upon muscle hypertrophy.

Study	**N**	**Classification**	**Weeks (sessions)**	**Intervention (BFR & HL)**	**Measurement of hypertrophy**	**Change in muscle mass % (BFR & HL)**	**Authors conclusion**
Kubo et al. (2006)	19	Adult, untrained males	12 (36)	20% 25-18-15-12 80% 4x10	MRI Quadriceps	7% 7%	No significant difference between groups.
Yasuda et al. (2011)	40	Adult, recreationally active	6 (18)	30% 30-15-15-15 75% 3x10	MRI Triceps	4% 8%	Significant greater increases for HL-group.
Laurentino et al. (2012)	29	Adult, untrained	8 (16)	20% 3-4x15 80% 3-4x8	MRI Quadriceps	6% 6%	No significant difference between groups.
Ozaki et al. (2013)	19	Adult, untrained males	6 (18)	30% 30-15-15-15 75% 3x10	MRI sum of triceps & pectoralis major	6% 11%	No significant difference between groups.
Ellefsen et al. (2015)	15	Adult, untrained females	12 (24)	30% 5xfailure 75-92% 3x6-10 to failure	MRI Quadriceps	6-9% 7-10%	No significant difference between groups.
	35		12 (24)	20% 2-3x15		4-5%	

Lixandrão et al. (2015)		Adult, untrained males		40% 2-3x15 80% 2-3x10	MRI Quadriceps	0-3% 5%	No significant difference between groups.
Vechin et al. (2015)	23	Elderly untrained	12 (24)	20-30% 3-4x15 70-80% 3-4x8	MRI Quadriceps	8% 6%	No significant difference between groups.
Libardi et al. (2015)	25	Elderly untrained	12 (24)	20-30% 30-15-15-15 70-80% 4x10	MRI Quadriceps	6% 7%	No significant difference between groups.
Cook et al. (2017)	36	Elderly untrained	12 (24)	30% 3xfailure 70% 3xfailure	MRI Quadriceps		No significant difference between groups.
Ramis et al. (2020)	28	Adult untrained	8 (24)	30% 4x volume equated 80% 4x8	Ultrasound Biceps brachii & Quadriceps	3-6% 3-9%	No significant difference between groups.
Jessee et al. (2018)	46	Adult untrained	8 (16)	15% 4xfailure 70% 4xfailure	Ultrasound Quadriceps		No significant difference between groups.
Brandner et al. (2019)	39	Adult untrained	8 (20)	20% 30-15-15-15 70% 4x8-10	CT Biceps brachii, triceps, pectoralis major, quadriceps, hamstrings,	0-12% 1-13%	Significant greater biceps hypertrophy increases for HL group. No significant differences for other muscles.

					calf & tibialis anterior		
Korkmaz et al. (2022)	23	Athletes	6 (12)	30% 30-15-15-15 70% 4x8-10	Ultrasound Quadriceps	8-14% 4-5%	Significant greater increase in RF for BFR group. No significant difference in VL increases.
May et al. (2022)	26	Adult, untrained males	7 (21)	20% 30-15-15-15 70% 4x8	pQCT Quadriceps & hamstrings	3% 2%	No significant difference between groups.
Davids et al. (2021)	24	Trained adults	9 (27)	30-40% 30-15-15-15 75-80% 4x8	MRI Quadriceps	7% 4%	No significant difference between groups.
Kataoka et al. (2022)	27	Resistance trained adults	6 (18)	30% 4xfailure 70% 4x failure	Ultrasound Gastrocnemius	4% 1%	No significant difference between groups.

Note: BFR, blood flow restriction; HL, high load; MRI, magnetic resonance imaging; CT; computerised tomography, RF, rectus femoris; VL, vastus lateralis; pQCT, quantitative computed tomography. The training protocol is reported with intensity in % of 1 repetition maximum and sets x repetitions.

Table 2 Overview of the intervention studies assessing BFR and the effect upon strength.

Study	N	Classification	Weeks (sessions)	Intervention	Measurement of strength	Strength change % (BFR & HL)	Authors conclusion
Kubo et al. (2006)	19	Adult, untrained males	12 (36)	20% 25-18-15-12 80% 4x10	Isometric leg extension	7% 16%	No significant difference between groups.
Clark et al. (2011)	17	Adult, untrained	4 (12)	30% 3x failure 80% 3x failure	Isometric leg extension	6% 11%	No significant difference between groups.
Karabulut et al. (2010)	37	Adult and elderly, recreationally active males	6 (18)	20% 30-15-15 80% 3x8	1RM leg extension, leg press, lat-pulldown, shoulder press & biceps curl	9-18% 7-30%	Significant greater strength gains in leg extension for HL-group. No significant differences for the other exercises.
Yasuda et al. (2011)	40	Adult, recreationally active	6 (18)	30% 30-15-15-15 75% 3x10	1RM bench-press & isometric triceps	-0.2-8% 11-19%	Significant greater strength gains for HL-group.
Laurentino et al. (2012)	29	Adult, untrained	8 (16)	20% 3-4x15 80% 3-4x8	1RM leg extension	40% 3%	No significant difference between groups.
	39		5 (10)	20% 30-15-15-15		7%	

Martín-Hernández et al. (2013)		Adult, recreationally active males		85% 3x8	1RM leg extension & isokinetic leg extension	18%	No significant difference between groups.
Ozaki et al. (2013)	19	Adult, untrained males	6 (18)	30% 30-15-15-15 75% 3x10	1RM bench-press	8% 17%	No significant difference between groups.
Ellefsen et al. (2015)	15	Adult, untrained females	12 (24)	30% 5xfailure 75-92% 3x6-10 to failure	1RM leg extension	11% 11%	No significant difference between groups.
Lixandrão et al. (2015)	35	Adult, untrained males	12 (24)	20% 2-3x15 40% 2-3x15 80% 2-3x10	1RM leg extension	10-13% 12% 21%	Uses magnitude-based interference and by that standard, there is a trend towards significantly greater strength increase in HL-group.
Vechin et al. (2015)	23	Elderly untrained	12 (24)	20-30% 3-4x15 70-80% 3-4x8	1RM leg press	17% 54%	Considered CI that did not cross zero as significant. By this standard, there was significantly greater strength gains for HL-group.
Libardi et al. (2015)	25	Elderly untrained	12 (24)	20-30% 30-15-15-15 70-80% 4x10	1RM leg press	24% 37%	No significant difference between groups.

Cook et al. (2017)	36	Elderly untrained	12 (24)	30% 3xfailure 70% 3xfailure	1RM leg extension, leg curl & isokinetic leg press		Significant greater leg press gains for HL-group. No significant differences for other exercises.
Sugiarto et al. (2017)	18	Adult, untrained males	5 (10)	30% 30-15-15-15 70% 3x12	Isokinetic biceps curl	43-79% 25-57%	No significant difference between groups.
Sousa et al. (2017)	37	Adult, untrained	6 (12)	30% 4xfailure 80% 4xfailure	Isometric leg extension	22% 42%	No significant difference between groups.
Ramis et al. (2020)	28	Adult untrained	8 (24)	30% 4x volume equated 80% 4x8	Isometric & isokinetic bicep curl & leg extension	5-127% 11-76%	Significant greater isometric bicep curls & isokinetic leg extension for HL-group. No significant differences for the other exercises.
Letieri et al. (2018)	56	Elderly, untrained females	16 (48)	20-30% 3-4x12 70-80% 3-4x6-8	Isokinetic leg extension & leg curl	15-27% 13-30%	No significant difference between groups.
Jessee et al. (2018)	46	Adult untrained	8 (16)	15% 4xfailure 70% 4xfailure	1RM, isometric & isokinetic leg extension		Significant greater 1RM strength gains for HL-group.
Cook et al. (2018)	18	Adult untrained	6 (18)	20% 2x25 + 1xfailure 70% 2x10 + 1xfailure	1RM & isometric leg extension	-2-14% 17-34%	No significant difference between groups.

Laswati et al. (2018)	18	Adult, untrained males	5 (10)	30% 4x30 70% 3x12	Isokinetic bicep curl	47% 27%	Significant greater isokinetic strength gains for BFR-group.
Brandner et al. (2019)	39	Adult untrained	8 (20)	20% 30-15-15-15 70% 4x8-10	1RM leg extension, back-squat, calf raise, Bench press, seated row & bicep curl	11% 21%	Significant greater seated row strength increases for HL-group. No significant difference for strength increases in the other exercises.
Korkmaz et al. (2022)	23	Athletes	6 (12)	30% 30-15-15-15 70% 4x8-10	Isokinetic leg extension & leg curl	10-13% 0-2%	Significant greater LE gains in BFR-group. No significant differences for LC.
May et al. (2022)	26	Adult, untrained males	7 (21)	20% 30-15-15-15 70% 4x8	1RM leg extension & leg curl	11-19% 16-19%	No significant difference between groups.
Davids et al. (2021)	24	Trained adults	9 (27)	30-40% 30-15-15-15 75-80% 4x8	1RM back-squat, isokinetic leg extension & leg curl	5-15% 2-17%	Significant greater squat strength increases in HL group. Trend towards greater isokinetic leg curl strength gains in BFR group.
Wang et al. (2022)	18	Athletes	8 (24)	30% 30-15-15-15 70% 4x8	Isokinetic leg extension & leg curl, 1RM half-squat	10% 17%	Significant greater strength gains in HL-group.

Note: BFR, blood flow restriction; HL, high load; 1RM, one repetition maximum; CI, confidence interval; LE, leg extension; LC, leg curl. The training protocol is reported with intensity in % of 1 repetition maximum and sets x repetitions.

Quality assessment

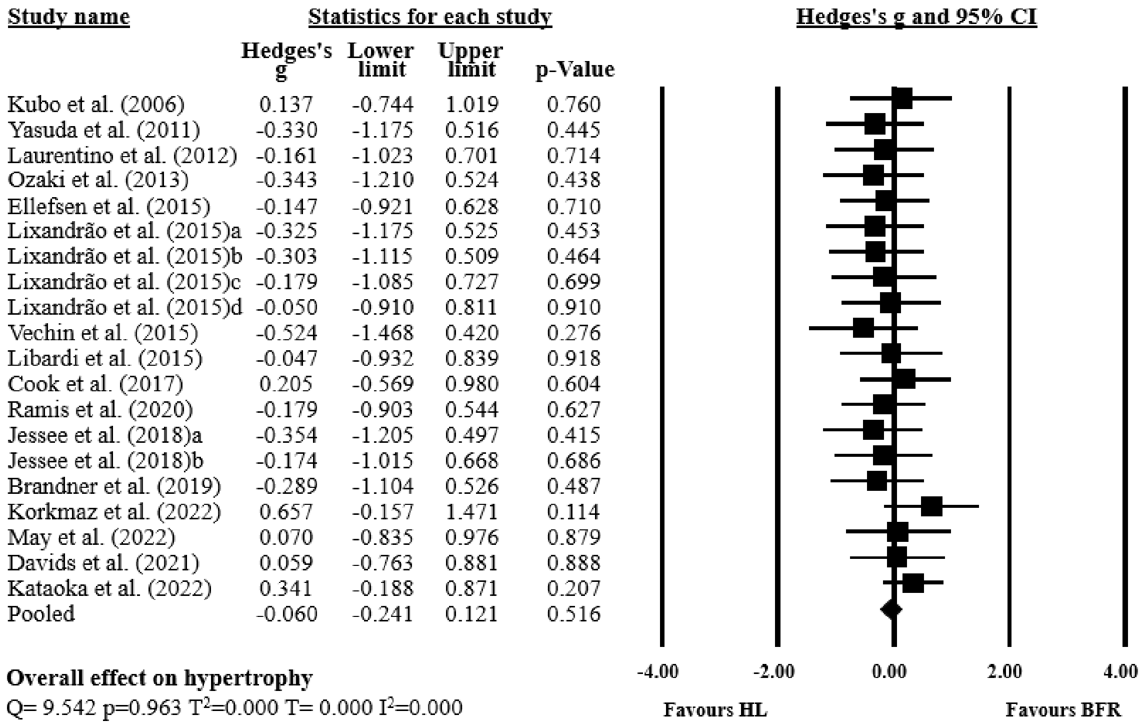
The results from the TESTEX quality assessment are presented in table 3. The scores ranged from 8-14, with an average score of 9.6. The scores of study quality criteria ranged from 1-5 with an average score of 2.5. The scores of study reporting criteria ranged from 5-9 with an average score of 7.2. Eight studies were considered “fair” quality (Clark et al., 2011; Gil et al., 2017; Kubo et al., 2006; Libardi et al., 2015; Lixandrão et al., 2015; Ozaki et al., 2013; Sousa et al., 2017; Sugiarto et al., 2017; Vechin et al., 2015; Wang et al., 2022), Twelve studies were considered “good” quality (Brandner et al., 2019; Cook et al., 2018; Ellefsen et al., 2015; Jessee et al., 2018; Jones et al., 2023; Kataoka et al., 2022; Korkmaz et al., 2022; Laswati et al., 2018; Laurentino et al., 2012; Martín-Hernández et al., 2013; May et al., 2022; Ramis et al., 2020; Yasuda et al., 2011), and four studies were considered “excellent” quality (Cook et al., 2017; Davids et al., 2021; Karabulut et al., 2010; Letieri et al., 2018).

Table 3, TESTEX quality assessment.

	1	2	3	4	5	6a	6b	6c	7	8a	8b	9	10	11	12	Total score (max. 15)
Kubo et al. (2006)	0	0	0	1	0	1	0	0	1	1	1	1	1	0	1	8
Clark et al. (2011)	1	0	0	0	0	1	0	0	0	1	1	1	1	1	1	8
Karabulut et al. (2010)	1	1	1	0	0	1	1	1	0	1	1	1	1	1	1	12
Yasuda et al. (2011)	1	0	1	1	0	1	0	0	0	1	1	1	1	0	1	9
Laurentino et al. (2012)	1	0	1	1	0	1	1	0	0	1	1	1	1	1	1	11
Martín-Hernández et al. (2013)	1	0	1	1	0	1	0	0	0	1	1	1	1	0	1	9
Ozaki et al. (2013)	1	0	0	1	0	1	0	0	0	1	1	1	1	0	1	8
Ellefsen et al. (2015)	1	0	1	1	0	0	1	0	0	1	1	1	1	1	1	10
Lixandrão et al. (2015)	1	0	1	1	0	0	0	0	0	1	1	1	1	0	1	8
Vechin et al. (2015)	1	0	0	0	0	1	0	0	0	1	1	1	1	1	1	8
Libardi et al. (2015)	1	0	0	1	0	1	0	0	0	1	1	1	1	0	1	8
Cook et al. (2017)	1	1	1	1	0	1	1	0	1	1	1	1	1	1	1	12
Sugiarto et al. (2017)	1	0	0	1	0	1	0	0	0	1	1	1	1	0	1	8
Sousa et al. (2017)	1	0	0	1	0	1	0	0	0	1	1	1	1	1	1	9
Ramis et al. (2020)	1	0	0	1	0	1	1	1	0	1	1	1	1	0	1	10
Letieri et al. (2018)	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	14
Jessee et al. (2018)	1	0	1	1	1	1	1	1	0	1	1	1	1	0	1	11
Cook et al. (2018)	0	1	0	1	0	1	1	1	0	1	1	1	1	1	1	11
Laswati et al. (2018)	1	0	0	1	0	1	0	0	0	1	1	1	1	1	1	9
Brandner et al. (2019)	1	0	1	1	0	1	1	0	0	1	1	1	1	1	1	11
Korkmaz et al. (2022)	1	0	1	1	0	1	0	0	0	1	1	1	1	0	1	9
May et al. (2022)	1	0	1	1	0	1	0	0	0	1	1	1	1	0	1	9
Davids et al. (2021)	1	1	0	1	0	1	1	1	0	1	1	1	1	1	1	12
Kataoka et al. (2022)	1	0	0	1	0	1	1	0	0	1	1	1	1	1	1	10
Wang et al. (2022)	1	0	0	1	0	1	0	0	0	1	1	1	1	0	1	8
Average																9.6

Between group comparison on changes in muscle size

The meta-analysis revealed no significant differences in hypertrophy between the BFR-group and the HL-group (figure 2), with a Hedge`s g of -0.060 (95% CI = -0.241 to 0,121; *p* = 0.516). One-study-removal test showed that none of the individual studies had any large impact on the results. Since the Q-value is less than its degrees of freedom (p=0.807), we can assume that the studies are somewhat homogene, which also can be observed by the overlap of confidence limits across studies. Any variance in effects can therefore likely be a result of sampling errors, rather than true variance (I^2=0).



Study name	Hedges's g	Lower limit	Upper limit	p-Value
Kubo et al. (2006)	0.137	-0.744	1.019	0.760
Yasuda et al. (2011)	-0.330	-1.175	0.516	0.445
Laurentino et al. (2012)	-0.161	-1.023	0.701	0.714
Ozaki et al. (2013)	-0.343	-1.210	0.524	0.438
Ellefsen et al. (2015)	-0.147	-0.921	0.628	0.710
Lixandrão et al. (2015)a	-0.325	-1.175	0.525	0.453
Lixandrão et al. (2015)b	-0.303	-1.115	0.509	0.464
Lixandrão et al. (2015)c	-0.179	-1.085	0.727	0.699
Lixandrão et al. (2015)d	-0.050	-0.910	0.811	0.910
Vechin et al. (2015)	-0.524	-1.468	0.420	0.276
Libardi et al. (2015)	-0.047	-0.932	0.839	0.918
Cook et al. (2017)	0.205	-0.569	0.980	0.604
Ramis et al. (2020)	-0.179	-0.903	0.544	0.627
Jessee et al. (2018)a	-0.354	-1.205	0.497	0.415
Jessee et al. (2018)b	-0.174	-1.015	0.668	0.686
Brandner et al. (2019)	-0.289	-1.104	0.526	0.487
Korkmaz et al. (2022)	0.657	-0.157	1.471	0.114
May et al. (2022)	0.070	-0.835	0.976	0.879
Davids et al. (2021)	0.059	-0.763	0.881	0.888
Kataoka et al. (2022)	0.341	-0.188	0.871	0.207
Pooled	-0.060	-0.241	0.121	0.516

Overall effect on hypertrophy

Q= 9.542 p=0.963 T^2=0.000 T= 0.000 I^2=0.000

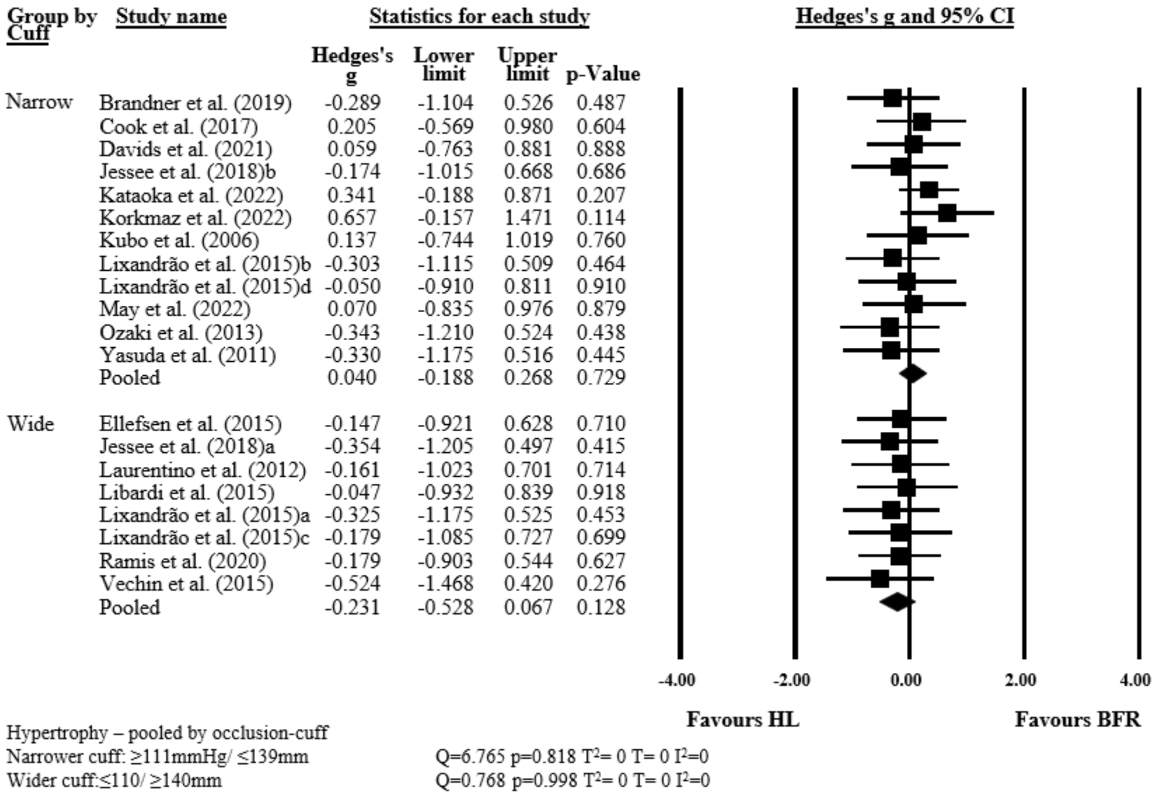
Figur 2. Forest plot displaying the effect size difference for muscle hypertrophy between high-load (HL) training and blood flow restriction (BFR) training. Different letters for the same study represent different protocols.

Upper- & lower-body

No differences between groups were evident when only examining the lower body (g= -0.019, 95% CI from -0.208 to 0.171 p= 0.845). Only examining upper-body muscles resulted in a Hedge`s g of -0.348 (95% CI = -0.752 to 0.056; p = 0.092). Removing the studies with muscles proximal to the occlusion cuffs changed hedges g to -0.384 (p= 0.100).

Occlusion pressure

Pooling studies according to the occlusion pressure resulted in no significant differences in hypertrophy between the BFR-group and the HL-group (figure 3), either for narrow cuffs (g=0.040, p= 0.729) or wide cuffs (-0.231, p= 0.128).



Group by Cuff	Study name	Hedges's g	Lower limit	Upper limit	p-Value
Narrow	Brandner et al. (2019)	-0.289	-1.104	0.526	0.487
	Cook et al. (2017)	0.205	-0.569	0.980	0.604
	Davids et al. (2021)	0.059	-0.763	0.881	0.888
	Jessee et al. (2018)b	-0.174	-1.015	0.668	0.686
	Kataoka et al. (2022)	0.341	-0.188	0.871	0.207
	Korkmaz et al. (2022)	0.657	-0.157	1.471	0.114
	Kubo et al. (2006)	0.137	-0.744	1.019	0.760
	Lixandrão et al. (2015)b	-0.303	-1.115	0.509	0.464
	Lixandrão et al. (2015)d	-0.050	-0.910	0.811	0.910
	May et al. (2022)	0.070	-0.835	0.976	0.879
	Ozaki et al. (2013)	-0.343	-1.210	0.524	0.438
	Yasuda et al. (2011)	-0.330	-1.175	0.516	0.445
	Pooled	0.040	-0.188	0.268	0.729
Wide	Ellefsen et al. (2015)	-0.147	-0.921	0.628	0.710
	Jessee et al. (2018)a	-0.354	-1.205	0.497	0.415
	Laurentino et al. (2012)	-0.161	-1.023	0.701	0.714
	Libardi et al. (2015)	-0.047	-0.932	0.839	0.918
	Lixandrão et al. (2015)a	-0.325	-1.175	0.525	0.453
	Lixandrão et al. (2015)c	-0.179	-1.085	0.727	0.699
	Ramis et al. (2020)	-0.179	-0.903	0.544	0.627
	Vechin et al. (2015)	-0.524	-1.468	0.420	0.276
	Pooled	-0.231	-0.528	0.067	0.128

Hypertrophy – pooled by occlusion-cuff

Narrower cuff: ≥111mmHg/ ≤139mm Q=6.765 p=0.818 T^2= 0 T= 0 I^2=0

Wider cuff:≤110/ ≥140mm Q=0.768 p=0.998 T^2= 0 T= 0 I^2=0

Figur 3. Forest plot displaying the effect size difference for muscle hypertrophy between high-load (HL) training and blood flow restriction (BFR) training according to occlusion cuff with. Different letters for the same study represent different protocols.

Age

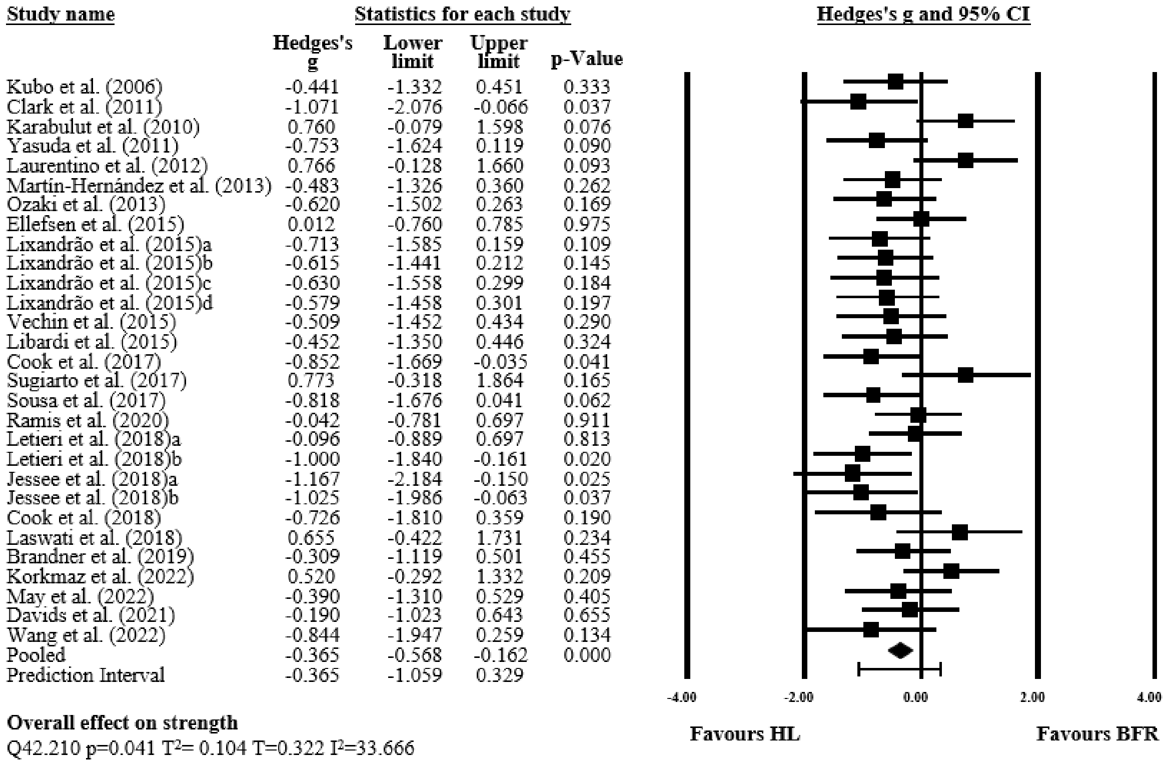
Pooling by age (under 60 vs 60+) revealed similar patterns as the overall effects (under 60: g= -0.058, 95% CI ranged from -0.252 to 0.137; p=0.561. For 60+: g= -0.075, 95% CI from -0.571 to 0.421; p = 0.766).

Failure

Only five of the studies reported that the participants performed sets to failure. When grouping studies based on performing sets to failure, the analysis revealed no differences between groups for either those going to failure (g=0.060, p=0.715) or those not performing sets to failure (g= -0.116, p=0.300).

Between group comparison on changes in strength

The analysis revealed a significant difference favouring HL-group when comparing changes in strength, with effect-size-confidence interval ranging from small to large (g = -0.365, 95% CI from -0.568 to -0.162; p <0.001, figure 4). The prediction interval ranged from -1.059 to 0.329, meaning that the true effect size in 95% of all comparable populations falls in this range. One-study-removal sensitivity analysis revealed that none of the individual studies had any large impact on the results. The Q-value reveals that the observed effects vary more than would be expected based on within-study-errors (Q=42.210, p=0.041). 33% of this observed variance can be considered due to differences in real effects.



Study name	Hedges's g	Lower limit	Upper limit	p-Value
Kubo et al. (2006)	-0.441	-1.332	0.451	0.333
Clark et al. (2011)	-1.071	-2.076	-0.066	0.037
Karabulut et al. (2010)	0.760	-0.079	1.598	0.076
Yasuda et al. (2011)	-0.753	-1.624	0.119	0.090
Laurentino et al. (2012)	0.766	-0.128	1.660	0.093
Martín-Hernández et al. (2013)	-0.483	-1.326	0.360	0.262
Ozaki et al. (2013)	-0.620	-1.502	0.263	0.169
Ellefsen et al. (2015)	0.012	-0.760	0.785	0.975
Lixandrão et al. (2015)a	-0.713	-1.585	0.159	0.109
Lixandrão et al. (2015)b	-0.615	-1.441	0.212	0.145
Lixandrão et al. (2015)c	-0.630	-1.558	0.299	0.184
Lixandrão et al. (2015)d	-0.579	-1.458	0.301	0.197
Vechin et al. (2015)	-0.509	-1.452	0.434	0.290
Libardi et al. (2015)	-0.452	-1.350	0.446	0.324
Cook et al. (2017)	-0.852	-1.669	-0.035	0.041
Sugiarto et al. (2017)	0.773	-0.318	1.864	0.165
Sousa et al. (2017)	-0.818	-1.676	0.041	0.062
Ramis et al. (2020)	-0.042	-0.781	0.697	0.911
Letieri et al. (2018)a	-0.096	-0.889	0.697	0.813
Letieri et al. (2018)b	-1.000	-1.840	-0.161	0.020
Jessee et al. (2018)a	-1.167	-2.184	-0.150	0.025
Jessee et al. (2018)b	-1.025	-1.986	-0.063	0.037
Cook et al. (2018)	-0.726	-1.810	0.359	0.190
Laswati et al. (2018)	0.655	-0.422	1.731	0.234
Brandner et al. (2019)	-0.309	-1.119	0.501	0.455
Korkmaz et al. (2022)	0.520	-0.292	1.332	0.209
May et al. (2022)	-0.390	-1.310	0.529	0.405
Davids et al. (2021)	-0.190	-1.023	0.643	0.655
Wang et al. (2022)	-0.844	-1.947	0.259	0.134
Pooled	-0.365	-0.568	-0.162	0.000
Prediction Interval	-0.365	-1.059	0.329	

Overall effect on strength

Q42.210 p=0.041 T^2= 0.104 T=0.322 I^2=33.666

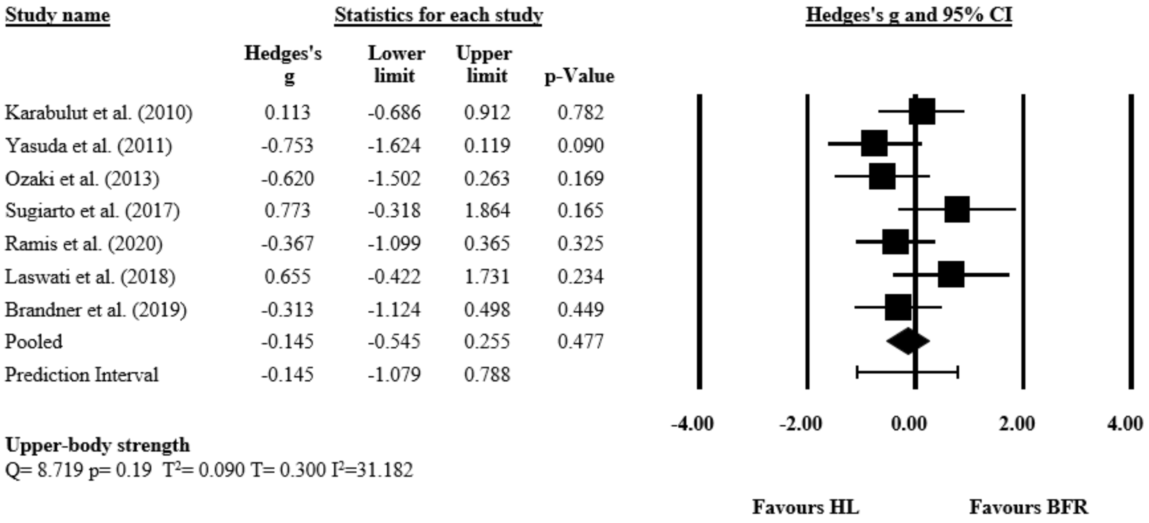
Figur 4. Forest plot displaying the effect size difference for muscle strength between high-load (HL) training and blood flow restriction (BFR) training. Different letters for the same study represent different protocols.

Age

Similar patterns could be observed when pooling for age, with hedge`s g favouring HL for both groups, but with a bit larger effect-size for those over 60 years old (under 60; g = -0.318, 95% CI: -0.553 to -0.083; p = 0.008. And 60+; g = -0.579, 95% CI: -0.961 to -0.198; p = 0.003)

Upper- & lower-body

When only including upper-body-strength, there were no significant difference between groups (g = -0.145, 95% CI= -0.545 to 0.255; p=0.477, figure 5). For lower body strength the results were similar to the one of the overall-strength analysis (g = -0.361, 95% CI from -0.615 to -0.107; p = 0.005). Sensitivity analysis showed that none of the studies had any large impact on that result.



Study name	Hedges's g	Lower limit	Upper limit	p-Value
Karabulut et al. (2010)	0.113	-0.686	0.912	0.782
Yasuda et al. (2011)	-0.753	-1.624	0.119	0.090
Ozaki et al. (2013)	-0.620	-1.502	0.263	0.169
Sugiarto et al. (2017)	0.773	-0.318	1.864	0.165
Ramis et al. (2020)	-0.367	-1.099	0.365	0.325
Laswati et al. (2018)	0.655	-0.422	1.731	0.234
Brandner et al. (2019)	-0.313	-1.124	0.498	0.449
Pooled	-0.145	-0.545	0.255	0.477
Prediction Interval	-0.145	-1.079	0.788	

Upper-body strength
Q= 8.719 p= 0.19 T^2= 0.090 T= 0.300 I^2=31.182

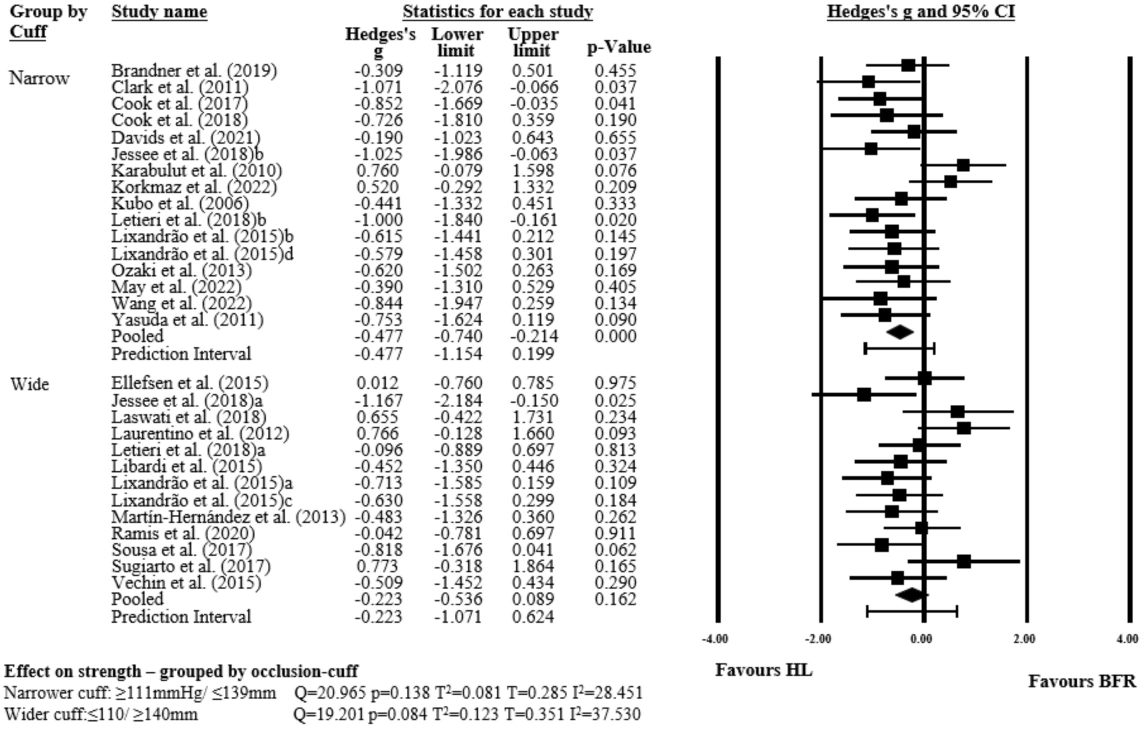
Figur 5. Forest plot displaying the effect size difference for muscle strength between high-load (HL) training and blood flow restriction (BFR) training, when only including upper-body outcomes.

Test-specificity

For test-specificity, both the non-specific and the specific test group favoured control-group conditions, but the effect for non-specific tests can be considered moderate (i.e., isometric & isokinetic; -0.379, 95% CI= -0.667 to -0.090; p= 0.010. With a prediction interval from -1.283 to 0.526), while for specific tests it can be considered large (i.e., 1RM & AMRAP; g = -0.580, 95% CI = -0.907 to -0.254; p<0.000. With a prediction interval from -1.893 to 0.732). When only including non-specific tests, and grouping them by isokinetic and isometric, the isokinetic showed no difference between groups (g= 0.087, 95% CI from -0.537 to 0.363, p=0.703), while the isometric strength test favoured HL-training with a very large effect-size (-0.885, 95% CI from -1.261 to -0.509, p<0.000).

Occlusion pressure

Pooling studies according to occlusion pressure resulted in no significant difference between groups for those studies with wider cuffs (g = -0.223, 95% CI = -0.536 to 0.089; p = 0.162), with a prediction interval of -1.071 to 0.624. For those with narrower occlusion cuffs the results were similar to the overall strength analysis (g = -0.477, 95% CI = -0.740 to -0.214, p< 0.000), but with a bit lower upper limit of the prediction interval, which ranged from -1.154 to 0.199, as demonstrated in figure 6.



Group by Cuff	Study name	Hedges's g	Lower limit	Upper limit	p-Value
Narrow	Brandner et al. (2019)	-0.309	-1.119	0.501	0.455
	Clark et al. (2011)	-1.071	-2.076	-0.066	0.037
	Cook et al. (2017)	-0.852	-1.669	-0.035	0.041
	Cook et al. (2018)	-0.726	-1.810	0.359	0.190
	Davids et al. (2021)	-0.190	-1.023	0.643	0.655
	Jessee et al. (2018)b	-1.025	-1.986	-0.063	0.037
	Karabulut et al. (2010)	0.760	-0.079	1.598	0.076
	Korkmaz et al. (2022)	0.520	-0.292	1.332	0.209
	Kubo et al. (2006)	-0.441	-1.332	0.451	0.333
	Letieri et al. (2018)b	-1.000	-1.840	-0.161	0.020
	Lixandrão et al. (2015)b	-0.615	-1.441	0.212	0.145
	Lixandrão et al. (2015)d	-0.579	-1.458	0.301	0.197
	Ozaki et al. (2013)	-0.620	-1.502	0.263	0.169
	May et al. (2022)	-0.390	-1.310	0.529	0.405
	Wang et al. (2022)	-0.844	-1.947	0.259	0.134
	Yasuda et al. (2011)	-0.753	-1.624	0.119	0.090
	Pooled	-0.477	-0.740	-0.214	0.000
	Prediction Interval	-0.477	-1.154	0.199	
Wide	Ellefsen et al. (2015)	0.012	-0.760	0.785	0.975
	Jessee et al. (2018)a	-1.167	-2.184	-0.150	0.025
	Laswati et al. (2018)	0.655	-0.422	1.731	0.234
	Laurentino et al. (2012)	0.766	-0.128	1.660	0.093
	Letieri et al. (2018)a	-0.096	-0.889	0.697	0.813
	Libardi et al. (2015)	-0.452	-1.350	0.446	0.324
	Lixandrão et al. (2015)a	-0.713	-1.585	0.159	0.109
	Lixandrão et al. (2015)c	-0.630	-1.558	0.299	0.184
	Martín-Hernández et al. (2013)	-0.483	-1.326	0.360	0.262
	Ramis et al. (2020)	-0.042	-0.781	0.697	0.911
	Sousa et al. (2017)	-0.818	-1.676	0.041	0.062
	Sugiarto et al. (2017)	0.773	-0.318	1.864	0.165
	Vechin et al. (2015)	-0.509	-1.452	0.434	0.290
	Pooled	-0.223	-0.536	0.089	0.162
	Prediction Interval	-0.223	-1.071	0.624	

Effect on strength – grouped by occlusion-cuff

Narrower cuff: ≥111mmHg/ ≤139mm Q=20.965 p=0.138 T^2=0.081 T=0.285 I^2=28.451

Wider cuff:≤110/ ≥140mm Q=19.201 p=0.084 T^2=0.123 T=0.351 I^2=37.530

Figur 6. Forest plot displaying the effect size difference for muscle strength between high-load (HL) training and blood flow restriction (BFR) training according to occlusion cuff-with. Different letters for the same study represent different protocols.

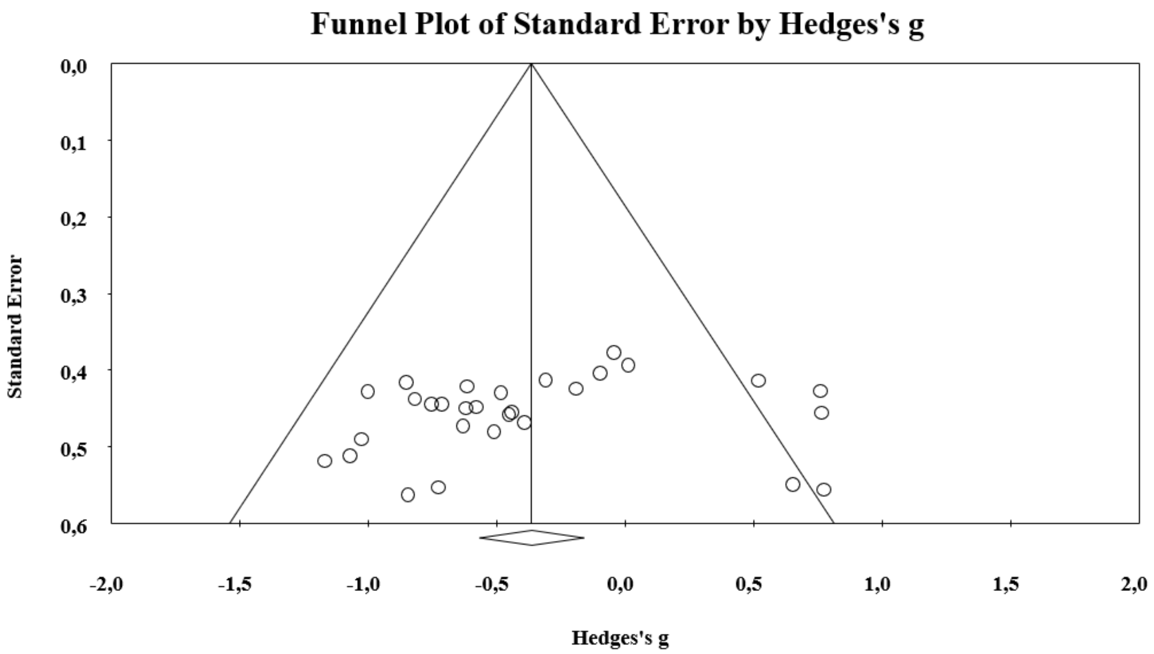
Risk of publication bias and sensitivity-analysis

The funnel-plot visual analysis for the hypertrophy studies revealed that the studies were distributed somewhat symmetrical around the combined effect-size, with equal number of studies on the right and left sides of the mean. Publication bias was therefore not suspected.

Funnel-plot analysis of the strength studies were also performed. There could be observed a small asymmetry in the funnel-plot with more smaller studies on the HL-side of the mean, and fewer studies reporting effect-sizes from 0-0.5 on the BFR-side of the mean (figure 7).

Examining the statistics showed no significance that there in fact was any publication bias, with an Egger`s test of the interception was equal to -1.776 (1-tailed p= 0.218), Kendall`s tau with continuing correction of -0.184 (1-tailed p= 0.079). The classical fail-safe N suggested that 114 “null” studies in order for the combined 2-tailed p-value to exceed 0.050.

Sensitivity analyses were performed to see if the results were robust to lower correlation-coefficients and changing the R-value to 0.6 did not change the results for either the strength-, or the hypertrophy-analysis.



Figur 7. Funnel plot of studies comparing increases in muscle strength between high-load training and blood flow restricted training.

Discussion

The purpose of the present study was to systematical review the literature regarding the effects of blood flow restriction on skeletal muscle hypertrophy and strength. The main findings were that there were no significant differences between the two training methods with regard to changes in muscle hypertrophy. However, for strength, there were significant differences favoring HL. These results did not differ when grouping by age-groups, but occlusion pressure seemed to affect the strength-results, with narrower cuffs favoring high loads, while wider cuff widths showed no significant differences between protocols.

Skeletal muscle hypertrophy

We found no significant difference between the two methods with regard to skeletal muscle hypertrophy, which are similar to the previous meta-analysis published by Lixandrao et al. (2018). Meaning that the inclusion of 12 studies (Brandner et al., 2019; Cook et al., 2017; Cook et al., 2018; Davids et al., 2021; Jessee et al., 2018; Kataoka et al., 2022; Korkmaz et al., 2022; Laswati et al., 2018; Letieri et al., 2018; May et al., 2022; Ramis et al., 2020; Sousa et al., 2017; Sugiarto et al., 2017; Wang et al., 2022) did not change the results of the overall body of literature. Moreover, since our meta-analysis showed low heterogeneity, the variations in effects are likely due to sampling error rather than true variations, meaning that the result of most of similar studies should fall between the confidence interval of this study (Borenstein et al., 2021).

One of the studies pooled triceps and pectoralis major when examining muscle hypertrophy (Ozaki et al., 2013). As pectoralis major is proximal to the occlusion cuff, this could affect the results, as some of the mechanisms expected to play a part in making BFR an effective strategy for enhancing muscle hypertrophy should not affect the muscles proximal to the cuff. Earlier meta-analysis, examining the effect of BFR training on upper body muscles proximal to the occlusion cuff, had findings suggesting that low load BFR training resulted in similar muscle hypertrophy as HL-training in muscles not directly under occluded conditions, but with little certainty as only a few studies were included (Pavlou et al., 2023). As our sensitivity analysis showed that removing the Ozaki et al. (2013) study from the analysis would not change the results. Therefore, it was included in the overall hypertrophy analysis. When examining the differences in effects for upper and lower body, the analysis showed trends favouring HL-group with moderate effect-size for the upper body. When taking out the studies with muscles proximal to the occlusion cuff, the effect size was almost unchanged, but with larger p-values. This could possibly be due to lack of power, as only three studies remained in the analysis.

One of the suggested mechanisms behind BFR is that the occlusion leads to hypoxia, causing an accumulation of metabolites and thereby may enhance muscle hypertrophy trough metabolic stress (Pope et al., 2013; Wackerhage et al., 2019). This raised a hypothesis that narrower cuff, with higher occlusion pressure could be more efficient than wider cuffs because it probably would lead to a greater degree of hypoxia. The results of grouping by occlusion cuff analysis showed no differences in results between the two cuff-prescriptions. A review by Spitz et al. (2022) compared perceived discomfort between performing resistance exercise with and without BFR and reported that narrower occlusion pressure resulted in more perceived discomfort than wider occlusion pressure in the lower body. In the upper body there seemed to be less discomfortable to use narrower cuffs. Therefore, since we found no impact on occlusion cuff pressure on skeletal muscle hypertrophy, we suggest using wider cuff (≤110mmHg) for the lower body and narrower cuffs (≥110mmHg) for the upper body when BFR are used in resistance training to enhance muscle hypertrophy.

When examining the training-prescription for the included studies, questions were raised as only a few studies mentioned performing sets to failure. As going to failure, or at least being close to failure has been seen to promote muscle hypertrophy to a greater degree than for those not performing the sets to failure (Vieira et al., 2021). When grouping the studies based on who reported performing sets to failure, the results showed no differences from the overall analysis. This was not surprising, as HL-groups taking sets to failure were compared to BFR-groups performing sets to failure. When comparing the training prescription for those studies not reporting performing sets to failure, one can argue that based on the prescription, the HL-groups should be closer to failure than the BFR-groups, as despite individual differences and occlusion cuffs, 8-10 reps at 80% of 1RM should be closer to failure than 20-30 reps at 20-30% of 1RM. This could possibly influence the results (Baechle & Earle, 2008; Dos Remedios, 2007).

Another factor playing a major role for hypertrophy studies is exercise volume, as it has shown a dose-response relationship for muscle hypertrophy (Figueiredo et al., 2018). Only one of the studies (Ramis et al., 2020) was volume equated in terms of total tonnage (sets x reps x kg lifted). Because of the high number of repetitions used in the BFR-training-prescriptions, BFR-groups usually have slightly larger volume in terms of total tonnage. However, most of the different BFR-training-prescriptions used shorter inter-set-rest periods (~30s) compared to the HL-training prescriptions (~3min). As longer inter-set-rest periods (>60s) have been suggested as superior for muscle hypertrophy (Grgic et al., 2017), one can speculate that there is need of higher exercise volume when implementing low-load BFR training as compared with high-load training to achieve the same results in skeletal muscle hypertrophy.

Muscular strength

The results from the overall effects on strength-outcomes were similar to an earlier review of Lixandrao et al. (2018) and found that HL-training is more efficient then BFR-training on increasing muscle strength. However, when only including studies and outcomes examining strength gains in the upper body, there were no significant differences between the two methods.

The differences in muscle strength adaptions between the two protocols may be related to the principle of specificity, as training with high loads is more similar to typical strength tests. This is somewhat in accordance with the results of the pooled by test-specificity, where HL-training were a lot more effective than BFR-training when using 1RM and AMRAP tests, which are considered specific strength tests. HL-training was also more effective than BFR-training for the nonspecific tests, but these effects were lower. Interestingly, when pooling the different non-specific tests, a very large effect size favouring HL-groups were evident for isometric strength. For the isokinetic strength tests however, BFR-groups showed similar effects as HL-groups for enhancing isokinetic strength. However, the reason for this difference is beyond the scope of this review.

Another assumption to why HL-training enhances muscle strength to a greater degree than BFR-training could be associated with the motor unit recruitment. Motor unit recruitment is typically estimated via surface electromyography (sEMG), and some studies has shown higher sEMG-amplitudes in HL-groups compared to low-loads with BFR-groups (Cook et al., 2013; Manini & Clark, 2009). These arguments should nevertheless be interpreted with caution as sEMG amplitudes alone do not necessary represent the motor unit recruitment, especially when comparing high load conditions with low load conditions, as fatigued motor units can be momentarily de-recruited to reduce fatigue (Vigotsky et al., 2017). This phenomenon was referred to as motor unit cycling. However, one can still assume that HL-training may lead to greater motor unit recruitment than BFR-training, as the results of this meta-analysis revealed that HL-training resulted in greater increases in isometric maximal voluntary contractions than the BFR-training.

The superior gains in muscle strength observed by the HL-protocols could also be related to Muscle-fibre-type as a recent review on the topic had intriguing preliminary evidence that suggesting that BFR-training might enhance type I muscle-fibre hypertrophy to as great as, and sometimes greater than type II (Schoenfeld et al., 2023). In contrast, this is usually not the case when performing HL-training, where type II hypertrophy tends to be considerably greater than type I hypertrophy (Schoenfeld et al., 2023). As type II muscle fibres are known to produce greater force than type I fibres(Lieber, 2002), this could be a reason to why HL-training promotes strength to a greater degree than BFR-training. However, this is only speculation as this meta-analysis lacks the data to discuss muscle fibre specific hypertrophy.

Moreover, pooling studies according to occlusion pressure resulted in similar results as the overall strength analysis for those using narrow cuffs, but for those using wide cuffs we found no significant differences between groups. It is speculated that this could be because narrower cuffs result in earlier fatigue of the muscles distal from the occlusion pressure, probably achieving higher velocity-loss during sets compared to those using wider cuffs. This speculation is based on that it is observed a reverse u-shaped relationship between velocity-loss and maximal strength gains, where the most effectively velocity-loss to contribute to maximum strength development ranged between 20-30% (Zhang et al., 2023). This review lacks the data to further examine whether any of these protocols falls in the optimal range and can therefore not conclude that the this is the reason for these results.

Limitations and implications for future studies

Unfortunately, this study was not able to include the hypertrophy-data of Martín-Hernández et al. (2013) due to lack of reporting. However, the sensitivity analysis showed that none of the included studies alone had any large impact on the results. Additionally, the data on hypertrophy were considered homogeny. Therefore, we can assume that the inclusion of the Martín-Hernández et al. (2013) study would not have changed these results.

Due to limited studies examining the effect of BFR on resistance-trained individuals, it was not possible to group the studies based on training-status. This should be addressed in more future studies to further examine the effects of BFR-training for the more athletic population. When examining the effect of BFR-training on hypertrophy in the upper body, results suggested a lack of power because of few included studies. Future studies should therefore seek to further examine the effect of BFR-training on the upper-body muscles.

Conclusion and practical application

In conclusion, our findings indicates that both BFR and HL-training are equally effective in enhancing skeletal muscle hypertrophy. However, our results suggest that HL-training may be more effective than BFR in increasing overall and lower-body strength, whereas BFR are equally effective as HL training in enhancing upper-body strength. This makes BFR a resource for those aiming to enhance skeletal muscle hypertrophy and strength, but who does not have the capacity, resource or possibility to training with HL.

References

Baechle, T. R., & Earle, R. W. (2008). *Essentials of strength training and conditioning*. Human kinetics.

Borenstein, M., Hedges, L. V., Higgins, J. P., & Rothstein, H. R. (2021). *Introduction to meta-analysis*. John Wiley & Sons.

Brandner, C. R., Clarkson, M. J., Kidgell, D. J., & Warmington, S. A. (2019). Muscular adaptations to whole body blood flow restriction training and detraining. *Frontiers in physiology*, *10*, 1099.

Centner, C., Wiegel, P., Gollhofer, A., & König, D. (2019). Effects of blood flow restriction training on muscular strength and hypertrophy in older individuals: a systematic review and meta-analysis. *Sports Medicine*, *49,* 95-108.

Clark, B. C., Manini, T., Hoffman, R., Williams, P., Guiler, M., Knutson, M., McGlynn, M., & Kushnick, M. (2011). Relative safety of 4 weeks of blood flow-restricted resistance exercise in young, healthy adults. *Scandinavian journal of medicine & science in sports*, *21*(5), 653-662.

Cohen, J. (1988). edition 2. Statistical power analysis for the behavioral sciences. Hillsdale. L. In: Erlbaum Associates.

Cook, S. B., LaRoche, D. P., Villa, M. R., Barile, H., & Manini, T. M. (2017). Blood flow restricted resistance training in older adults at risk of mobility limitations. *Experimental gerontology*, *99*, 138-145.

Cook, S. B., Murphy, B. G., & Labarbera, K. E. (2013). Neuromuscular function after a bout of low-load blood flow-restricted exercise. *Medicine and science in sports and exercise*, *45*(1), 67-74.

Cook, S. B., Scott, B. R., Hayes, K. L., & Murphy, B. G. (2018). Neuromuscular adaptations to low-load blood flow restricted resistance training. *Journal of sports science & medicine*, *17*(1), 66.

Davids, C. J., Næss, T. C., Moen, M., Cumming, K. T., Horwath, O., Psilander, N., Ekblom, B., Coombes, J. S., Peake, J., & Raastad, T. (2021). Acute cellular and molecular responses and chronic adaptations to low-load blood flow restriction and high-load resistance exercise in trained individuals. *Journal of applied physiology*, *131*(6), 1731-1749.

Dos Remedios, R. (2007). *Men's Health Power Training: Build Bigger, Stronger Muscles Through Performance-Based Conditioning*. Rodale Books.

Ellefsen, S., Hammarström, D., Strand, T. A., Zacharoff, E., Whist, J. E., Rauk, I., Nygaard, H., Vegge, G., Hanestadhaugen, M., & Wernbom, M. (2015). Blood flow-restricted strength training displays high functional and biological efficacy in women: a within-subject comparison with high-load strength training. *American Journal of Physiology-Regulatory, Integrative and Comparative Physiology, 309*(7), R767-R779.

Figueiredo, V. C., de Salles, B. F., & Trajano, G. S. (2018). Volume for muscle hypertrophy and health outcomes: the most effective variable in resistance training. *Sports Medicine*, *48*, 499-505.

Garber, C. E., Blissmer, B., Deschenes, M. R., Franklin, B. A., Lamonte, M. J., Lee, I.-M., Nieman, D. C., & Swain, D. P. (2011). American College of Sports Medicine position stand. Quantity and quality of exercise for developing and maintaining cardiorespiratory, musculoskeletal, and neuromotor fitness in apparently healthy adults: guidance for prescribing exercise. *Medicine and science in sports and exercise, 43*(7), 1334-1359.

Gil, A. L., Neto, G. R., Sousa, M. S., Dias, I., Vianna, J., Nunes, R. A., & Novaes, J. S. (2017). Effect of strength training with blood flow restriction on muscle power and submaximal strength in eumenorrheic women. *Clinical Physiology and Functional Imaging*, *37*(2), 221-228.

Grgic, J., Lazinica, B., Mikulic, P., Krieger, J. W., & Schoenfeld, B. J. (2017). The effects of short versus long inter-set rest intervals in resistance training on measures of muscle hypertrophy: A systematic review. *European journal of sport science*, *17*(8), 983-993.

Grønfeldt, B. M., Lindberg Nielsen, J., Mieritz, R. M., Lund, H., & Aagaard, P. (2020). Effect of blood-flow restricted vs heavy-load strength training on muscle strength: systematic review and meta-analysis. *Scandinavian journal of medicine & science in sports*, *30*(5), 837-848.

Higgins, J. P., Thomas, J., Chandler, J., Cumpston, M., Li, T., Page, M. J., & Welch, V. A. (2019). *Cochrane handbook for systematic reviews of interventions*. John Wiley & Sons.

Hughes, L., Paton, B., Rosenblatt, B., Gissane, C., & Patterson, S. D. (2017). Blood flow restriction training in clinical musculoskeletal rehabilitation: a systematic review and meta-analysis. *British journal of sports medicine*, *51*(13), 1003-1011.

Hwang, P. S., & Willoughby, D. S. (2019). Mechanisms behind blood flow–restricted training and its effect toward muscle growth. *The Journal of Strength & Conditioning Research*, *33*, S167-S179.

Jessee, M. B., Buckner, S. L., Mouser, J. G., Mattocks, K. T., Dankel, S. J., Abe, T., Bell, Z. W., Bentley, J. P., & Loenneke, J. P. (2018). Muscle adaptations to high-load training and very low-load training with and without blood flow restriction. *Frontiers in physiology*, *9*, 1448.

Jones, M. J., Dominguez, J. F., Macatugal, C., Coleman, K., Reed, B., & Schroeder, E. (2023). Low Load With BFR vs. High Load Without BFR Eccentric Hamstring Training Have Similar Outcomes on Muscle Adaptation. *Journal of Strength and Conditioning Research*, *37*(1), 55-61.

Karabulut, M., Abe, T., Sato, Y., & Bemben, M. G. (2010). The effects of low-intensity resistance training with vascular restriction on leg muscle strength in older men. *European Journal of Applied Physiology*, *108*, 147-155.

Kataoka, R., Vasenina, E., Hammert, W. B., Ibrahim, A. H., Dankel, S. J., & Buckner, S. L. (2022). Muscle growth adaptations to high-load training and low-load training with blood flow restriction in calf muscles. *European Journal of Applied Physiology*, *122*(3), 623-634.

Korkmaz, E., Dönmez, G., Uzuner, K., Babayeva, N., Torgutalp, Ş. Ş., & Özçakar, L. (2022). Effects of blood flow restriction training on muscle strength and architecture. *Journal of Strength and Conditioning Research*, *36*(5), 1396-1403.

Kubo, K., Komuro, T., Ishiguro, N., Tsunoda, N., Sato, Y., Ishii, N., Kanehisa, H., & Fukunaga, T. (2006). Effects of low-load resistance training with vascular occlusion on the mechanical properties of muscle and tendon. *Journal of applied biomechanics*, *22*(2), 112-119.

Laswati, H., Sugiarto, D., Poerwandari, D., Pangkahila, J. A., & Kimura, H. (2018). Low-intensity exercise with blood flow restriction increases muscle strength without altering hsCRP and fibrinogen levels in healthy subjects. *Chin J Physiol*, *61*(3), 188-195.

Laurentino, G. C., Ugrinowitsch, C., Roschel, H., Aoki, M. S., Soares, A. G., Neves Jr, M., Aihara, A. Y., Fernandes Ada, R., & Tricoli, V. (2012). Strength training with blood flow restriction diminishes myostatin gene expression. *Med Sci Sports Exerc*, *44*(3), 406-412.

Letieri, R. V., Teixeira, A. M., Furtado, G. E., Lamboglia, C. G., Rees, J. L., & Gomes, B. B. (2018). Effect of 16 weeks of resistance exercise and detraining comparing two methods of blood flow restriction in muscle strength of healthy older women: A randomized controlled trial. *Experimental gerontology*, *114*, 78-86.

Libardi, C., Chacon-Mikahil, M., Cavaglieri, C., Tricoli, V., Roschel, H., Vechin, F., Conceição, M., & Ugrinowitsch, C. (2015). Effect of concurrent training with blood flow restriction in the elderly. *International Journal of Sports Medicine, 36*(05), 395-399.

Lieber, R. L. (2002). *Skeletal muscle structure, function, and plasticity*. Lippincott Williams & Wilkins.

Lixandrao, M. E., Ugrinowitsch, C., Berton, R., Vechin, F. C., Conceição, M. S., Damas, F., Libardi, C. A., & Roschel, H. (2018). Magnitude of muscle strength and mass adaptations between high-load resistance training versus low-load resistance training associated with blood-flow restriction: a systematic review and meta-analysis. *Sports Medicine, 48*, 361-378.

Lixandrão, M. E., Ugrinowitsch, C., Laurentino, G., Libardi, C. A., Aihara, A. Y., Cardoso, F. N., Tricoli, V., & Roschel, H. (2015). Effects of exercise intensity and occlusion pressure after 12 weeks of resistance training with blood-flow restriction. *European Journal of Applied Physiology*, *115*, 2471-2480.

Manini, T. M., & Clark, B. C. (2009). Blood flow restricted exercise and skeletal muscle health. *Exercise and sport sciences reviews*, *37*(2), 78-85.

Martín-Hernández, J., Marín, P., Menéndez, H., Ferrero, C., Loenneke, J., & Herrero, A. (2013). Muscular adaptations after two different volumes of blood flow-restricted training. *Scandinavian journal of medicine & science in sports*, *23*(2), e114-e120.

May, A. K., Russell, A. P., Della Gatta, P. A., & Warmington, S. A. (2022). Muscle Adaptations to Heavy-Load and Blood Flow Restriction Resistance Training Methods. *Frontiers in physiology*, 82.

Ozaki, H., Yasuda, T., Ogasawara, R., Sakamaki-Sunaga, M., Naito, H., & Abe, T. (2013). Effects of high-intensity and blood flow-restricted low-intensity resistance training on carotid arterial compliance: role of blood pressure during training sessions. *European Journal of Applied Physiology*, *113*, 167-174.

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., & Brennan, S. E. (2021). The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *Systematic reviews, 10*(1), 1-11.

Pavlou, K., Korakakis, V., Whiteley, R., Karagiannis, C., Ploutarchou, G., & Savva, C. (2023). The effects of upper body blood flow restriction training on muscles located proximal to the applied occlusive pressure: A systematic review with meta-analysis. *PLoS One*, *18*(3), e0283309.

Pope, Z. K., Willardson, J. M., & Schoenfeld, B. J. (2013). Exercise and blood flow restriction. *The Journal of Strength & Conditioning Research*, *27*(10), 2914-2926.

Ramis, T. R., de Lemos Muller, C. H., Boeno, F. P., Teixeira, B. C., Rech, A., Pompermayer, M. G., da Silva Medeiros, N., de Oliveira, Á. R., Pinto, R. S., & Ribeiro, J. L. (2020). Effects of traditional and vascular restricted strength training program with equalized volume on isometric and dynamic strength, muscle thickness, electromyographic activity, and endothelial function adaptations in young adults. *The Journal of Strength & Conditioning Research*, *34*(3), 689-698.

Ratamess, N. A., Alvar, B. A., Evetoch, T. E., Housh, T. J., Ben Kibler, W., Kraemer, W. J., & Triplett, N. T. (2009). Progression models in resistance training for healthy adults. *Medicine and science in sports and exercise*, *41*(3), 687-708.

Schoenfeld, B. J. (2020). *Science and development of muscle hypertrophy*. Human Kinetics.

Schoenfeld, B. J., Ogborn, D., Piñero, A., Burke, R., Coleman, M., & Rolnick, N. (2023). Fiber-Type-Specific Hypertrophy with the Use of Low-Load Blood Flow Restriction Resistance Training: A Systematic Review. *Journal of Functional Morphology and Kinesiology*, *8*(2), 51.

Smart, N. A., Waldron, M., Ismail, H., Giallauria, F., Vigorito, C., Cornelissen, V., & Dieberg, G. (2015). Validation of a new tool for the assessment of study quality and reporting in exercise training studies: TESTEX. *JBI Evidence Implementation*, *13*(1), 9-18.

Sousa, J., Neto, G., Santos, H., Araújo, J., Silva, H., & Cirilo-Sousa, M. (2017). Effects of strength training with blood flow restriction on torque, muscle activation and local muscular endurance in healthy subjects. *Biology of sport*, *34*(1), 83-90.

Spitz, R. W., Wong, V., Bell, Z. W., Viana, R. B., Chatakondi, R. N., Abe, T., & Loenneke, J. P. (2022). Blood flow restricted exercise and discomfort: a review. *Journal of Strength and Conditioning Research*, *36*(3), 871-879.

Sugiarto, D., Andriati, A., Laswati, H., & Kimura, H. (2017). Comparison of the increase of both muscle strength and hypertrophy of biceps brachii muscle in strengthening exercise with low-intensity resistance training with and without the application of blood flow restriction and high-intensity resistance training. *Bali Medical Journal*, *6*(2), 251-257.

Vanwye, W. R., Weatherholt, A. M., & Mikesky, A. E. (2017). Blood flow restriction training: implementation into clinical practice. *International journal of exercise science*, *10*(5), 649.

Vechin, F. C., Libardi, C. A., Conceição, M. S., Damas, F. R., Lixandrão, M. E., Berton, R. P., Tricoli, V. A., Roschel, H. A., Cavaglieri, C. R., & Chacon-Mikahil, M. P. T. (2015). Comparisons between low-intensity resistance training with blood flow restriction and high-intensity resistance training on quadriceps muscle mass and strength in elderly. *The Journal of Strength & Conditioning Research*, *29*(4), 1071-1076.

Vieira, A. F., Umpierre, D., Teodoro, J. L., Lisboa, S. C., Baroni, B. M., Izquierdo, M., & Cadore, E. L. (2021). Effects of resistance training performed to failure or not to failure on muscle strength, hypertrophy, and power output: a systematic review with meta-analysis. *The Journal of Strength & Conditioning Research*, *35*(4), 1165-1175.

Vigotsky, A. D., Beardsley, C., Contreras, B., Steele, J., Ogborn, D., & Phillips, S. M. (2017). Greater electromyographic responses do not imply greater motor unit recruitment and 'hypertrophic potential'cannot be inferred. *The Journal of Strength & Conditioning Research*, *31*(1), e1-e4.

Wackerhage, H., Schoenfeld, B. J., Hamilton, D. L., Lehti, M., & Hulmi, J. J. (2019). Stimuli and sensors that initiate skeletal muscle hypertrophy following resistance exercise. *Journal of applied physiology*.

Wang, J., Fu, H., QiangZhang, Zhang, M., & Fan, Y. (2022). Effect of Leg Half-Squat Training With Blood Flow Restriction Under Different External Loads on Strength and Vertical Jumping Performance in Well-Trained Volleyball Players. *Dose-Response*, *20*(3), 15593258221123673.

Wortman, R. J., Brown, S. M., Savage-Elliott, I., Finley, Z. J., & Mulcahey, M. K. (2021). Blood flow restriction training for athletes: A systematic review. *The American journal of sports medicine*, *49*(7), 1938-1944.

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. *European Journal of Applied Physiology*, *111*, 2525-2533.

Zhang, X., Feng, S., & Li, H. (2023). The Effect of Velocity Loss on Strength Development and Related Training Efficiency: A Dose–Response Meta–Analysis. Healthcare,