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RESEARCH

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The effects of blood flow restriction combined with endurance training on athletes' aerobic capacity, lower limb muscle strength, anaerobic power and sports performance: a meta-analysis

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Abstract

Objective To evaluate the effects of blood flow restriction (BFR) combined with endurance training on aerobic capacity, lower limb muscle strength, anaerobic power, and sports performance to supply effective scientific guidance for training. Two reviewers independently screened the literature, extracted data, and assessed the risk of bias of the included studies. We searched PubMed, Medline, Cochrane, SPORTDiscus and Web of Science databases up to 28 October 2024. Two reviewers independently screened the literature, extracted data, and assessed the risk of bias of the included studies. We calculated the effect size using standardized mean difference values and the random effects model. The results showed a medium effect size on maximal oxygen uptake ($\dot{V}O_2$max), a large effect size on lower limb muscle strength, a small effect size on anaerobic power and sports performance. In conclusion, while BFR training during endurance training had a significant positive effect on lower limb muscle strength and moderate improvement in $\dot{V}O_2$max, its impact on anaerobic power and sports performance was relatively small. These findings suggest that BFR training may be effective for enhancing muscle strength and aerobic capacity, but its benefits on anaerobic power and sport-specific performance may be limited. Therefore, it is important to carefully design BFR training programs to target specific outcomes.

Keywords Aerobic capacity, BFR, Endurance training, Meta-analysis, Sports performance

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Introduction

Blood flow restriction (BFR) training was first introduced by Dr. Yoshiaki Sato in 1966, also called Kaatsu training [1, 2]. BFR training is a method of using designed compression devices, such as a cuff or tourniquet, to wrap around the proximal part of the limbs, reducing arterial blood flow and restricting venous return to increase the effectiveness of muscle training [3]. In 1997, Japanese researchers first published their findings on BFR training and demonstrated that using BFR training could increase muscle strength and muscle mass while reducing the load

[1, 2]. Since then, BFR training has received widespread attention and application.

BFR training has been shown to improve metabolic efficiency [4], enhance neuromuscular activity such as fiber recruitment and intramuscular signaling [5, 6]. It has been shown to promote protein synthesis, cell swelling, and satellite cell proliferation [7, 8]. It's helpful for injured people to reduce pain signals, and alleviate muscle atrophy [9]. It could also improve skeletal muscle blood flow, induce vascular growth and enhance functional sympathetic nervous system [10, 11]. BFR training has been applied in the rehabilitation field [12] and public health [13], and has also attracted widespread attention from trainers.

BFR training has been shown to be effective in increasing muscle hypertrophy and strength [14]. The majority of BFR interventions were conducted with resistance exercise, and the results have shown benefits for athletes in muscle strength, hypertrophy, and sports performance [15]. However, in contrast, few studies have assessed its effects on the endurance training of athletes [16–18]. This scarcity may stem from the fact that muscle strength and hypertrophy are typically not induced in aerobic endurance exercises. Classic endurance training is known to result in enhanced cardiac output, maximal oxygen consumption, and mitochondrial biogenesis [19]. The overall improvement in both central and peripheral tissues allows for enhanced exercise economy and a greater ability for an individual to run for longer distances and times [20]. In contrast, strength training results in increases in muscle size (cross-sectional area [CSA]), neural adaptations (motor output), and improved strength (maximal force production) [21].

The results have shown that endurance exercise combined with BFR can promote improvements in muscle size, strength, maximal oxygen uptake ($\dot{V}O_2$max) and sports performance [22, 23]. BFR combined with aerobic endurance training could also provide a practical training method for improving cardiorespiratory fitness in clinical people, while maintaining or improving aerobic capacity in more trained individuals at reduced exercise intensity [24]. Aerobic power is often assessed through the measurement of $\dot{V}O_2$max, and other measures of sports performance such as time trial (TT) and lower limb muscle strength are also assessed commonly [24]. VO_2max is a widely accepted indicator of aerobic power and cardiorespiratory fitness, representing an athlete's ability to perform sustained aerobic work, which is crucial for endurance sports such as running, cycling, and rowing. Similarly, anaerobic power complements VO_2max by reflecting an athlete's ability to generate energy during high-intensity efforts when aerobic metabolism is insufficient. For endurance athletes, TT assesses an individual's ability to maintain high-intensity efforts over a fixed duration or distance. Lower limb muscle strength plays a significant role in endurance performance, as the lower body is primarily engaged during activities such as running, cycling, and rowing. Machine learning and data mining methods have increasingly demonstrated their importance in analyzing complex physiological and biomechanical datasets. These methods provide valuable insights into predicting sports performance and identifying injury risks in athletes [25–27].

Therefore, the objective of this study was to use a meta-analysis to evaluate the effect of BFR combined with endurance training on $\dot{V}O_2$max, lower limb muscle strength, anaerobic power, and sports performance of athletes and considered the impact of moderator variables.

Materials and method

We conducted the study according to the systematic review flowchart presented in preferred reporting items for systematic reviews and meta-analysis (PRISMA) (Table S1). Our research project has been registered with the International Prospective Register of Systematic Reviews (Prospero), registration number CRD42022349079.

Search strategy

Systematic searches were conducted on PubMed, Medline, Cochrane, SPORTDiscus and Web of Science from inception until 28 October 2024. The search algorithm included all possible keyword: ("blood flow restriction" OR "occlusion" OR "BFR" OR "restricted blood flow" OR "tourniquets" OR "KAATSU" OR "ischemia" OR "Vascular occlusion") AND ("players" OR "sportsman" OR "athlete" OR "sports person" OR "sportswomen") AND ("training" OR "exercise") (Table S2). In addition, the reference lists of each included study were searched for relevant publications.

Eligibility criteria

Inclusion criteria

The inclusion criteria were constructed around the population, intervention, comparison, outcome and study design (PICOS) tool [28]. 1) population: Healthy athletes with no previous injury history; 2) intervention: BFR combined with endurance training; 3) comparison: endurance training without BFR or no training; 4) outcome: $\dot{V}O2$max, lower limb muscle strength, anaerobic power and sports performance; and 5) study design: The included studies had to be randomized controlled trials (RCTs) or matched pairs design (MPD) trails. Muscle strength was assessed using an isokinetic dynamometer (e.g., Biodex System 3) and the exact tests used (e.g., one-repetition maximum (1RM), handgrip strength, or dynamometry). Sports performance was evaluated using the performance tests (e.g., agility tests, endurance tests, sprints, CMJ) and sport-specific skills (e.g., Futsal special performance test, running performance). Aerobic capacity was measured using VO_2max. Anaerobic power was assessed via a 30-s Wingate test using a cycle ergometer.

Exclusion criteria

Non-English studies were excluded. The exclusion criteria included: 1) non-trails; 2) studies that did not provide clear statistical data, such as standard deviations and mean values; and 3) studies for which the full text was unavailable.

Study selection

The management software Endnote 20 (Clarivate, Philadelphia, PA, USA) was used for the screening and exclusion of studies. First, two researchers used Endnote software for deduplication. Second, the included and excluded articles were determined after reading the titles and abstracts of the articles. Finally, we read the full texts and made further decisions about whether to include or exclude. Any disagreements were discussed and resolved by a third researcher.

Data extraction

We extracted data from original articles based on research, including 1) author, 2) sample size, 3) age, 4) year of publication, 5) outcome measures, 6) training duration, frequency and volume, 7) intervention measures, 8) sports event and country, 9) BFR protocol: cuff location, width and pressure, and 10) competitive level, i.e., professional and sub-professional, i.e. semi-professional [29].

Risk of bias of individual studies

The risk of bias (ROB) was assessed using the Cochrane Handbook (version 5.1.0): 1) randomization; 2) allocation concealment; 3) participant blinding; 4) outcome assessment blinding; 5) incomplete outcome data; 6) selective reporting; and 7) other bias. ROB is divided into three levels: high risk (five or more), moderate risk (three or four), and low risk (two or fewer) [30].

Data analysis

The meta-analysis was performed using Review Manager software (RevMan 5.4, Cochrane Collaboration, Oxford, UK) and Stata 14 software (StataCorp LLC, College Station, TX, USA). The data was extracted in the form of mean & SD (Table S3). There were potential differences between the studies, so we chose a random-effects model for the analysis instead of a fixed-effects model [28]. And I^2 statistics were used to determine heterogeneity between studies [31]. The significance was set at $\alpha = 0.05$. The magnitude of the outcome for all variables were determined by the standardized mean differences adjusted by Hedge's g and a 95% confidence interval (CI) due to the small sample size of the included studies [32]. The effect size for Hedge's g was categorized as ≤ 0.19 [trivial], 0.20–0.59 [small], 0.60–1.19 [moderate], and ≥ 1.20 [large] [33]. Funnel plot [34] and Egger's tests [35] were used to evaluate publication bias. Meta-regression is used to evaluate the impact of moderating variables on the outcome variable [36]. To assess the validity of the meta-regression assumptions, we performed diagnostic checks for outliers. Outliers were identified based on standardized residuals (absolute values greater than 3) [37]. Additionally, we generated boxplots to visually inspect the distribution of residuals (Supplementary Figure S2). Moderating variables are variables included in the meta-analysis that help explain more methodological differences [38]. In addition, we performed a sensitivity analysis to determine whether the pooled results were influenced by individual studies [39]. We used a leave-one-out approach to sequentially remove individual studies, ensuring that the pooled estimates were not unduly influenced by any single study.

Results

Study identification and selection

The flow chart for the selection of the literature is shown in Fig. 1, which shows that 9 studies were included after applying the eligibility criteria.

Characteristics of the included studies

Of the 9 studies, two study reports were extracted from one study. The age of the subjects ranged from 16 to 27 years, and the total sample size was 221 (male: 97%; female: 3%). All participants were at a semi-professional level (Table 1). Among the included studies, only one study had a three-arm design, while others had a two-arm design. Continuous pressure during training and recovery periods, training period pressure, and recovery period pressure were used in 4, 4, and 2 studies. The control groups all performed an equal amount of endurance training. Five studies focused on aerobic endurance training, while five studies focused on anaerobic endurance training. The duration of training ranged from 2 to 10 weeks. The frequency of training ranged from 2 to 3 sessions per week (Table 2).

Quality assessment of the included studies

The assessment of the quality is shown in Figs. 2 and 3. Randomization was mentioned in 7 studies. Specific allocation concealment methods were described in 1 study.

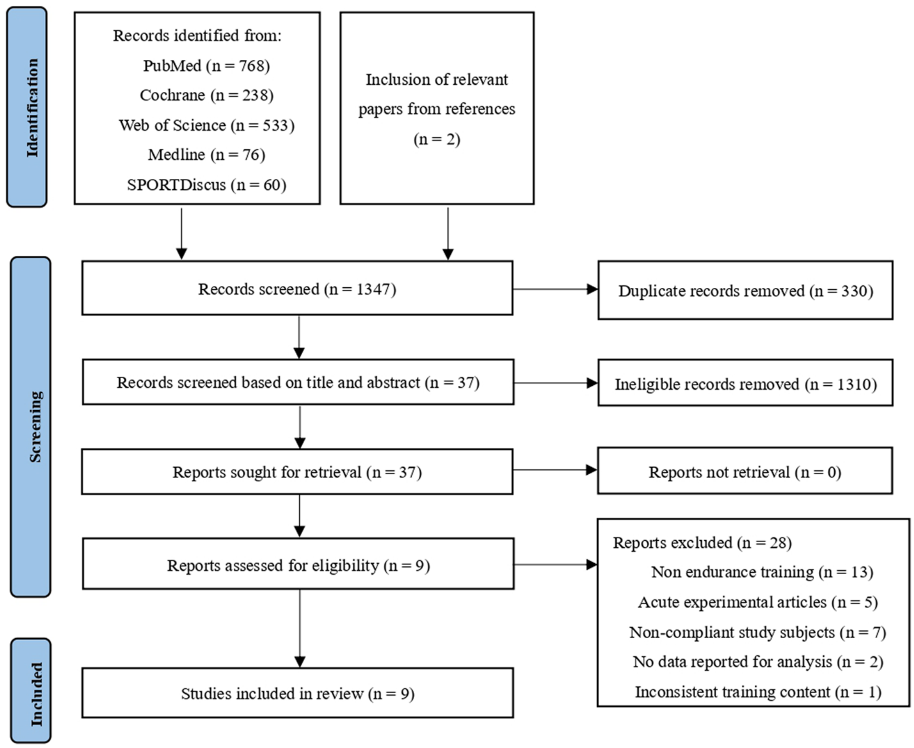

Fig. 1 Flow chart for inclusion and exclusion of studies

Table 1 Summary of included studies

Study	Study Design	Subjects (M, F)	Age (Mean ± SD)	Sport	Competitive Level	Country
Amani (2018) [40]	RCT	28, 0	23.89 ± 2.26	Soccer	semi-professional	Iran
Amani-Shalamzari (2019) [41, 42]	RCT	12, 0	23 ± 2	Soccer	semi-professional	Iran
Amani-Shalamzari (2020) [43]	RCT	12, 0	23 ± 2	Soccer	semi-professional	Iran
Held (2020) [44]	RCT	23, 8	21.9 ± 3.2	Rowing	semi-professional	Germany
Giovanna (2022) [45]	RCT	29, 0	25.6 ± 5.7	Endurance	semi-professional	Switzerland
Chen (2022) [46]	RCT	20, 0	21.5 ± 2.2	Middle- and Long-distance Running	semi-professional	Taiwan
Hosseini Kakhak (2022) [47]	RCT	19, 0	15.9 ± 0.8	Soccer	semi-professional	Iran
Mitchell (2019) [48]	RCT	21, 0	23 ± 5	Cycling	semi-professional	England
Taylor (2016) [23]	RCT	20, 0	27 ± 7	Cycling	semi-professional	England

7 studies were considered at high risk of performance bias. 8 studies had a low risk of reporting bias. Therefore, 1 study had a low risk of bias. And 8 studies had a moderate risk of bias. There was no study with a high risk of bias.

Meta-analysis

VO_2max

Seven studies were included to report the effects of BFR combined with endurance training on VO_2max (Fig. 4). The results showed a medium effect size on VO_2max with no heterogeneity between studies.

Lower limb muscle strength

Six studies were included to report the effects of BFR combined with endurance training on the lower limb muscle strength of athletes (Fig. 5). The results showed a large effect size on lower limb muscle strength with no heterogeneity between studies. The results of subgroup analysis showed a large effect size in muscle endurance,

Table 2 Experimental protocols and outcomes of included studies

Study	Group, Subjects	BFR protocol: cuff location / width/pressure	Duration, Frequency	Exercise Interventions	Outcome
Amani (2018) [40]	BFR-c, 9	The upper section of thigh, 180 mmHg	2 weeks, 2 sessions/week, 25–30 min/session	Week 1: 400 m, 3 × 4, 60–65% MHR; Week 2: 400 m, 4 × 4, 65–70% HHR	RPE, $\dot{V}O_2$max ($P < 0.05$)
	CON, 10			Week 1: 400 m, 3 × 4, 60–65% MHR; Week 2: 400 m, 4 × 4, 65–70% HHR	RPE, $\dot{V}O_2$max ($P > 0.05$)
Amani-Shalamzari (2019) [41, 42]	BFR-t, 6	The upper section of thigh, 13 × 124 cm, 110–140% SBP, 130–175 mmHg	3 weeks, 10 sessions, 20–30 min/session	SSG: 3 min × 4–8 reps, rest 2 min, 80–100 HRmax	FSPT, vastus lateralis, vastus medialis, Knee extension and flexion, vastus femoris ($p < 0.05$)
	CON, 6			SSG: 3 min × 4–8 reps, rest 2 min, 80–100 HRmax	FSPT($p > 0.05$); vastus lateralis, vastus medialis, Knee extension and flexion, vastus femoris ($p < 0.05$)
Amani-Shalamzari (2020) [43]	BFR-t, 6	The upper section of thigh, 13 × 124 cm, 110–140% SBP, 130–175 mmHg	3 weeks, 10 sessions, 20–30 min/session	SSG: 3 min × 4–8 reps, rest 2 min, 80–100 HRmax	$\dot{V}O_2$max, RE, TTF, AP, PP, MP (Wingate 30 s, $p < 0.05$)
	CON, 6			SSG: 3 min × 4–8 reps, rest 2 min, 80–100 HRmax	$\dot{V}O_2$max, PP ($p < 0.05$); RE, TTF, AP, MP (Wingate 30 s, $p > 0.05$)
Held (2020) [44]	BFR-c, 16	The upper section of thigh, 200 × 13 cm (cuff)	5 weeks, 3 sessions/week, 20 min/session	Rowing (low, medium, high intensity), cross (running and cycling) and strength training Low intensity: 65% MHR; Medium intensity: between the first lactate threshold and the second threshold; High intensity: above he second threshold	$\dot{V}O_2$max, AP ($p < 0.05$); 1RM single-leg Squat ($p > 0.05$)
	CON, 15			Rowing (low, medium, high intensity), cross (running and cycling) and strength training	$\dot{V}O_2$max, AP, 1RM single-leg Squat ($p > 0.05$)
Giovanna (2022) [45]	BFR-t, 10	The upper section of thigh, 88.2 ± 10.1 mmHg, 45% AOP	2 weeks, 3 sessions/week, 20 min/session	10 s sprint: 5 × 4	PP ($p < 0.05$); $\dot{V}O_2$max, VE, TT ($p > 0.05$)
	BFR-r, 10			10 s sprint: 5 × 4	PP ($p < 0.05$); $\dot{V}O_2$max, VE, TT ($p > 0.05$)
	CON, 9			10 s sprint: 5 × 4	PP ($p < 0.05$); $\dot{V}O_2$max, VE, TT ($p > 0.05$)
Chen (2022) [46]	BFR-c, 10	154 ± 6mmh g, the upper section of thigh, 14.2 cm × 67.5 cm	8 weeks, 3 sessions/week, 20 min/session	3 min running × 5, 1 min rest, 50% HHR	Running performance, Knee extension ($p < 0.05$); Knee flexion ($p > 0.05$)
	CON, 10			3 min running × 5, 1 min rest, 50% HHR	Running performance, Knee extension and flexion ($p > 0.05$)

Table 2 (continued)

Study	Group, Subjects	BFR protocol: cuff location / width/pressure	Duration, Frequency	Exercise Interventions	Outcome
Hosseini Kakhak (2022) [47]	BFR-c, 10	The upper section of thigh, 40×4 cm, 210 mmHg	6 weeks, 3 sessions/week, 45–60 min/session	SSG: 10–15 min, 65–80% HRmax, gradually increase the difficulty; Soccer training: 45–80% HRmax, 10–15 min; Plyometric training: 8–15 min, Running: 45–55% HRmax, 10–20 min	Hoff ($p < 0.05$); CMJ, 40 m sprint, COD ability, 1RM squat ($p > 0.05$)
	CON, 9			SSG: 10–15 min, 65–80% HRmax, gradually increase the difficulty; Soccer training: 45–80% HRmax, 10–15 min; Plyometric training: 8–15 min, Running: 45–55% HRmax, 10–20 min	Hoff ($p < 0.05$); CMJ, 40 m sprint, COD ability, 1RM squat ($p > 0.05$)
Mitchell (2019) [48]	BFR-r, 11	The upper section of thigh, 120 mmHg	4 weeks, 2 sessions/week, 24–30 min/session	30 s sprint × 4–7 reps, rest 4.5 min	$\dot{V}O_2max$ ($p < 0.05$); PP, MP ($p > 0.05$)
	CON, 10			30 s sprint × 4–7 reps, rest 4.5 min	$\dot{V}O_2max$, PP, MP ($p > 0.05$)
Taylor (2016) [23]	BFR-r, 10	The upper section of thigh, 130 mmHg	4 weeks, 2 sessions/week, 24–30 min/session	30 s sprint × 4–7 reps, rest 4.5 min	$\dot{V}O_2max$ ($p < 0.05$); PP, AP, MAP, TT ($p > 0.05$)
	CON, 10			30 s sprint × 4–7 reps, rest 4.5 min	$\dot{V}O_2max$, PP, AP, MAP, TT ($p > 0.05$)

BFR-c Continuous pressure during training and recovery periods, *BFR-t* pressure during training period, *BFR-r* Pressure during recovery period, *CON* Control group, *SBP* Systolic blood pressure, *TTF* run time to fatigue, *RE* Running economy, *PP* Peak power, *AP* Average power, *VE* Maximal minute ventilation, *CMJ* Counter movement jump, *RER* Respiratory exchange ratio, *RPE* Rate of perceived exertion, *TT* Time trial, *AOP* Arterial occlusion pressure, *HHR* Maximum heart rate reserve, *HRmax* Maximal heart rate, *Hoff* Soccer-specific endurance test, *SSG* Small-sided games, *FSPT* Futsal special performance test, *MP* Minimum power, *MAP* Maximal aerobic power

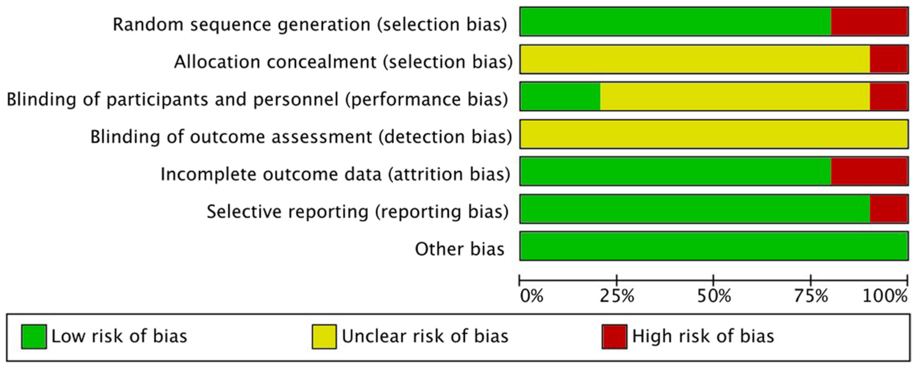

Fig. 2 Graph of risk of bias of the studies included

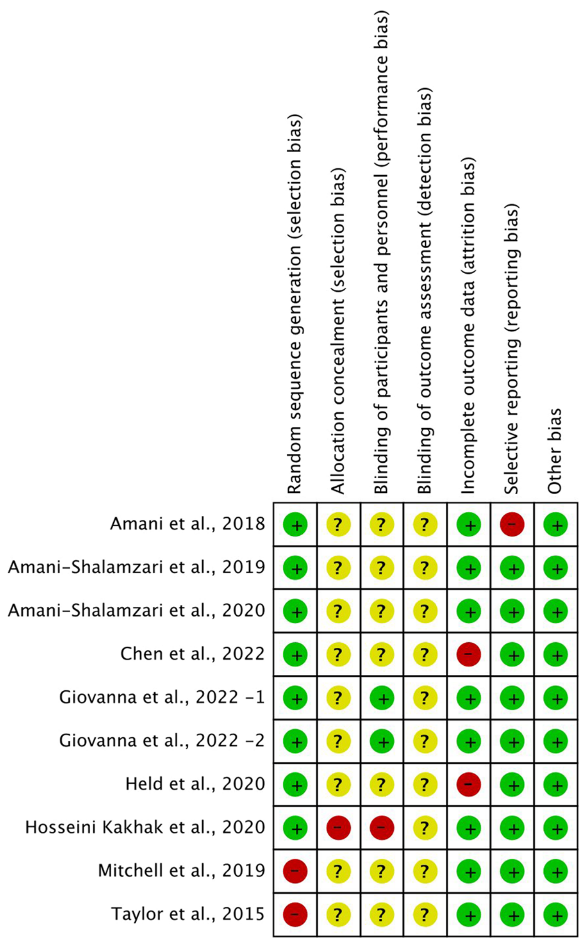

Fig. 3 Summary of risk of bias of the studies included

and a large effect size in knee extension strength and knee flexion strength.

Anaerobic power

Eight studies were included to report the effects of BFR combined with endurance training on the anaerobic power of athletes (Fig. 6). The results showed a small effect size on the anaerobic power with no heterogeneity between studies. The results of subgroup analysis showed a small effect size in mean power, and a small effect size in peak power.

Sports performance

A total of 4 studies reported the effects of BFR combined with endurance training on the sports performance of athletes (Fig. 7). The results showed a large effect size on sports performance with a high level of heterogeneity between studies.

Publication bias and sensitivity analysis

We constructed separate funnel plots for all the outcome measures to test for possible publication bias (Figure S1). The visual inspection of the funnel plots was largely symmetrical, and there may have been some degree of publication bias. The Egger test results showed that there was no significant publication bias for VO_2max ($p = 0.417$), for lower limb muscle strength ($p = 0.123$), anaerobic power ($p = 0.177$) and for sports performance ($p = 0.509$) (Table 3). No individual study altered the overall effect of anaerobic power significantly in the sensitivity analysis (Figure S3). With the exclusion of one study at a time, the pooled estimate was in the range of (*Hedge's* = 0.29; 95% CI: -0.13 to 0.70; $I^2 = 0\%$; $p = 0.18$) to (*Hedge's* = 0.43; 95% CI: 0.09 to 0.77; $I^2 = 0\%$; $p = 0.01$), with no significant change in the final assessment results. However, there were no significant changes in VO_2max and lower limb muscle strength. To solve the heterogeneity of sports performance, sensitivity analysis showed that when Hosseini Kakhak [47] were excluded, the heterogeneity decreased significantly ($I^2 = 0$, $p < 0.05$), and the effect size also decreased from large to small (*Hedge's* = 0.45, 95% CI: -0.11 to 1.01), so a combined analysis was performed after this item was excluded.

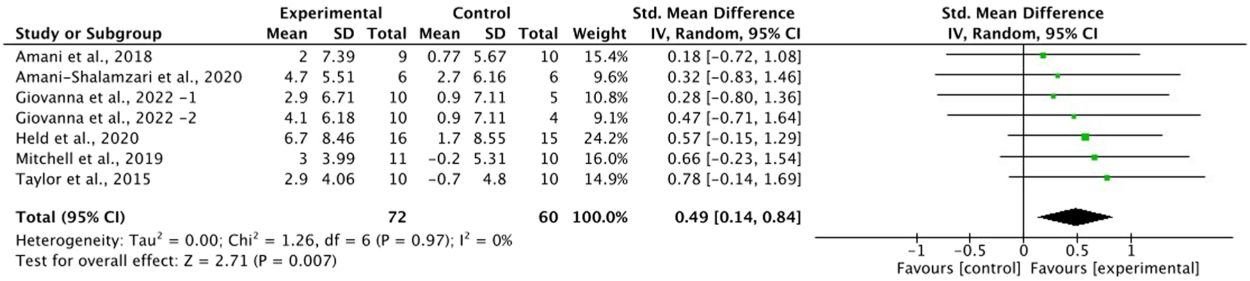

Fig. 4 The effects of BFR combined with endurance training on V̇O_2max of athletes (ml/min/kg)

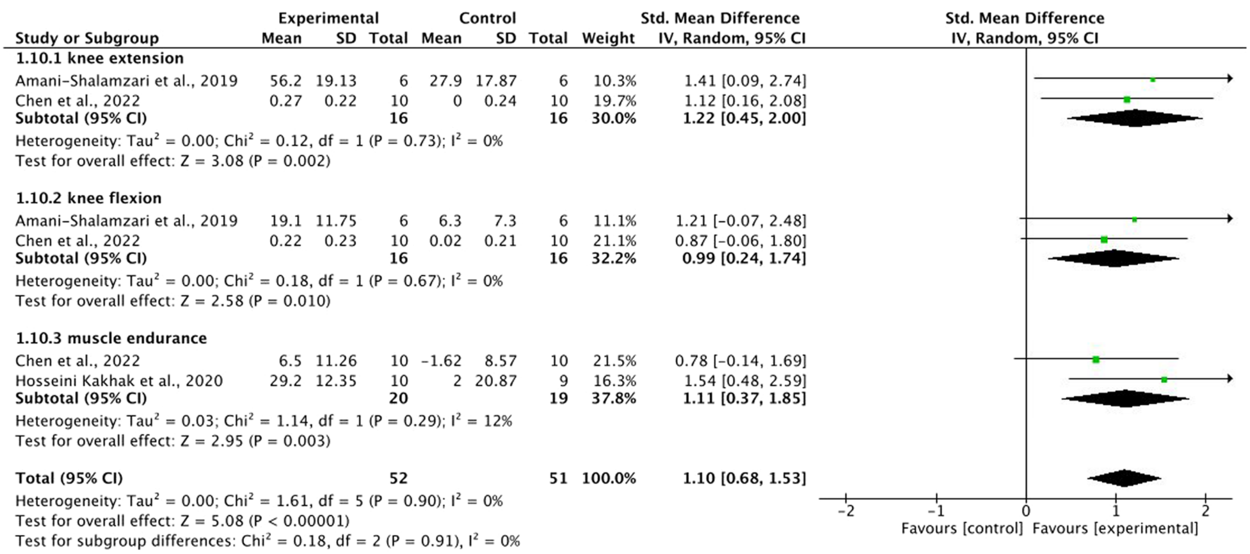

Fig. 5 The effects of BFR combined with endurance training on lower limb muscle strength of athletes (e.g., peak torque [Nm])

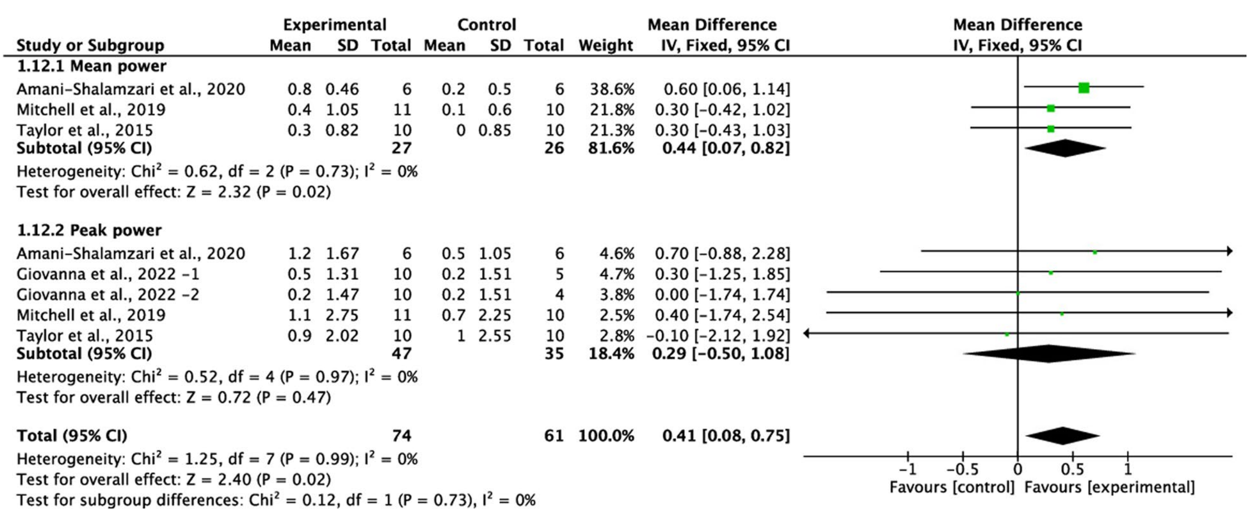

Fig. 6 The effects of BFR combined with endurance training on the anaerobic power of athletes (W/kg)

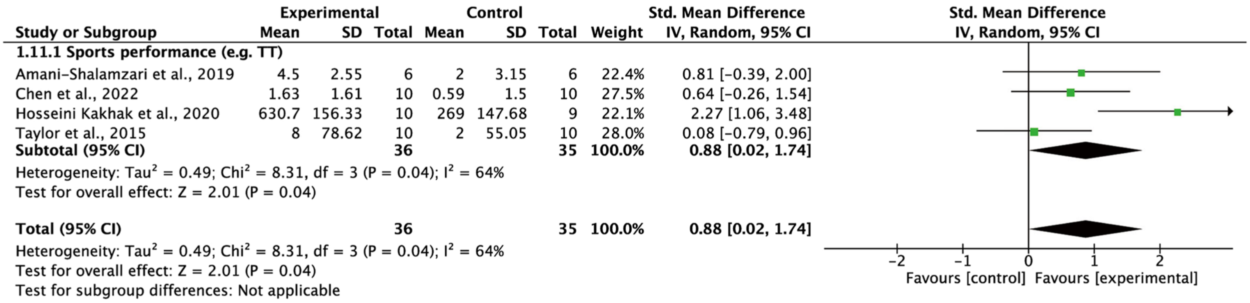

Fig. 7 The effects of BFR combined with endurance training on sports performance of athletes (e.g., TT [s])

Table 3 Egger's test results

Indicators	Std_Eff	Coef	Std.Err	t	*P*>|t|	[95% Conf.Interval]	
VO2max	slope	0.977,246,1	0.533,752,4	1.83	0.127	-0.394,808	2.3493
	bias	-0.986,758,5	1.116,619	-0.88	0.417	-3.857,119	1.883,602
Lower limb muscle strength	slope	-0.296,052	0.759,095,8	-0.39	0.716	-2.403,64	1.811,536
	bias	2.787,012	1.431,332	1.95	0.123	-1.187003	6.761027
Anaerobic power	slope	-0.877,102,7	0.773,412,6	-1.13	0.300	-2.76,957,5	1.015,37
	bias	2.359,891	1.541,417	1.53	0.177	-1.41,182,1	6.131,602
Sports performance	slope	-1.262,553	1.806,659	-0.70	0.612	-24.218,33	21.693,22
	bias	3.570,697	3.672,325	0.97	0.509	-43.090,62	50.232,01

Effect of moderator variables

To explore the effect of BFR combined with endurance training on various indicators, a random effects model was used, grouping by duration, frequency, total sessions, pressure type and training type, according to the distribution characteristics of the study. The specific results of analysis were shown in Tables 4 and 5. Meta-regression analysis showed no effect on the effect size ($p > 0.05$). The number of studies on sports performance indicators was insufficient for regression analysis.

Discussion

This meta-analysis included 9 RCTs and quantified the effects of BFR combined with endurance training on athletes' aerobic capacity, lower limb muscle strength, anaerobic power, and sports performance. With the addition of BFR to endurance training, athletes will experience greater gains in lower limb muscle strength and VO_2max. However, athletes experience little gains in anaerobic power and sports performance.

VO_2max

The results of this study do not support the previous findings of Castilla-López [17] which showed that the intervention effect on the maximal oxygen uptake of athletes had a large effect size, without statistical significance and with large heterogeneity, and combined with qualitative analysis, it could not significantly improve the aerobic capacity of athletes. However, our results

Table 4 Results of Meta-regression analysis

Moderator	VO^2max		Lower limb muscle strength		Anaerobic power	
	t	p	t	p	t	p
Pressure periods	-0.03	0.978	0.91	0.428	-0.21	0.840
Training type	0.42	0.718	–	–	-1.23	0.287
Duration	0.70	0.559	0.72	0.522	0.26	0.805
Frequency	0.07	0.954	–	–	-0.26	0.805
Total sessions	0.26	0.810	-0.91	0.428	1.23	0.287

Table 5 Results of subgroup analysis

Moderator	Sample size				SMD [95%CI]				I^2 (%)				P			
	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D
Pressure periods																
Continuous	50	79	–	–	0.42 [-0.14, 0.98]	1.05 [0.57, 1.53]	–	–	0	0	–	–	0.14	< 0.001	–	–
Training	48	24	53	–	0.45 [-0.13, 1.04]	1.31 [0.39, 2.22]	0.42 [-0.16, 1.00]	–	0	0	0	–	0.13	0.005	0.16	–
Recovery	34	–	82	–	0.66 [-0.06, 1.38]	–	0.20 [-0.24, 0.63]	–	0	–	0	–	0.07	–	0.38	–
Training type																
Aerobic	43	127	24	32	0.50 [0.11, 1.11]	0.99 [0.61, 1.37]	0.78 [-0.08, 1.63]	0.70 [-0.02, 1.42]	0	0	0	0	0.11	< 0.001	0.07	0.06
Anaerobic	89	–	111	–	0.49 [0.05, 0.92]	–	0.18 [-0.20, 0.56]	–	0	–	0	–	0.03	–	0.36	–
Duration (weeks)																
< 4	60	64	53	32	0.29 [-0.24, 0.82]	1.10 [0.56, 1.64]	0.42 [-0.16, 1.00]	0.70 [-0.02, 1.42]	0	0	0	0	0.28	< 0.001	0.16	0.06
4 ~ 8	72	39	82	–	0.65 [0.18, 1.13]	1.11 [0.37, 1.85]	0.20 [-0.24, 0.63]	–	0	12	0	–	0.007	0.003	0.38	–
Frequency (sessions/week)																
2	60	–	82	–	0.54 [0.02, 1.06]	–	0.20 [-0.24, 0.63]	–	0	–	0	–	0.04	–	0.38	–
> 2	72	127	53	32	0.45 [-0.03, 0.93]	0.99 [0.61, 1.37]	0.42 [-0.16, 1.00]	0.70 [-0.02, 1.42]	0	0	0	0	0.07	< 0.001	0.16	0.06
Total sessions																
< 10	89	24	111	–	0.49 [0.05, 0.92]	1.31 [0.39, 2.22]	0.18 [-0.20, 0.56]	–	0	0	0	–	0.03	0.005	0.36	–
≥ 10	43	79	24	32	0.50 [-0.11, 1.11]	1.05 [0.57, 1.53]	0.78 [-0.08, 1.63]	0.70 [-0.02, 1.42]	0	0	0	0	0.11	< 0.001	0.07	0.06

A VO_2max, *B* Lower limb muscle strength, *C* Anaerobic power, *D* Sports performance, Not applicable

showed that the effect size was moderate, and the statistical significance was significant. And there was no heterogeneity or publication bias, which increased the reliability of the evidence. Further analysis revealed that the study included trials on university students [41, 49], compared with athletes, VO_2max increases rapidly in university students [14], which may be the reason why this study has a larger effect size and heterogeneity. This review showed that the mean increase in VO_2max as a result of BFR training was 26.43 ml/km/kg greater than that seen in the control groups. Held [44] found a significant increase in VO_2max (9.1 ± 6.2% increase) after 5 weeks of low-intensity BFR training in rowing athletes. Chen [46] found a significant increase in VO_2max and maintained testosterone and cortisol ratio after 8 weeks of running combined with BFR training in endurance athletes. The mechanisms underlying this adaptive response are unknown; however, it seems likely that the observed increase in VO_2max is due to central adaptations such as increased cardiac output [48]. Given the higher expression of the angiogenic growth factor HIF-1, the current study provides preliminary evidence that enhanced skeletal muscle remodeling, particularly capillary density, may occur with BFR compared to SIT alone via enhanced hypoxia-induced cell signaling [23]. Finally, the results of the moderation analysis showed that potential factors did not play a role, and the effect sizes among subgroups did not differ significantly. Continuous pressure and recovery period pressure has a greater effect than training period pressure. Compared with training period pressure, applying pressure during the recovery period further exacerbates post-exercise lactate accumulation, challenging local energy metabolism, and achieving better training adaptations [50]. In terms of training volume and frequency, an 8-session training program (twice a week for four weeks) consisting of high-intensity interval running combined with BFR did not increase VO_2max significantly in college students [49]. The eight-session training program used in the study may not have been sufficient to induce the stimulus for capillary growth. It has been shown that increasing training intensity at the expense of training volume could decrease the protein content of vascular endothelial growth factor (VEGF) [51], which inhibits capillary growth [52].

Lower limb muscle strength

This review showed that the mean increase in knee extension strength as a result of BFR combined with endurance training was 1.22Nm [95% CI: 0.45, 2.00] greater than that seen in the control groups. The mean increase in knee flexion strength as a result of BFR combined with endurance training was 0.99Nm [95% CI: 0.24, 1.74] greater than that seen in the control groups. Slysz [53] found that 6 weeks of BFR aerobic exercise resulted in a strength mean improvement of 0.6Nm [95% CI: 0.4, 0.9] in human adult (>18 yr), while BFR resistance exercise resulted in a mean improvement of 0.3kg. In addition, BFR combined with aerobic endurance training could increase muscle strength and size in healthy men [54]. It has been shown that BFR combined with resistance training could increase athletes' muscle strength [55]. It may be because BFR training can increase muscle hypertrophy, blood oxygen saturation, and glycolytic capacity, resulting in greater muscle adaptive capacity [56–58]. The increase in strength is believed to depend on the mechanism of muscle hypertrophy, and BFR can trigger two main mechanisms of skeletal muscle adaptation: cellular swelling [6] and metabolite accumulation [59]. It stimulated the synthesis of anabolic hormones, further recruits fast-twitch muscle fibers and leads to an increase in strength [60]. It may also accelerate fatigue, thereby increasing the recruitment of motor units [61]. While a number of studies had shown that BFR training could lead to an increase in strength, there were also studies suggesting that BFR may simply be an additional supplement to high-load resistance training and may not result in greater strength adaptations (as measured by 1RM) [44]. It is possible that high volumes of endurance training may also inhibit strength adaptations, as there was a hypothesized interference effect between strength and endurance [62]. Finally, the results of the moderate variables showed that the potential factors did not have a moderating effect. There was a difference in the results between Chen [46] and Hosseini Kakhak [47]. It is no different from other studies in terms of training cycle, frequency, etc. However, in the Hosseini Kakhak [47], the subjects were young athletes, while other studies were all adult athletes. As observed with strength training, studies of the effects of endurance training on athletes of different ages had shown that 16-year-olds can get greater benefits from training than 21-year-old or 28-year-old [63, 64]. Additionally, the training plan included 10 min of plyometric training for the experimental group and control group, which could also be a contributing factor to the observed improvements. Plyometric training utilized the stretch–shortening cycle (SSC), which involves eccentric and concentric contractions of muscles and tendons, as well as the ability to transfer this energy into a horizontal push [65, 66]. At the same time, it can improve neuromuscular function (muscle coordination, size structure) and enhance surface reaction force [67, 68]. It can also improve the force and speed of muscle fiber contraction, Ca^+ sensitivity, fiber strength, and fiber size [69]. Therefore, the effect on muscle endurance should be considered carefully. And it should be studied in the future.

Anaerobic power

The results showed that BFR combined with endurance training has a small effect on anaerobic power (30s Wingate test). This review showed that the mean increase in mean power as a result of BFR training was 0.44W [95% CI: 0.07, 0.82] greater than that seen in the control groups. The mean increase in peak power as a result of BFR training was 0.29W [95% CI: -0.50, 1.08] greater than that seen in the control groups. An improvement in average power is important for endurance athletes. For example, the lactic-anaerobic system is the pre-dominant energy system in the football. Anaerobic interval training could improve athletes' anaerobic capacity, and adding BFR increases metabolic stress, leading to an increase in blood lactate [70]. In an acidic environment, there may be an increase in lactate tolerance, so it could improve the average power. The metabolic stress caused by BFR training is crucial in beginning muscle adaptations [71]. Dependence on anaerobic metabolism and disrupted oxygen transport during BFR training could result in increased muscle glycogen stores, which would boost anaerobic power [72]. The increase in peak power may be related to potential muscle hypertrophy and strength gains. For the moderator variables, significant differences were found between the subgroups in training type and total training sessions. It is well-known that compared with aerobic training, anaerobic interval training is more effective in improving anaerobic capacity. The results showed that 6 sessions of training over 2 weeks did not result in an improvement in maximum power output and muscle contraction efficiency, but significant differences were found after longer training periods [73]. A study with 3 sessions per week for 4 weeks, 12 sessions, improved related sports performance [74]. In addition, in 4 weeks of the repeat sprint training, an enhancement of average power and peak power was observed [75]. So, a longer period with higher total sessions would result in better effects. The small increase in peak and mean power could be attributed to the nature of the training protocols. The relatively short training durations in some studies (e.g., 6 sessions over 2 weeks) may not have provided enough stimulus to induce significant adaptations, particularly in peak power. And the effects of BFR training on anaerobic power might be more pronounced when combined with high-intensity interval training.

Sports performance

Our study supports the qualitative evaluation results of Castilla-López [17] on sports performance. The mean increase as a result of BFR training was 0.45s [95% CI: -0.11, 1.01] greater than that seen in the control groups (e.g., TT). However, the heterogeneity in sports performance outcomes highlights the complex relationship between training protocol and performance gains. Studies have shown that the effects of BFR training on sports performance are influenced by several factors, including the type of sport, the intensity of the training, and the duration. For example, Taylor [23] did not observe a significant improvement in the TT, longer duration TT was more likely limited by central fatigue. After a long time (> 30 min) and low-intensity TT, central nervous system fatigue may increase, reducing the sensitivity of TT performance, which may be why the effect of this study was not significant [76]. Inadequate training volume may not cause capillary growth. 4 weeks, 8 sessions of low-volume training did not cause capillary growth [48]. While after 6 weeks, 18 sessions of endurance training, the capillaries increased [77]. Based on the established relationship between capillary-to-fiber ratio and exhaustive high-intensity exercise lasting 30–40 min [78], the training effect on anaerobic and aerobic performance cannot be improved in a short time [79]. And improvements in Vo2max have been demonstrated to precede increases in skeletal muscle capillaries [80]. Therefore, despite large improvements in strength, and moderate improvements in VO_2max, the effect on performance was small. One study on presstherapy found that it did not observe any significant effect of presstherapy on jump performance when performed at various intervals after the previous exercise [81]. For optimal training outcomes, we recommend a moderate to high training volume over a 6-week period, with a mix of low and high-intensity sessions. Customizing the BFR protocol to match the specific needs of the athlete and sport will likely lead to better improvements in performance.

It should be noted that studies have shown that cuff width also affects the effectiveness of BFR training, with the wide cuff restricting blood flow at lower pressures than the narrow cuff [82]. The arterial occlusion pressure (AOP) measured at different body positions influence the final AOP [83]. With the wide and narrow cuffs, AOP was 148 ± 19 and 348 ± 94 mmHg in the supine position, respectively. In the seated position, this increased to 177 ± 20 and 409 ± 101 mmHg [83]. The BFR training stimulus may have been dramatically different between different AOP%. The 50% and 60% AOP BFR training significantly increased jump height, peak power compared to the 70% AOP group [84]. The muscle activation increased from 40 ~ 50% AOP, but did not increase further with a higher AOP (50 ~ 60% AOP) [85].

Tools such as Doppler ultrasound [86], handheld Doppler devices [87], pulse oximetry [88], and predictive equations [89] have been proposed to accurately assess and individualize BFRP, ensuring its safe and effective application. Cardiovascular disorders, hypertension, and a history of thrombosis were the main concerns of professionals regarding BFR technique users [90]. In a sample of 12,642 people who underwent the BFR technique, there were 7 cases (0.055%) of venous thrombosis and 1 case (0.008%) of pulmonary embolism [91]. A recent systematic review concluded that exercise with BFR does not exacerbate the activation of coagulation or enhance fibrinolytic activity [92]. However, the current body of literature with respect to risk of thrombosis resulting from BFRT does not completely exclude the potential for deep vein thrombosis (DVT) formation. The risk stratification for DVT is strongly encouraged to be included during the initial screening process prior to BFRT [93, 94]. The adapted thrombosis risk factor assessment from Caprini [95] represents a useful tool and was previously used in BFRT studies as exclusion criteria [96, 97]. BFR exercises can lead to elevated blood pressure due to the restricted blood flow. This increased hemodynamic response may be higher than traditional resistance training. However, with proper adjustments such as intermittent BFR protocols, individuals with hypertension or heart conditions can safely perform BFR exercises [98].

Limitations

(1) Cuff Pressure and Training Adherence: only one study reported arterial occlusion pressure (AOP%), two studies reported muscle circumference, and six studies mentioned cuff width, preventing determination of the optimal cuff pressure. Additionally, training adherence and attendance were not considered in this review; (2) Randomization and Blinding: The moderate overall risk of bias observed in the included studies highlights the need for cautious interpretation of the meta-analysis results. While the reporting quality was generally acceptable, some methodological limitations, particularly in randomization and allocation concealment, may have impacted the robustness of the findings; (3) Publication Bias: as the capacity to detect bias is limited when meta-analyses are based on a small number of trials, the results should be interpreted with caution; (4) Gender

Distribution: the studies included in this analysis were predominantly male (97%), which limits the generalizability of the findings to female athletes; (5) Comparison with Non-BFR Methods: while superior training effects were observed in the BFR combined with endurance training group, we did not explore specific non-BFR endurance methods (e.g., repeated sprint training, small-sided games, 400m running), which should be addressed in future studies. This review included only studies published in English, which may have introduced selection bias and limited the comprehensiveness of our analysis. While most of the included studies reported training attendance, which are critical for evaluating intervention effectiveness, Hosseini Kakhak [47] and Amani [40] did not provide this information. Future studies should include these to enhance the reliability of the findings. Additionally, the studies included semi-professional athletes, which may introduce bias due to differences in training and performance levels compared to other athlete populations.

Conclusion and future research recommendations

While BFR training during endurance training had a significant positive effect on lower limb muscle strength and moderate improvement in VO_2max, its impact on anaerobic power and sports performance was relatively small. These findings suggest that BFR training may be effective for enhancing muscle strength and aerobic capacity, but its benefits on anaerobic power and sport-specific performance may be limited. Therefore, it is important to carefully design BFR training programs to target specific outcomes. For improving anaerobic capacity, combining BFR with anaerobic endurance training may be more effective.

Future research should explore the integration of BFR into team sports settings. Specifically, pilot studies could be designed to examine the effects of varying AOPs (40%-80%) in combination with endurance training for athletes in team sports. These studies should include at least 10 sessions (20–30 min each) over a 4-week period, with 2–3 sessions per week, to induce measurable training adaptations. Grouping athletes according to different AOPs would help identify the optimal BFR pressure for maximizing performance improvements. Additionally, RCTs across a range of team sports, including soccer, basketball, and rugby, are needed to assess the impact of BFR on sport-specific endurance, muscle strength, and overall performance outcomes. Additionally, the pilot studies could be conducted across various demographics, including female and professional athletes, to enhance the applicability and relevance of the findings to a broader range of populations.

Supplementary Information

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Supplementary Material 1: Table S1. PRISMA checklist.

Supplementary Material 2: Table S2. The mean and standard deviation values of the variables taken from the primary studies.

Supplementary Material 3: Table S3. Search strategy.

Supplementary Material 4: Figure S1. Funnel plot.

Supplementary Material 5: Figure S2. Residuals boxplots.

Supplementary Material 6: Figure S3 Sensitivity analysis plot.

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Not applicable.

Authors' contributions
KD and JT conceived the study. DL, JT, WLG, CLX did the screening and data extraction. KD did the data analyses and the led the manuscript writing. JT and BC supervised the work and reviewed the manuscript. All authors have agreed the final version of the manuscript, with KD, DL, LQW and JT contributing to the manuscript revision.

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Data availability
The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate
Not applicable, this systematic review and meta-analysis was registered in PROSPERO.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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