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REVIEW

EXERCISE PHYSIOLOGY AND BIOMECHANICS

Effects of blood flow restriction training on sports performance in athletes: a systematic review with meta-analysis

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ABSTRACT

INTRODUCTION: Blood flow restriction training (BFRT) is an effective training method to improve sports performance in healthy athletes. Nevertheless, a systematic review with meta-analysis regarding how BFRT affects sports performance in athletes is still lacking. Consequently, the study attempted to expand and consolidate the prior studies regarding the effect of BFRT on technical and physical performance in athletes.
EVIDENCE ACQUISITION: This study was based on PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyzes) statement guidelines for a systematic review of the academic databases Scopus, Web of Science, PubMed, EBSCOhost (SportDiscus), and Google Scholar. The PEDro scale was used to assess the methodological quality of the included publications, which ranged from moderate to high quality. The systematic review protocol was registered on inplasy.com (INPLASY202380049).
EVIDENCE SYNTHESIS: Out of 249 studies identified, 93 articles were evaluated as eligible, and after the screening, 18 studies were finally included in this systematic review. Meta-analysis results showed a significant enhancement on vertical jump height in the BFRT group compared to the control group (SMD=1.39, 95% CI=0.30-2.49, P=0.01). BFRT was able to significantly increase maximal oxygen uptake (SMD=1.65, 95% CI=0.56-2.74, P<0.01). While no significant improvement in sprint time was observed (SMD= -0.18, 95% CI=-1.18-0.82, P=0.115).
CONCLUSIONS: The finding suggests that BFRT is beneficial to athletes as this training method can be effective in enhancing physical and technical performance in athletes. Nevertheless, further analysis needs to be conducted to fully determine the effectiveness of the moderators of the intervention on sports performance.

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KEY WORDS: Blood flow restriction therapy; Athletes; Physical fitness; Athletic performance; Meta-analysis.

Introduction

Sports performance is defined as competitive athletic performance, which is a determining factor for athletes to achieve outstanding success in sports competitions.[1] The collaboration between physical and technical qualities strongly given the sports performance, in addition, it is also based on the level of the specific motor skills performed by the athlete.[2] In short, athletes need a higher standard of athletic performance to successfully complete a specific sport task.

On the one hand, traditional resistance training (RT) is essential in sports exercise programs, and it has been considered an effective way to improve athletes' physical fitness.[3] The American College of Sports Medicine supported the use of 70% of maximal RT assist in improving muscular power and endurance, in addition to enhance speed and balance to better sports performance.[4, 5] Several studies have indicated that traditional high-load RT can significantly enhance physical fitness,[6-8] and effectively increase muscle cross-sectional area in athletes, causing muscle hypertrophy.[9, 10] On the other hand, one study confirmed that long periods during RT with high loads can give high fatigue and cause wear and tear damage to the joints.[11] Also, it has been suggested that the bigger muscle cross-sectional area could make the athletes' sports performance become stiffer which affects the sport specificity.[12] Consequently, it is evident that athletes must develop both physiological qualities and sport-specific techniques through more effective training methods if they desire excellent performance.[13] Fortunately, blood flow restriction training (BFRT) has been introduced in recent years as a new resistance training method that aims to provide additional inspiration for athletes to induce an efficient training response, this technique was also known as occlusion training or kaatsu training.[14]

An inflatable cuff wrap is applied on the maximal part of the extremities under movement to restrict blood flow to the muscles *via* a predefined pressure that blocks venous blood flow without affecting arterial circulation during BFRT.[15, 16] Additionally, BFRT was applied in low-load resistance training,[15] and several studies have proven that a 20-30% 1RM resistance load with BFRT can yield similar improvements as traditional high-intensity resistance training at no fatigue injury.[17-20] Many studies have shown that BFRT can increase power,[21-27] sprint,[21-23, 26, 28, 29] balance,[30] aerobic endurance performance[21, 31-35] and sport-specific performance.[26, 36, 37] Likewise, studies have shown that BFRT can also have a positive impact on the elderly[38] and the injured.[39] In particular, the physiological mechanism of BFRT was that restricting blood flow leads the extremities to a relatively ischemic and hypoxic status,[40] and since metabolites such as lactic acid cannot be removed efficiently in this process,[41] causing a significant subsequent increase for metabolic stress levels. There was a systematic review that have summarized that BFRT could provide significance on athletic performance among athletes,[42] however, there is no systematic review with meta-analysis that summarizes the critical information about BFRT on sports performance for athletes. With regard to this, the aim of this study was to consolidate and extend the existing research on the effects of BFRT on physical performance and technical performance in athletes.

Evidence acquisition

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses Protocols (PRISMA-P) guidelines[43] was followed for the collection of data, selection, and analysis in this systematic review with meta-analysis. Additionally, the review has been register on Inplasy.com (INPLASY202380049).

Search strategy

In this systematic review, we conducted a comprehensive literature search from inception until 12th August 2023 through electronic databases (Scopus, Web of Science, PubMed, EBSCOhost (SportDiscus) and Google Scholar). The main keywords searched were ("blood flow restriction training" OR "Kaatsu training" OR "vascular occlusion training" OR "occlusion training" OR "resistance training combined with BFR") AND ("sports performance" or "physical performance" or "technical performance" or "skill performance" or "athlete performance") AND ("athletes" or "players"). The search was done *via* title and abstract in each database. In addition, we screened the lists of references from the included articles for more relevant citations.

Eligibility criteria

Our inclusion criteria were established on the PICOS methodology (population, intervention, comparison, outcome, and study design) for this systematic review when we selected the literature (Table I). Thus, to be considered for inclusion in our study, each study had to satisfy the requirements listed below:

- the study population included healthy athletes of all levels without age restrictions;
- this study involved a BFRT and included other types

Table I.—*PICOS Eligibility criteria.*

PICOS	Detailed information
Population	Healthy athletes
Intervention	Blood flow restriction training
Comparison	Comparison between BFR group and non-BFR training group, between various exercises combined with BFR groups, and comparison within group with a single BFR group°
Outcome	Include varied sport performance (physical or technical) among athletes
Study design	RCT or non-RCT

of training in combination with BFRT (*e.g.*, low or high intensity resistance training);

- comparisons between the BFRT group and the non-BFRT group, between various exercises combined with BFRT groups, and within-group comparisons with a single BFRT group should all be included in the study;
- the outcomes of the study included the effect of BFRT on the sports performance (physical or technical) in athletes;
- the studies should be randomized controlled experimental studies (RCTs) and single-group pre- and post-test designs. The articles must be published in English.

Study selection

Two reviewers were responsible for the search and quality assessment of the articles. At first, articles were searched in electronic databases using keywords. To avoid duplicated material, any duplicates and unrelated studies should were removed from our database. Secondly, two independent authors (R.L., K.Y.) identified suitable studies that qualified and to obtain appropriate full-text publication by evaluating the abstracts and titles in light of the inclusion and exclusion criteria. Of note, all full-text articles that satisfied the requirements for inclusion had to be read as well as the reviewers would review these studies based on the criteria of population, intervention, comparison, outcome, and study design. Those articles without full text were dropped. On the other hand, two reviewed authors extracted data independently, and the opinion of the third reviewer (C.S.C.) was consulted in case of any discrepancy, which was determined through discussion until a consensus was reached.

Data extraction

When the search was finished, the details were gathered from qualified articles on: 1) authors together with the publication's year; 2) population characteristics (number, age, gender, type); 3) intervention characteristics (frequency and duration); 4) comparisons (type); 5) cuff location and pressure; 6) study outcomes.

Quality assessment

Two independent reviewers used the Physical Therapy Evidence Database (PEDro) scale to estimate the methodological quality in the studies of this review. The scale comprised of 11 items, but we chose to remove 5-7 items from the scale that were specifically blinded, considering that it is typically impossible to use blinding techniques while doing research on supervised exercise treatments. Previous systematic review in the field of sporting activities have used this strategy.[44]

The first item connected to the eligibility criteria was excluded from the total score, resulting in a maximum total score for the modified scale of 7. The study quality evaluation was performed using the same scoring method utilized in previous sport-related systematic reviews,[45, 46] and the following results: the total PEDro score was 6-7 for "excellent," 5 for "good," 4 for "moderate," and 0-3 for "poor" quality.

Statistical analysis

Microsoft Excel was utilized to arrange the data gathered for this investigation, and RevMan 5.4 software was used to conduct data statistics and meta-analysis. In order to determine effect sizes for ES with 95% confidence intervals (95% CI),[47] we employed standardized mean difference (SMD). Calculated ES were interpreted using the following scale: trivial: <0.2, small: 0.2-0.6, moderate: >0.6-1.2, large: >1.2-2.0, very large: >2.0-4.0, extremely large: >4.0.[47] The I^2 test was utilized to identify heterogeneity, a measure of low heterogeneity of 25% should be used as a fixed-effects model with P>0.01, whereas a measure of 25-75% and >75%, representing moderate and high levels of heterogeneity, respectively, should be used as a random-effects model with P≤0.01.[48] The relevant 95% CI were shown in the forest plots, and statistical significance was established at P<0.05.

Evidence synthesis

Results of the study selection

The search and screening process can be seen in Figure 1. The electronic database turned up 249 articles that might be pertinent in total. Following the removal of duplicates, the titles and abstracts of 190 studies were reviewed, and a total of 97 publications were excluded, following which 93 potentially available entire studies were read and the qualification was evaluated. Finally, 18 full-text articles in total were included as criteria and were considered for this systematic review.

Methodological quality assessment results

Based on the PEDro scale, Table II displays the results of the study quality assessment. Only one of the 18 papers included had a scale of 3 and thus was excluded as being of low quality.[49] The 17 articles included in this evaluation

TABLE II.—*Physiotherapy Evidence Database (PEDro) scale ratings.*

References	Item 1[a]	Item 2	Item 3	Item 4	Item 8	Item 9	Item 10	Item 11	Total
Abe *et al.*[15]	1	1	0	1	1	1	1	1	6
Park *et al.*[33]	1	1	0	1	1	0	1	1	5
Manimmanakorn *et al.*[21]	1	1	0	1	1	1	1	1	6
Cook *et al.*[22]	1	1	0	1	1	0	1	1	5
Behringer *et al.*[29]	1	1	0	1	1	0	1	1	5
Ghoraba *et al.*[49]	1	0	0	1	1	0	0	1	3
Scott *et al.*[23]	1	1	0	1	1	1	1	1	6
Amani *et al.*[32]	1	1	0	1	1	1	1	1	6
Haidar *et al.*[24]	1	0	0	1	1	1	1	1	5
Amani-Shalamzari *et al.*[36]	1	1	0	1	1	1	1	1	6
Elgammal *et al.*[34]	1	1	0	1	1	0	1	1	5
Akin and Kesilmiş[30]	1	0	0	1	1	1	1	1	5
Amani-Shalamzari *et al.*[35]	1	1	0	1	1	1	1	1	6
Chen *et al.*[31]	1	1	0	1	1	1	1	1	6
Yang *et al.*[25]	1	1	0	1	1	1	1	1	6
Wang *et al.*[27]	1	1	0	1	1	1	1	1	6
Boyanmis *et al.*[37]	1	0	0	1	1	1	1	1	5
Hosseini Kakhak *et al.*[26]	1	1	0	1	1	0	1	1	5

Item 1[a]: eligibility criteria that is not included in the calculation of the total PEDro score; Item 2: random allocation; Item 3: concealed allocation; Item 4: groups similar at baseline; Item 8: more than 85% of subjects' outcome; Item 9: intention to treat analysis; Item 10: between-group statistical comparison; Item 11: point measures and/or measures of variability.

had PEDro scores ranging from 4 to 6, eight publications receiving 5, and nine receiving 6. The articles consulted for this review had "moderate" to "good" methodological quality according to the results of the quality assessment.

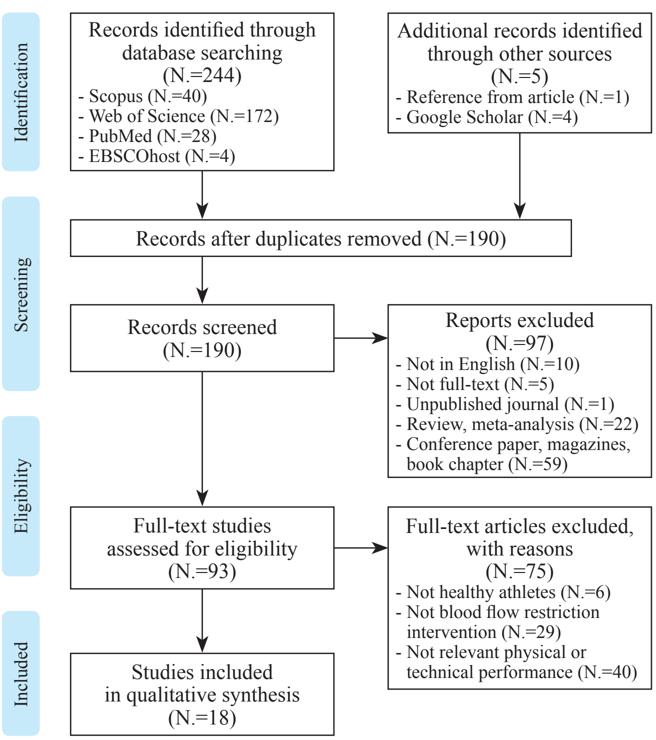

Figure 1.—PRISMA diagram of the study inclusion progress.

Study characteristics

Table III showed the population characteristics of the eighteen studies that qualified for inclusion. The type of athletes in the publications including netball players,[21] rugby players,[22] sprinters,[28, 29, 31] football players,[23] soccer players,[26, 32] artistic gymnast,[24] Futsal players,[35, 36] basketball players,[33, 34] taekwondo players,[30, 37] trampoline gymnasts[25] and volleyball players.[27] The included studies involved a total of 341 subjects, the ages of 11.3 and 27.3 years. Twelve studies recruited only male,[22, 23, 26-29, 31-36] two studies recruited only female,[21, 24] while three studies comprised both male and female.[25, 30, 37]

Among these studies, one study conducted the shortest length of intervention for 8 days[28] and the longest was 10 weeks.[24, 25] Most studies reported training frequency of three times per week, only three studies reported for two times a week.[23, 25, 29] However, one studies did not report the frequency of intervention.[32] Additionally, the occlusive cuff pressure ranged from 100 to 230 mmHg, and it was almost worn at the most proximal part of the thigh.

Results from the meta-analysis

This study used meta-analysis to measure sprint time (N.=6), vertical jump height (N.=6) and maximal oxygen uptake (VO_{2max}) (N.=6) exclusively. As the other outcomes had limited data, they were not considered for meta-analysis.

Synthesis data from six studies, including a total of

TABLE III.—*Characteristics of the studies examined in the present review.*

Study	Participants	Interventions			Main outcome
		Duration/ frequency	Training protocol / Training load	Cuff location/pressure	
Abe *et al.*[15]	N.=15, male sprinters and jumpers, age: NR	2 sessions/ day 8 days	Squats and leg curls: 3×15 reps, 20% 1RM	Most proximal portion of thigh /160-240 mmHg	30-m dash ↑ Standing jump ↔
Park *et al.*[33]	N.=12, male basketball players, age: 20.4±1.2 yr	24 sessions, 2 weeks	3-min walking bouts with BFR; 5 sets	Most proximal portion of thigh /160-220 mmHg	VO_{2max} ↑
Manimmanakorn *et al.*[21]	N.=30, female netball players, age: 20.2±3.3 yr	3 times/ week 5 weeks	Bilateral knee flexion and extension with BFR; 3 sets to failure, 20% 1RM	Most proximal portion of thigh /160-230 mmHg	5-m, 10-m sprint ↑, Vertical jump ↑, 20-m shuttle run test ↑ VO_{2max} ↑
Cook *et al.*[22]	N.=20, male rugby players, age: 21.5±1.4 yr	3 times/ week 3 weeks	Leg squat with BFR, 5×5 reps,70% 1RM	Most proximal portion of thigh /180 mmHg	40-m sprint ↑ CMJ ↑
Behringer *et al.*[29]	N.=24, male sprinters, age: 25.6±2.3 yr	Twice/week 6 weeks	100-m sprint training with BFR, 6 sets, 60-70% 1RM	Most proximal portion of thigh /7/10 perceived pressure	100-m dash ↑
Scott *et al.*[23]	N.=18, male football players, age: 19.8±1.5 yr	Twice/week 5 weeks	Squat training with BFR, 4sets, 20-30% 1RM	Most proximal portion of thigh /7/10 perceived pressure	CMJ ↔, 0-10 m, 0-20 m, 0-40 m, 20-40 m sprint ↔
Amani *et al.*[32]	N.=28, male soccer players, age: 23.89±2.26 yr	NR/ 2 weeks	400 m with BFR, 7 sets, 60-70% 1RM	Most proximal portion of thigh /140-180 mmHg	400-m test ↑ VO_{2max} ↑
Haidar *et al.*[24]	N.=20, female artistic gymnasts, age: 11.25±0.87 yr	3 times/ week 10 weeks	Normal training with BFR, NR	Most proximal portion of thigh /120-170 mmHg	Vertical jump ↑
Amani-Shalamzari *et al.*[36]	N.=12, male futsal players, age: 23±2 yr	10 sessions 3 weeks	SSG with BFR, 10 sets, 20% 1RM	Most proximal portion of thigh /110-200 mmHg	FSPT ↑
Elgammal *et al.*[34]	N.=24, male basketball players, age: 22.3±2.4 yr	3 times/ week 4 weeks	RST with BFR, 3×8 reps, 50-85% 1RM	Most proximal portion of thigh /100-160 mmHg	Suicide run test ↔, 20-m shuttle run test ↑ VO_{2max} ↑
Akin and Kesilmiş[30]	N.=31, mixed taekwondo players, age: 15-19 yr.	3 times/ week 6 weeks	TKD training with BFR, NR	Most proximal portion of thigh/ NR	Dynamic balance ↑
Amani-Shalamzari *et al.*[35]	N.=12, male futsal players, age: 23.0±2.0 yr	10 sessions, 3 weeks	Futsal specific training with BFR	Most proximal portion of thigh /110-160 mmHg	VO_{2max} ↑
Chen *et al.*[31]	N.=12, male sprinters, age: 22.7±4.6 yr	3 times/ week 8 weeks	3-min running exercise w ith BFR; 5 sets, low load	Most proximal portion of thigh /149.8±5.0 mmHg	60-m sprint ↔ VO_{2max} ↑
Yang *et al.*[25]	N.=15, mixed trampoline gymnasts, age:13.9±0.4 yr	2 times/ week 10 weeks	Back squats, jump training with BFR, 20-20% 1RM	Most proximal portion of the thigh /7/10 perceived pressure	Vertical jump ↑
Wang *et al.*[27]	N.=18, male volleyball players, age: 20.17±0.75 yr	3 times/ week 8 weeks	Half squat with BFR, 1×30+3×15 reps, 30% 1RM	Most proximal portion of the thigh/180 mmHg	Squat jump ↑ Three-footed takeoffs ↑
Boyanmis *et al.*[37]	N.=31, mixed taekwondo players, age: 15.36±1.63 yr	3 times/ week 6 weeks	PT with BFR, NR	Most proximal portion of the thighs/NR	Palding, Tolyochagi, Dwitchagi, Yopchagi kicks↑
Hosseini Kakhak *et al.*[26]	N.=19, male soccer players, age: 15.9±0.8 yr	3 times/ week 6 weeks	SSG, PT with BFR, 20-50% 1RM	Most proximal portion of thigh /160-210 mmHg	CMJ ↑, 40-yd sprint ↑ COD ↑, 20-m MSFT ↑

BFR: blood flow restriction; NR: not reported; CMJ: countermovement jump; SSG: small-sided game; repeated sprint training; PT: plyometric training; FSPT: Futsal Special Performance Test; TKD: Taekwondo; 1RM: one repetition maximum; COD: change of direction; VO_{2max}: maximal oxygen consumption; 20m MSFT: 20m Multistage Fitness Test; ↑: significant within-group improvement from pre-test to pos-test; ↔: non-significant within-group change from pre-test to post-test.

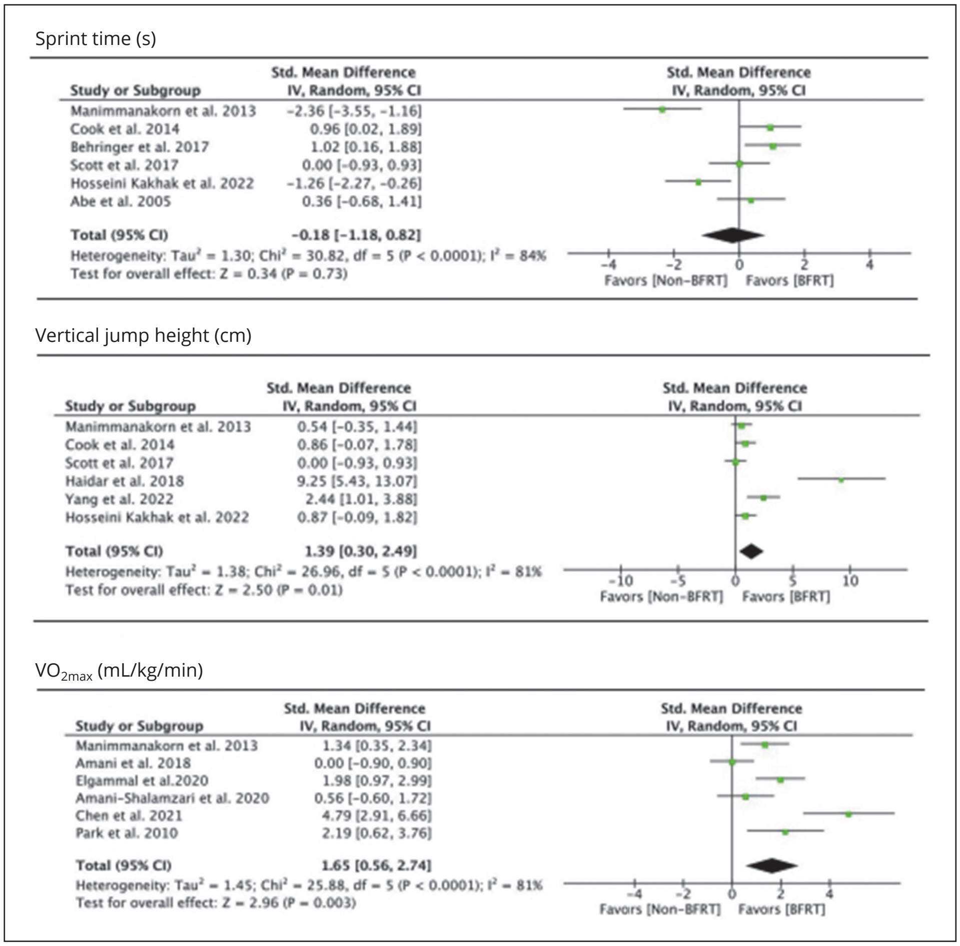

Figure 2.—The forest plot of changes in sports performance.

101 participants showed that BFRT did not significantly improve sprint time (P=0.73), had a trivial effect SMD= -0.18 (95% CI -1.18-0.82, Z=0.34) and high heterogeneity (I^2=84%, P<0.0001). A meta-analysis that included 6 studies with 108 subjects compared the differences between the BFRT and control groups and revealed that BFRT significantly increased vertical jump height (P=0.01), with a large effect size SMD=1.39 (95% CI 0.30-2.49, Z=2.50) and high heterogeneity (I^2=81%, P<0.0001). Results from a meta-analysis of a total of 6 included items with 107 participants demonstrated a significant increase in VO_{2max} by BFRT (P=0.003), with a large effect size SMD=1.65 (95% CI 0.56-2.74, Z=2.96) and high heterogeneity (I^2=81%, P<0.0001) (Figure 2).

Effects of BFRT power performance

Of the included eighteen studies, seven studies presented data about the effects of BFRT on power performance. In these articles, three studies used the vertical jump test (VJ),[21, 24, 25] three studies used the countermovement jump (CMJ),[22, 23, 26] one studies used the squat jump test (SJ) as well as three footed takeoffs[27] to measure power performance respectively. Most studies demonstrated a significant enhancement in power performance after BFRT. Of these, Manimmanakorn found that the VJ was substantially improved after BFRT (P<0.05).[21] Furthermore, after comparing post-test results, one study observed a considerable difference in VJ between the BFRT group and the RT group.[25]

According to study outcomes, there was a substantial increase in CMJ between the BFRT group and the RT group, with a 5.0 cm improvement in CMJ height for BFRT(P<0.001) and for RT by 3.3 cm (P=0.001),[25] while only one studies showed no significant difference in CMJ after 5 weeks of BFRT.[23] Furthermore, the SJ performance was observed a significant improve between BFRT group (P<0.001) and RT group (P=0.005).[27] Another study included three groups: high-load BFRT (HL-BFRT), low-load BFRT (LL-BFRT), and high-load RT (HLRT). The result demonstrated that only a considerably difference between HL-BFRT and LL-BFRT in the post-test.[27] Likewise, these studies revealed significant increase between pre- and post-test in three-footed takeoffs (P=0.015).

Effects of BFRT on sprint performance

Seven of these studies determined the effects of BFRT on sprint performance. These studies utilized the following tests: 5-m and 10-m test,[21] acceleration ability and maximal sprinting test (0-10 m, 0-2-m, 0-40 m and 20-40 m),[23] 30 m sprint test,[28] 40 m sprint test,[22, 26] 60 m sprint,[31] and 100 m dash test.[29] Six studies reported statistically significant improvements in comparisons between BFRT group and control group. On the one hand, two of these studies found significantly greater differences for the 40m sprint (P=0.0023)[22] and (P<0.001)[21] as well as 100 m dash (P<0.001)[26] in pre- and post-test. However, only one study observed a significant change between groups at 0-10 m sprint, but there were no differences in the other splits before and after the BFRT.[23] In contrast, a study revealed a substantially improved (P<0.05) in 5m and 10m sprint after 5 weeks of BFRT.[21]

Effects of BFRT on aerobic endurance performance

Seven studies have reported on the effects of BFRT on aerobic performance. Among these studies, the maximal oxygen consumption (VO_{2max}),[21, 31-35] 20-m shuttle run test[21, 34] and the 400-m test,[32] the suicide run test[34] and the 20-m multistage fitness test (20-m MSFT)[26] were used to measure aerobic endurance performance. Most studies demonstrated significant enhancements in aerobic endurance performance after the BFRT, except for one study which reported a small change in suicide running between groups post-test.[34] The results of six studies presented the statistically significant differences in VO_{2max} (P<0.05)[21, 31-35] and 20m MSFT (P<0.001)[26] for post-test. Nonetheless, the results demonstrated substantial enhancement in only one study in the 20-m shuttle run test within the group after 5 weeks of BFRT (P<0.05).[21]

Effects of BFRT on sport-specific performance

In this systematic review, only one study investigated the change on the futsal-specific performance and used the Futsal-Specific Performance Test (FSPT) to assess performance time and total time for each of the nine steps.[36] This study revealed a significant decrease in time of futsal-special performance after 3 weeks of BFRT (P<0.05) by-11% for pre- and post-test within group.[36] In addition, one study evaluated the effect of BFRT on soccer-specific performance and assessed based on the Hoff test,[26] which included hurdles to cross and dribbling backwards and forwards. This test required participants to the longest distance that individuals can run when dribbling the ball under control in ten minutes period.[50] The significant improvement was observed for distance in the soccer-special performance for the for the post-test (P<0.001). Moreover, one studies assessed the effect of BFRT on combat performance.[37] This study found the statistically significant improvements in all technical kick force among taekwondo players who were applied BFRT (P<0.05). Furthermore, a statistically significant difference was observed in tolyochagi kicks and yopchagi kicks for the post-test in both the BFRT group and plyometric training group (P<0.05), but the positive development was not found in normal training.

Discussion

This is the first systematic review with meta-analysis to examine the effects of BFRT on sports performance only in healthy athletes, and it is intended to consolidate and extend the existing findings on both physical performance and skill performance among athletes by BFRT. The main findings were that BFRT was able to provide large improvements on power (ES=1.39) and aerobic endurance (ES=1.65), whereas there was almost no change in the sprinting time by BFRT (ES=-0.18), with high levels of heterogeneity in all of the above results (I^2 81-84%). The results showed that there were substantial differences in agility, balance and skill-specific performance after the intervention, with BFRT (P<0.05). The finding was consistent with previous reviews[42] supporting that BFRT could be utilized as a safer low-intensity training model to enhance sports performance in healthy athletes. Additionally, just one of the 18 included studies was removed from the analysis owing to its poor methodological quality,[49] and 17 of the remaining studies had ratings of moderate to high quality, indicating the reliability of the findings in this review.

Effects of BFRT on power performance

Power qualities are essential for explosive sports performance,[51] many of the crucial movements are performed as powerfully and speedily as possible, the force and velocity as a product determine power outputs.[52] Generally, the vertical jump is the most frequently used test to measure power output in athletes[53] and has proven to be an effective method utilized to determine lower extremity muscular power in different populations.[54] Present meta-analysis results demonstrated that BFRT had a great increase in vertical jump height of athletes (SMD=1.39).[55] These neuromuscular effects were an important mechanism for improving power performance, it is believed that BFRI induces changes in vertical jump because neural adaptations increase maximal power output,[56] the combination of blood flow restriction during maximal voluntary contraction causes activation of motor units which induced the replenishment of fast muscle fibers[57] and promoted neuromuscular actuators to enhance explosive power.[58] Wortman *et al.* also observed that BFRT was able to significantly improve the vertical jump in athletes.[42] Conversely, the studies included in this review by Scott *et al.* showed no significant changes on vertical jump performance in soccer players after BFRT combined with RT.[23] This discrepancy might be due to differences in intervention protocols (training duration, frequency, cuff pressure).[42] Based on this finding from BFRT on power performance was in agreement with the previous meta-analysis.[42] Thus, BFRT had a positive effect on power, while the contradictory can be explored in future studies with additional subgroup analyses.

Effects of BFRT on sprint performance

Sprint capability is an important component in sports that can define successful outcomes in many situations.[59] Likewise, the level of sprinting is a basic requirement for athletes of team sports, and faster sprint speed plays a crucial role during team sports competitions.[60] Faster football players may turn the game around at critical moments in the game, such as scrambling for the ball and shooting dashes for goal.[61] According to the results from the meta-analysis we learned that BFRT did not reduce the athletes' sprinting time and had no statistically significant effect on sprinting performance (SMD=-0.18). Two studies in this review produced results consistent with the meta-analytic results, which showed 0-20 m, 0-40 m, 20-40 m and 60 m sprint showed no significant changes.[23, 31] Study by Fostiak *et al.* also demonstrated no benefits in 0-30 m sprint times for team athletes after BFR training.[62] There are two possible reasons for the lack of enhanced speed performance after the BFRT: 1) there are discrepancies in the muscular locations where the kaatsu cuff has been applied, and the lower extremities should require more cuff pressure than the upper extremities.[63] 2) The duration and intensity performed is not sufficient to achieve a beneficial result, thus an inappropriate training pattern could have a negative influence on motor performance.[64]

Nevertheless, the four studies included in this study showed improved sprint performance after BFRT,[21, 22, 28, 29] this outcome is the same as in the systematic review by Wortman *et al.*[42] Performing BFRT during exercise probably increased metabolic stimulation and replenishment of fast muscle fibers as well as enhanced intramuscular signaling for protein synthesis, each of which are crucial elements in improving sprint ability.[65] Based on this contradictory outcome, the reason for this may be that the speed is related to the effect of different sports on specific distances in sprinting,[66] therefore more experiments are needed in the future to validate the efficacy of BFRT on sprint times for specific distances in different sports.

Effects of BFRT on aerobic endurance performance

One of the most crucial metrics for assessing the capacity of individuals for aerobic endurance is maximum oxygen uptake (VO_{2max}).[67] Taylor *et al.* have found a significantly improved VO_{2max} performance in healthy adults after four weeks of BFR training.[68] Similarly, the results from meta-analysis shown the statistically significant increases in VO_{2max} among athletes after the BFRT.[69] That could be explained by a possible improvement in capillary density within muscle tissue during the recovery period following the implementation of BFRT, and thus a subsequent increase in VO_{2max}.[70] Also, it has been suggested that it probably reflects the increase in compensation for distal venous occlusion, and the lactic acid buildup in muscle produces greater metabolic pressure, thereby improving aerobic endurance and anaerobic capacity.[71] From this finding, we can support that BFRT is useful for aerobic endurance performance with restricted blood flow and may be performed in a variety of sports.

Effects of BFRT on sport-specific performance

Aerobic and anaerobic training combined with BFR is an effective method.[72, 73] The finding demonstrated that the futsal-specific and soccer-specific performance had significant improve after BFRT combined with small side game training. Moreover, this finding was the same as that of previous studies, Impellizzeri *et al.* found that BFR combined with small side games could help futsal players improve their fitness.[74] However, Castilla-López *et al.* found in a systematic review that BFRT did not produce statistically significant change in the variables of sport-specific performance.[75] According to these conflicting findings, we cannot prove that the change represents a true effect, foremost, further experimental studies should be conducted to explore the evidence of BFRT on sport-specific performance with more certainty. Furthermore, present results shown that BFRT could increase combat performance, while Wortman *et al.* did not consider this parameter, and there were few studies to compare this outcome, thus, we focused on the physiological mechanisms of combat techniques.[42] One study supported that wrestling demands a greater anaerobic energy system, raises the level of heart rate, and accumulates considerable lactate concentration after training.[76-80] To be specific, BFR combined with low-intensity training when it allows vascular adaptation causes an increase in muscle mass and enhances muscle blood flow capacity as well as metabolite exchange, which helps to improve muscular endurance providing various performance enhancements after BFR training.[80] As a result, muscle vascular and physical adaptations reflected better performance and significantly better combat performance.[37] Given the points above, it seems that we can explain why BFRI can enhance combat performance and can support the applied to future experiments.

Limitations of the study

This systematic review with meta-analysis should consider some limitations. Firstly, the publications we included were restricted to English articles exclusively. Secondly, the searched database documentation was small, with only 18 studies met our inclusion criteria. And third, five papers were not included in the meta-analysis since they lacked data on the control group or did not give enough information. In addition, some outcomes were excluded from our meta-analysis due to the insufficient number of studies involved (*e.g.*, agility, balance, and sport-specific performance). Finally, the present meta-analysis did not conduct subgroup analyses to investigate the effects of mediating variables (training duration, frequency, intensity, and cuff pressure) on the results.

Conclusions

This systematic review with meta-analysis indicated that BFRT was able to evoke neuromuscular adaptations with the potential to increase physical performance and technical performance (*i.e.*, vertical jump height, maximal oxygen uptake, and specific sport performance) among athletes, however, conflicting observations were generated with the sprinting time, requiring more high-quality studies in the future to prove its precise results. Furthermore, more research needs to explore the role of moderating variables in BFRT. It is recommended that the moderating effects of BFRT on athletic performance be considered in terms of both demographic characteristics (gender and age) and training intervention characteristics (training duration, frequency, intensity and cuff pressure) to help players to seek a better sports performance during the training process.

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Conflicts of interest

The authors certify that there is no conflict of interest with any financial organization regarding the material discussed in the manuscript.

Authors' contributions

Rui Li and Kun Yang conducted the literature search and selection study. Rui Li and Chen S. Chee provided data interpretation. The article was drafted by Rui Li, and Chen S. Chee, Tengku F. Kamalden and Alif S. Ramli critically revised and gave final approval to the article. All authors contributed to the manuscript, read and approved the final manuscript.

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