

Review

Influence of blood flow restriction training on the aerobic capacity: a systematic review and meta-analysis

Qun Yang^{1,†}, Duan Ying Li^{1,†}, Jia Xin He¹, Zhi Yong Zhang¹, Hong Wei Zhu¹,
Guo Xing Li², Shi Cong Ding³, Xiao Ning Sun^{2,*}, Jian Sun^{1,*}

¹Digitalized Performance Training Laboratory, Guang Zhou Sport of University, 510500 Guang Zhou, Guangdong, China

²Sports Training Institute, Guang Zhou Sport of University, 510500 Guang Zhou, Guangdong, China

³Guangdong Heavy Competitive Sports Training Center, 510500 Guang Zhou, Guangdong, China

*Correspondence: sunjian@gzsport.edu.cn (Jian Sun); sunxn@gzsport.edu.cn (Xiao Ning Sun)

†These authors contributed equally.

Submitted: 10 September 2021 Accepted: 22 November 2021 Published: 2 March 2022

Abstract

Background: Blood flow restriction training (also known as KAATSU training) uses professional equipment to apply pressure to the base of the limbs to limit the blood flow at the distal end of the limbs during exercise, thereby stimulating muscle growth and improving muscle strength with a low exercise intensity. This study aimed to conduct a meta-analysis on the effects of blood flow restriction training on aerobic capacity. **Methods:** A systematic review and quantitative evidence synthesis (QES) was used to examine the effects of blood flow restriction training on the aerobic capacity. A literature search was performed on relevant databases. Search engines used were MEDLINE, EMBASE, PubMed, Web of Science, SPORT-Discus, CINAHL, ScienceDirect, and the Cochrane Library. Search terms were KAATSU training, blood flow restriction training, and occlusion training. Thirteen articles (a total sample size of 246 participants) fulfilled the inclusion criteria and were included. **Results:** Blood flow restriction training promoted the improvement in aerobic capacity (standard mean difference (SMD) = 0.40, 95% confidence interval (CI) (0.14–0.66), $I^2 = 0\%$, $p < 0.01$), showing no publication bias. In subgroup analysis, intervention methods, and intervention frequencies had different effects on aerobic capacity. **Conclusions:** Blood flow restriction training, which is a low intensity exercise, significantly affected aerobic capacity. Twelve blood flow restriction training sessions a week achieved significantly better results than a frequency of two to four training sessions per week. A daily blood flow restriction training session of 6 to 30 min significantly improved aerobic capacity.

Keywords: Blood flow restriction training; Aerobic capacity; Maximum oxygen uptake (VO_{2max}); Meta-analysis

1. Introduction

Blood flow restriction training (also called KAATSU training) uses professional equipment to apply appropriate pressure to the base of the limbs to limit the blood flow at the distal end of the limbs during exercise, thereby stimulating muscle growth and improving muscle strength with a low intensity [1]. Blood flow restriction training research worldwide has been mainly focused on the impact on muscle shape and function [2–9]. In addition, the effect of high-intensity exercise is achieved with only a low-intensity load under blood flow restriction training, which has the advantages of low intensity, high frequency, and fast recovery [10–13]. Combining blood flow restriction training and aerobic exercise may provide a useful and practical training that can maintain or improve the aerobic performance of individuals while reducing the training intensity [10–12]. In addition, maintaining a good aerobic ability thorough suitable aerobic exercise could improve athletic performance and recovery ability [13]. Although studies have focused on whether blood flow restriction training effectively improves aerobic fitness and promotes sports performance, the results are not consistent [14–17], and the aerobic capacity improvement varies from study to study due to different in-

terventions, frequencies, intensities of exercise, study populations, and sample sizes. There are systematic reviews on blood flow restriction training and aerobic capacity, but at this stage no meta-analysis was performed. Therefore, this study aimed to conduct a meta-analysis on the effects of blood flow restriction training on aerobic capacity.

2. Information and research methods

We conducted this meta-analysis according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) reporting guidelines.

2.1 Literature search strategy

The PubMed, EMBASE, Medline, Web of Science, SPORT-Discus, CINAHL, ScienceDirect, and Cochrane library databases were used for literature search from the establishment of the databases to April 2021 using the keywords as follows: “blood flow restriction training”, “KAATSU”, “Vascular occlusion training”, “BFR training”, “restricted blood flow”, “maximum oxygen uptake”, “maximal oxygen consumption”, “aerobic capacity”, “aerobic performance”, “aerobic power”, and “oxygen consumption”. Additionally, hand searches were conducted



#1 “KAATSU training” [Title/Abstract] OR “blood flow restriction training” [Title/Abstract]
 OR “BFRT” [Title/Abstract] OR “blood flow restriction exercise” [Title/Abstract] OR “occlusion
 raining” [Title/Abstract]

#2 “maximum oxygen up take” [Title/Abstract] OR “maximal oxygen consumption” [Title/
 Abstract] OR “Aerobic Capacity” [Title/Abstract] OR “Aerobic Performance” [Title/Abstract]
 OR “aerobic power” [Title/Abstract] OR “oxygen consumption” [Title/Abstract]

#3 #1 AND #2

#4 randomized controlled trial [Publication Type OR controlled clinical trial Publication Type]
 OR randomized [Title/Abstract]

#5 #3 AND #4

Fig. 1. Schematic diagram of the literature retrieval formula.

through reference lists to locate more relevant articles; this complemented for the computer-based systematic literature search. Fig. 1 presents the specific strategy for the literature search.

2.2 Literature inclusion and screening

The literature inclusion criteria of this meta-analysis were based on the participants, intervention, comparison, outcome, and study (PICOS) format for evidence-based medicine.

The type of research was interventional trials of blood flow restriction training on aerobic capacity. The participants were healthy people and athletes. The studies were all randomized controlled trials (RCTs). The control group had conventional training without blood flow restriction training. The intervention group had blood flow restriction training. The functional indicator was maximum oxygen uptake (VO_{2max}). The following reports were excluded: (1) non-randomized experiments, self-controlled experiments, and randomized crossover experiments; (2) studies lacking the desired outcome data, such as pain and functional indicators; (3) meeting abstracts or reviews; (4) reports that the participants were unhealthy individuals; and (5) animal studies.

2.3 Literature screening and data extraction

The articles in Chinese and English databases were imported into the EndnoteX9 software (9.0, Clarivate Analytics, London, UK) to remove duplicates. Then, two independent researchers screened the articles according to the inclusion and exclusion criteria. The inter-rater reliability was evaluated using Kappa with a concordance of 95% between the two investigators. Any disagreements between the two researchers were resolved by consulting a third researcher.

The extracted content mainly included: (1) basic information of the included research, such as research title, first author's name, publication journal, and time; (2) baseline characteristics of the research participants, including the number of samples in each group, the age, and sex of the research participants; (3) specific details of intervention measures and duration of the intervention; (4) key elements of bias risk evaluations; and (5) the outcome indicators and outcome measures of interest.

2.4 Quality evaluation

The Cochrane risk of bias assessment tool was used to evaluate the literature's methodology from six aspects: selection bias, performance bias, detection bias, attrition bias, reporting bias, and other bias. Each indicator was judged by “low risk of bias”, “unclear risk of bias”, and “high risk of bias”, and was divided into three levels: Level A—low risk for four or more items; Level B—low risk for two or three items; Level C—low risk for one or no items, so bias might occur.

2.5 Data analysis

The RevMan5.4 software (Cochrane, London, UK) and STATA version 15 (STATA Corp, College Station, TX, USA) were used for data analysis, and the Q test was used to analyze the data heterogeneity of the included research literature (the test level was $\alpha = 0.1$), according to the size of heterogeneity between the studies to select the corresponding statistical model to test the effect size. When the value of I^2 was $\leq 50\%$ ($p \geq 0.1$), there was no obvious heterogeneity between the studies, and the fixed effects model was used; when the value of I^2 was $> 50\%$ ($p < 0.1$), there was obvious heterogeneity among the studies, and the random-effects model was selected. The effect size was presented as standard mean difference (SMD) value and 95% CI. The

subgroup analysis was performed on the moderating variables, and the effect size was presented as 0.2, 0.5, and 0.8, with 0.2–0.5 representing a small effect size, 0.5–0.8 a medium effect size, and ≥ 0.8 a large effect size.

3. Results

3.1 Basic characteristics of the literature

According to the PRISMA reporting guidelines, 13 trials were included in the analysis [12,14,15,18–26]. Fig. 2 showed the meta-analysis retrieval in a research flow chart. The included research experiments were all RCT. Two hundred forty-six participants were evaluated, and the average age of the participants was 23.5 ± 4.1 years. The intervention content in the sports intervention program was mainly low-intensity aerobic training (e.g., 20% $\text{VO}_{2\max}$), cycling, resistance training, and walking. The time range of a single intervention was 6–25 min (mostly was 10–20 min). The frequency of interventions varied from two to 12 times per week, with three times per week being the most common. The intervention period ranged from two to twelve weeks, with four and eight weeks being the most frequent. The control group usually adopted the previous lifestyle and daily physical exercise. The outcome indicator was the $\text{VO}_{2\max}$.

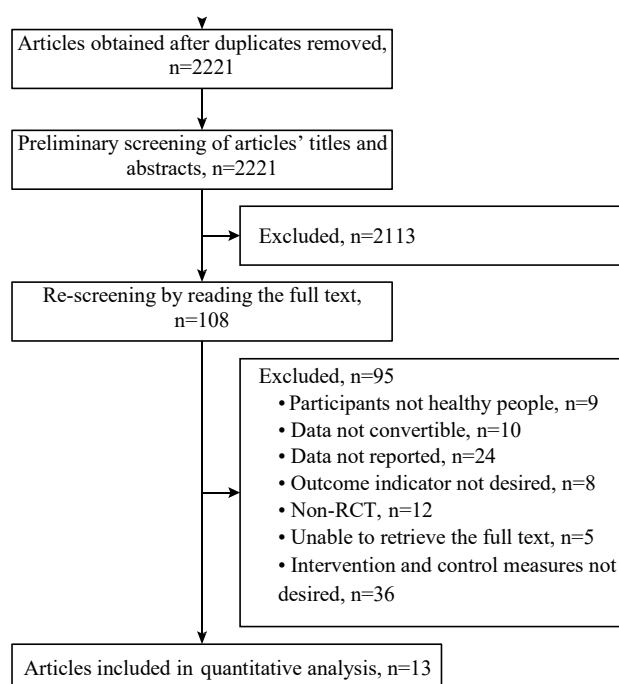


Fig. 2. Flow of studies within the review process.

The Cochrane assessment tool showed that the quality of the included literature was relatively high with the research-grade of Level A (showed in Fig. 3). Among the 13 trials, four studied treadmill training with or without blood flow restriction training, eight studied bicycle train-

ing with or without blood flow restriction training, and one studied resistance training with or without blood flow restriction training. Table 1 (Ref. [12,14,15,18–26]) shows the baseline characteristics of the participants and the experimental protocol of each study.

3.2 Reporting bias

In Fig. 4, a funnel chart was prepared to test the publication bias for the aerobic capacity score outcome indicators. The distribution of each research point was symmetrical, indicating that there was low risk of publication bias.

3.3 Test of the total effect of blood flow restriction training on aerobic capacity

A total of 13 RCTs [12,14,15,18–22,24–26,26] were included in this meta-analysis, including 246 participants. The results of the fixed effects model in the meta-analysis showed that the improvement of aerobic capacity ($\text{VO}_{2\text{peak}}$ mL/min/kg) in the compression group was significantly better than that in the conventional training group [SMD = 0.40, 95% CI (0.14–0.66), $I^2 = 0\%$, $p < 0.01$] (Fig. 5).

3.4 Subgroup analysis

3.4.1 Intervention intensity

This meta-analysis included a total of 246 participants and 13 RCTs. However, considering that the training intensity was all low, subgroup analysis couldn't be done for Intervention intensity.

3.4.2 Intervention cycle

We defined 2–4 weeks as short cycle ($n = 84$) and 4–8 weeks as long cycle ($n = 141$). This variable group included a total of 225 samples, and the effect sizes of the two groups (short cycle group and long cycle group) were highly heterogeneous ($I^2 = 64.1\%$, for intervention duration), indicating that the intervention period had a certain influence on the relationship between blood flow restriction training and aerobic capacity. Among them, the intervention for 2–4 weeks had the most pronounced effect on improving aerobic capacity $d = 0.565$ ($p = 0.014$), (95% CI: 0.116–1.014, $I^2 = 11.2\%$), followed by the intervention group for 4–8 weeks, with the effect size of $d = 0.439$ ($p = 0.011$), (95% CI: 0.102–0.776, $I^2 = 0\%$). The intervention effect size gradually decreased with the extension of exercise time. The improvement effect of the blood flow restriction training on the $\text{VO}_{2\max}$ of the two groups was significantly better than that of the conventional training group.

3.4.3 Intervention frequency

This variable group included 246 samples, and the weekly intervention frequency was 12 times/week ($n = 16$) and 2–4 times/week ($n = 230$) in two subgroups. Among them, the intervention 12 times/week had the most pronounced effect on improving aerobic capacity $d = 1.480$ ($p = 0.015$), (95% CI: 0.293–2.668, $I^2 = 53.4\%$), followed by

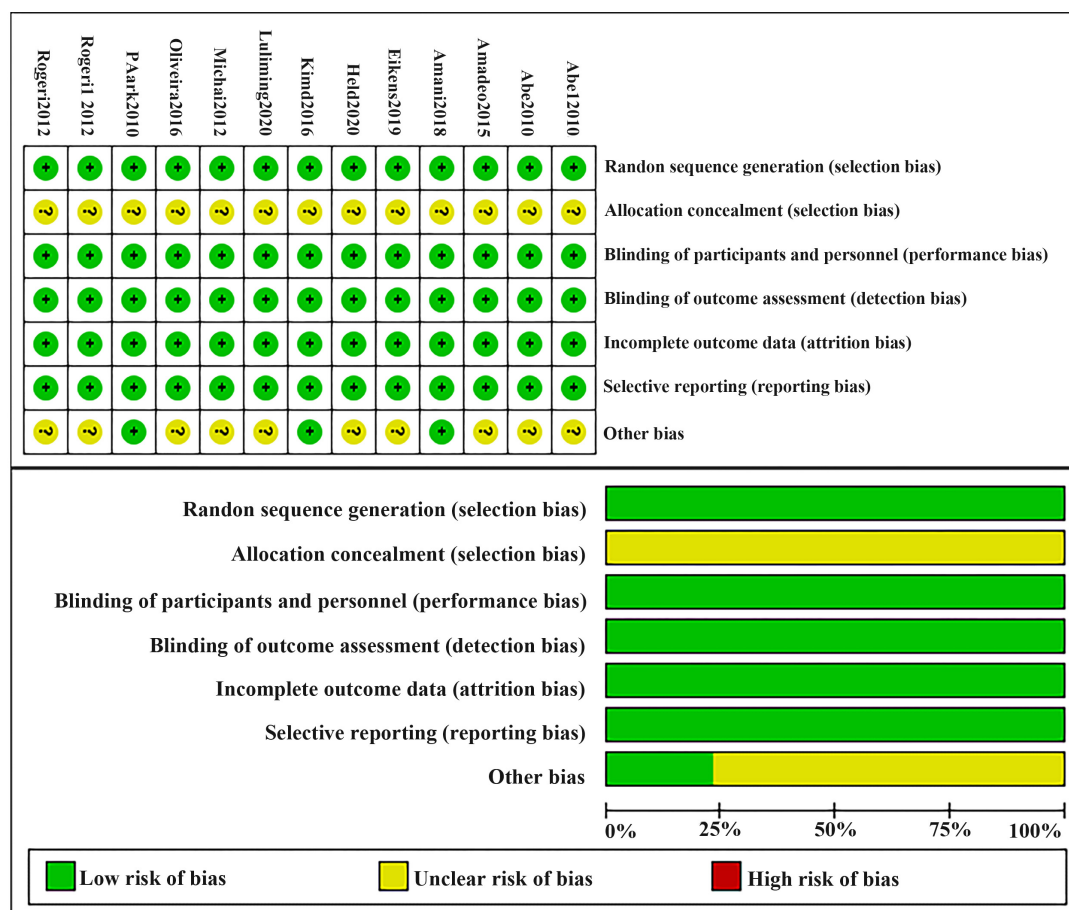


Fig. 3. Quality evaluation information chart.

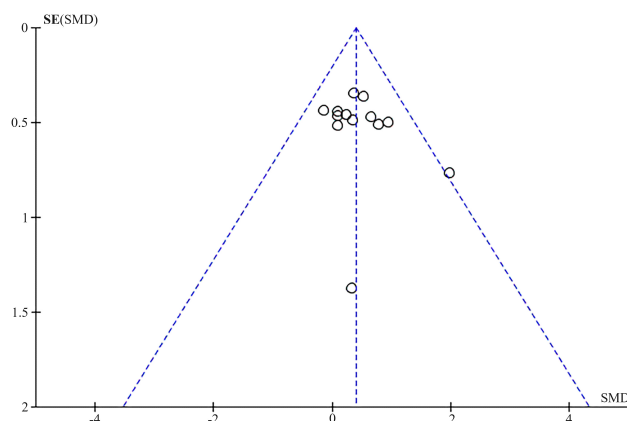


Fig. 4. Plot of publication bias.

2–4 times/week in the intervention group, the effect size $d = 0.439$ ($p = 0.005$), (95% CI: 0.112–0.639, $I^2 = 0\%$). The intervention effect size gradually increased with the increase of the number of exercises. The improvement of the intervention of both blood flow restriction training groups in the VO_{2max} was significantly better than that of the conventional training group.

3.4.4 Intervention methods

This variable group included 203 samples. The intervention was divided into three groups: low-intensity blood flow restriction training combined with treadmills group ($n = 85$), resistance exercise group ($n = 18$), and low-intensity blood flow restriction training combined with cycling group ($n = 103$). Among them, the low-intensity blood flow restriction training combined with treadmills group had the most pronounced effect on improving aerobic capacity $d = 0.567$ ($p = 0.015$) (95% CI: 0.117–1.018, $I^2 = 42.7\%$), followed by the low-intensity blood flow restriction training combined with cycling group, with the effect size of $d = 0.484$, ($p = 0.014$), (95% CI: 0.099–0.870, $I^2 = 0\%$). Although the effect size of the blood flow restriction training combined with resistance training group was the highest, $d = 0.994$ ($p = 0.048$) (95% CI: 0.008–1.980), only one experiment was analyzed.

3.5 Sensitivity analysis

The method of excluding individual studies one by one was used to analyze the sensitivity of the VO_{2max} , and the combined results did not change directionally, suggesting that the meta-analysis results were relatively stable (Fig. 6).

Table 1. List of basic characteristics of the included articles.

Author and publication year	Age (mean)	Sample size (C:T)	Exercise style	Exercise intensity	Exercise frequency	Exercise duration	Blood flow restriction training measures
Abe 2010 [12]	60–80	8:11	Walking	40% VO_{2max}	3 times/week	8 weeks	Pressure belt: 5 cm Applied pressure: 160–210 mmHg Compression duration: 18 min
Abe 2010 [18]	20.3 \pm 1.7	9:10	Cycling	40% VO_{2max}	3 times/week	8 weeks	Pressure belt: 5 cm Applied pressure: 160–200 mmHg Compression duration: 23 min
Park 2010 [15]	20.1 \pm 1.2	5:7	Walking	40% VO_{2max}	12 times/week	2 weeks	Pressure belt: 11 cm Applied pressure: 160–210 mmHg Compression duration: 19 min
Corvino 2019 [23]	25 \pm 5	7:8	Cycling	30% HR peak value	3 times/week	4 weeks	Pressure belt: 18 cm Applied pressure: 140–200 mmHg Compression duration: *
Corvino 2019 [23]	25 \pm 5	7:8	Cycling	20% HR peak value	3 times/week	4 weeks	Pressure belt: 18 cm Applied pressure: 140–200 mmHg Compression duration: *
Keramidas 2012 [14]	27 \pm 5	10:10	Cycling	30 W	3 times/week	6 weeks	Pressure belt: 5 cm Applied pressure: +90 mmHg Compression duration: 6 min
Salvador 2016 [19]	20 \pm 5	2:2	Jogging	40% maximum speed	12 times/week	4 weeks	Pressure belt: 5 cm Applied pressure: +90 mmHg Compression duration: 10 min
Oliveira 2016 [22]	23.8 \pm 4	7:10	Cycling	30% VO_{2max}	3 times/week	4 weeks	Pressure belt: 5 cm Applied pressure: +90 mmHg Compression duration: 8 min
Amani 2018 [20]	23.89 \pm 2.26	9:10	Jogging	60% HR RMAX	3 times/week	2 weeks	Pressure belt: 5 cm Applied pressure: 140–180 mmHg Compression duration: 8–10 min
CONCEIÇÃO [21]	21 \pm 3	10:10	Jogging	30% VO_{2max}	4 times/week	8 weeks	Pressure belt: 5 cm Applied pressure: 80% pressure Compression duration: 30 min
Eikens 2018 [25]	58.1 \pm 10.4	17:17	Cycling	40% VO_{2max}	3 times/week	6 weeks	Pressure belt: 5 cm Applied pressure: 140 mmHg Compression duration: *
Held 2020 [26]	21.9 \pm 3.2	16:15	Cycling	30 W increments to exhaustion	2 times/week	5 weeks	Pressure belt: 5 cm Applied pressure: * Compression duration: 20 min
Lu 2020 [24]	22.4 \pm 1.94	5:7	Resistance exercise	20% 1RM	3 times/week	12 weeks	Pressure belt: 8 cm Applied pressure: 120 mmHg Compression duration: 20 min

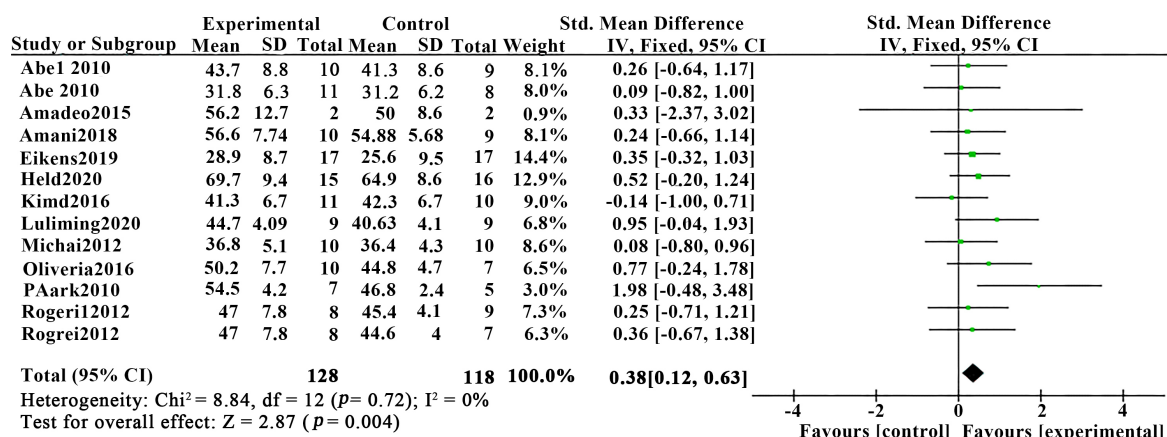


Fig. 5. Forest plot of aerobic capacity(mL/min/kg) improvement by blood flow restriction training.

4. Discussion

The level of aerobic capacity greatly determines the ability to repeat a high-intensity exercise. It also plays a role in the intermittent recovery period and delays or eliminates some fatigue, and helps the body make better choices under fatigue conditions, thereby ensuring stable technical and tactical output. In addition, it plays an important role in the assessment of daily physical labor level in ordinary people, the evaluation of the cardiopulmonary function, the diagnosis of organ function of patients, and the formulation of empirical exercise prescriptions. This study mainly explored the effects of blood flow restriction training on aerobic capacity-related indicators of the participants. Aerobic capacity-related indicators are often used in the evaluation of athletes' competitive ability, and the indicators are useful for evaluating the aerobic capacity of athletes, understanding their aerobic endurance, evaluating training effects, making training plans, and monitoring athletic training [12,13,15]. Our study showed that the intervention method combined with the blood flow restriction training had a significant improvement effect on aerobic capacity ($p < 0.01$), which was consistent with previous reports [12,17], and showed that the VO_{2max} of the blood flow restriction training groups increased by 5.5% and 5.1%. Among the 31 athletes who underwent five weeks of blood flow restriction training, the VO_{2max} increased more in the blood flow restriction training group (9.1%) than in the control group (2.5%) during a power cycling test under low-intensity conditions [26]. The results of subgroup analysis suggested that the effect of training frequency of 12 times/week was better than that of training frequency of 2–4 times/week Table 2. In addition, the short cycle (2–4-week intervention period) was better than that of long cycle (the 4–8-week intervention period). The best intervention method was the treadmill combined with blood flow restriction training. Although cycling combined with blood flow restriction training was not significantly better than running, it increased the VO_{2max} by 2.33 standard de-

viations. Resistance training showed the most pronounced effect on VO_{2max} . However, only one study used blood flow restriction training combined with resistance exercise, so there might be a bias. There are many reasons for improving aerobic capacity, and the possible mechanisms include central (oxygen transport) and peripheral (oxygen utilization) factors (Fig. 7).

This study did not aim to provide a deep discussion on the physiology of blood flow restriction training, however the results of the meta-analysis allow some discussion of following aspects: impacts on lung ventilation and lung diffusion capacity; blood ejection ability of the heart; oxygen transport in the blood; ability of skeletal muscle to utilize oxygen. The lungs obtaining oxygen from the environment is the basis for oxygen supply during exercise. Respiratory muscles play an important role in the entire process of breathing and gas exchange. Studies have shown that high-intensity exercises induce fatigue similarly in respiratory muscles and skeletal muscles [27,28]. Although the load intensity used for blood flow restriction training is often at low intensity, the physiological load produced is the same as the effect produced by high intensity. The result is even better than the effect produced under high-intensity physical load [29]. Evans *et al.* [30] indicated that oxygen partial pressure difference and oxygen saturation decrease would cause the oxygen diffusion rate in the lungs to limit VO_{2max} in the body. Corvino *et al.* [23] applied 140–200 mmHg pressure on both sides of the thighs of participants in the blood flow restriction training group. Comparison of before and after the interventions showed that high-intensity training and blood flow restriction training combined with low-intensity interval training effectively improved the lungs' transport capacity [31,32]. The cardiac output depends on end diastolic volume and left ventricular ejection fraction. Wei *et al.* [33] showed that under blood flow restriction training the minute ventilation increased. Furthermore, during blood flow restriction training, the amount of blood remaining at the entrance of the arteries in the limbs is in-

Table 2. Table showing the subgroup analysis characteristics.

Research characteristics	Index classification	Sample size	SMD	95% CI		<i>p</i>	I ² (%)	<i>p</i> of SMD
Intervention cycle	Short (2–4 weeks)	84	0.565	0.116	1.014	0.344	11.2	0.014
	Long (4–8 weeks)	141	0.439	0.102	0.776	0.734	0	0.011
Intervention frequency	12 times/week	16	1.48	0.293	2.668	0.143	54.3	0.015
	2–3 times/week	230	0.391	0.118	0.663	0.881	0	0.005
Intervention method	Cycling	103	0.365	−0.058	0.77	0.966	0	0.092
	Treadmill	85	0.567	0.117	1.018	0.137	42.7	0.015
	Resistance exercise	18	0.994	0.008	1.98	*	*	0.048

Note: * represents no data.

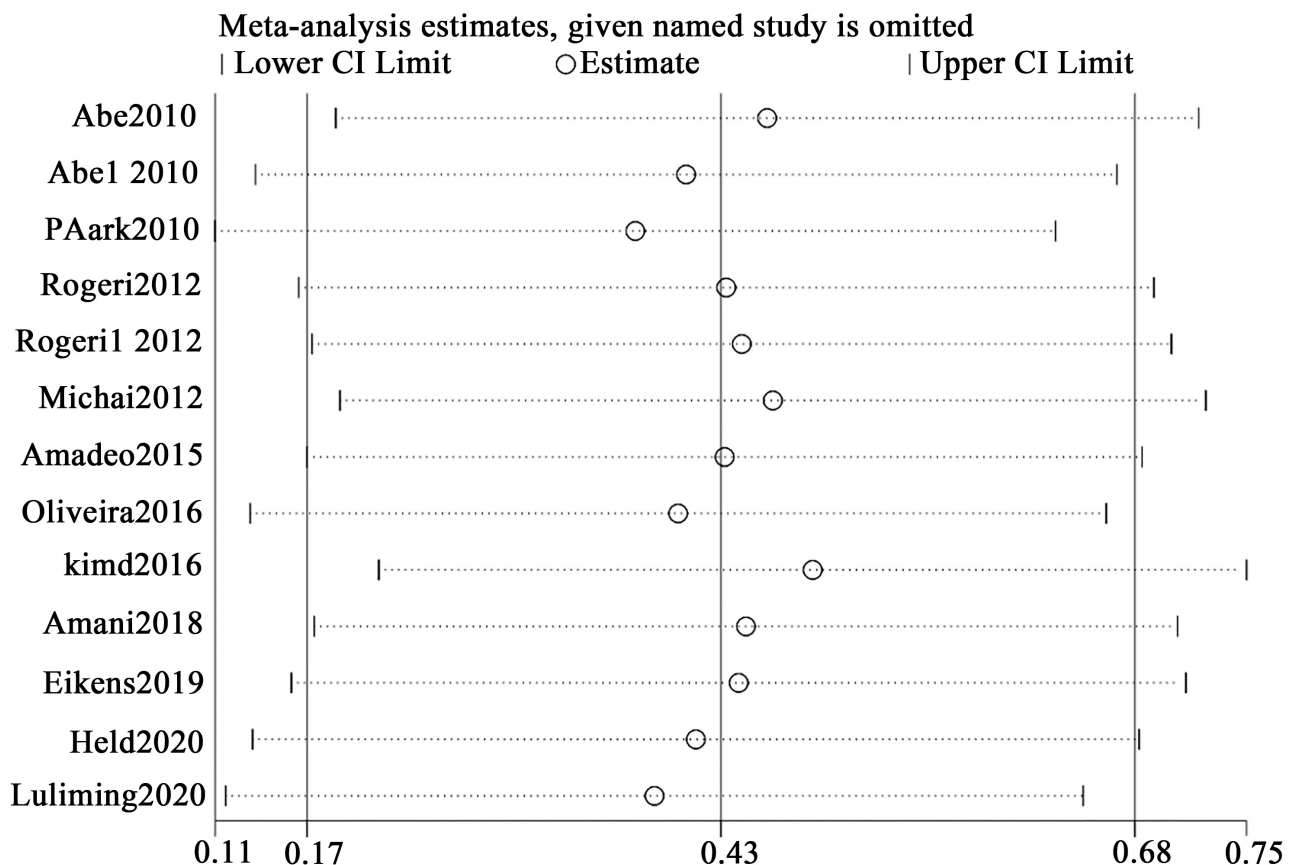


Fig. 6. Sensitivity analysis results.

creased, and the amount of blood flowing into the arteries of the limbs is decreased because the entrance of the arteries in the limbs and the exit of the veins are restricted. In addition, the amount of blood remaining in the veins of the limbs is increased, while the amount of blood returning from the lower limbs to the heart is decreased. This results in a decrease in the venous return and an increase in the peripheral resistance of the heart when pumping blood due to the increase in the blood volume at the entrance of the arteries of the lower limbs [34]. Hemoglobin (HB) in the blood is the carrier for oxygen, and the amount of HB in the blood is one of the important factors affecting oxygen transport.

Studies have shown that the blood oxygen-carrying capacity is closely related to VO_{2max} [35]. The formation of a hypoxic environment under blood flow restriction training increases muscle acidity and promotes nitric oxide release [36]. In addition, HB and vascular endothelial growth factor can improve oxygen transport and absorption, and promote the release of vascular endothelial growth factor under hypoxia. Corvino *et al.* [23] randomized 30 healthy young men into the blood flow restriction training group or non-blood flow restriction training group. After an 8-week interventional trial, males in the blood flow restriction training group showed increased muscle strength and increased the

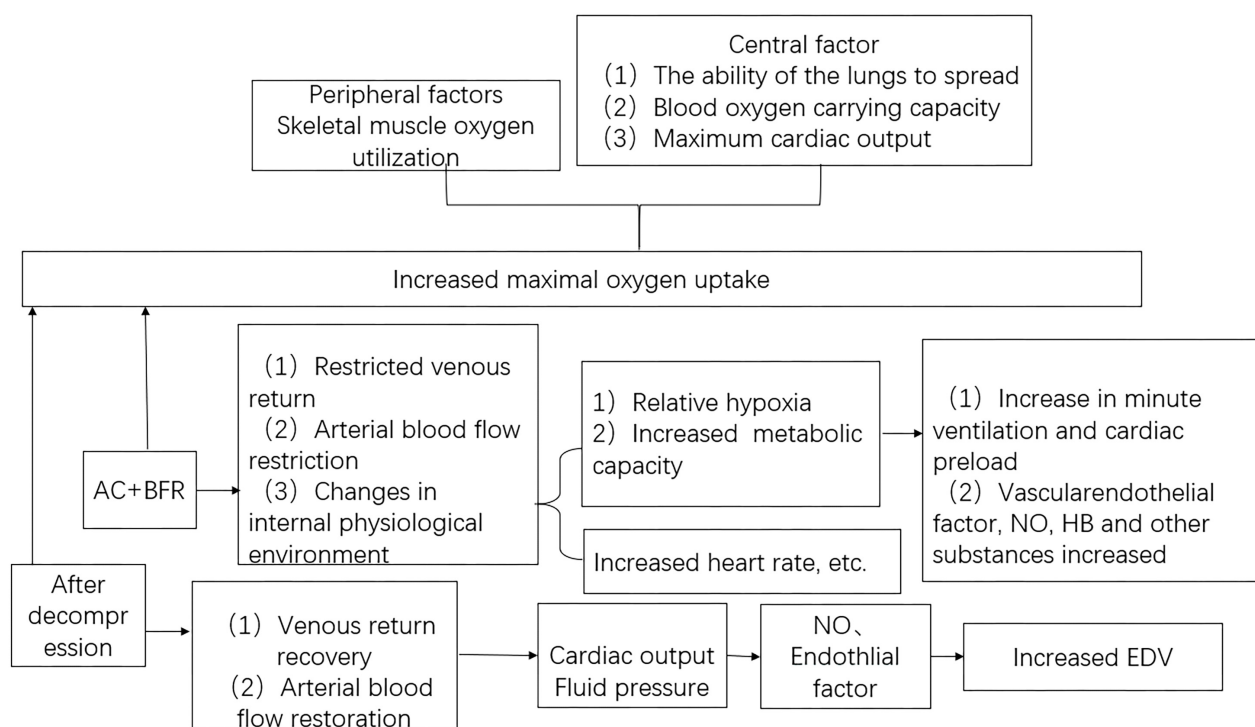


Fig. 7. Potential mechanism for improving aerobic capacity during and after the intervention of blood flow restriction training.

VO_{2max} . Like the increase in muscle strength, the increase in VO_{2max} was related to vascular endothelial growth factor and was induced under low-intensity conditions [21]. The ability of the skeletal muscle to use oxygen is mainly affected by factors such as peripheral diffusion concentration difference, mitochondrial enzyme levels, and capillary density. Muscles must contract to stimulate mitochondrial activity and cause an increase in oxygen uptake in the body [36]. In addition, the density of capillaries in skeletal muscles has a certain relationship with the VO_{2max} level [21]. The main effect of the increase in aerobic capacity caused by the increase in capillary density is achieved through decreased diffusion distance and increased diffusion time between blood and skeletal muscle tissue [37]. Blood flow restriction training during the recovery period from sprinting may increase the density of muscle tissue capillaries, leading to an increase in VO_{2max} [38]. Moreover, due to the moderate restriction of blood flow during the blood flow restriction training, the body is in a relatively hypoxic environment, and the resistance to oxygen diffusion increases. Therefore, the body will adapt to environmental changes by increasing the density of capillaries and the number of mitochondria, suggesting that this may improve aerobic capacity. Similarly, Paton *et al.* [16] randomly assigned 16 participants to the blood flow restriction training and control groups for eight training sessions. The participants completed an incremental test before and after the training [16]. Through the exhaustive exercise time under the VO_{2max} , both groups completed 80% heart rate (HR) and 30-second

incremental training. The results were $6.3 \pm 3.5\%$ and $4.0 \pm 3.3\%$ in the blood flow restriction training group and the control group, respectively. The improvement in the VO_{2max} caused by blood flow restriction training may be due to muscle function rather than cardiovascular function [39]. Taken together, blood flow restriction training improves VO_{2max} mostly through changes in muscle adaptability and function, showing a weaker correlation with the improvement of cardiovascular function than with the improvement of the muscular system [14,40].

5. Strengths and limitations

We strictly followed PRISMA guidelines to conduct this meta-analysis. The quality of included literatures was all level A with low-risk of publication bias. The limitations were as followings: (1) the analysis included a small number of reports and a small total sample size; (2) because some studies only have abstracts and no full texts, detailed data could not be found; (3) most studies only used VO_{2max} to evaluate the aerobic capacity. Thus, it's impossible for us to calculate other factors, such as respiratory rate, stroke volume and heart rate. In summary, this study showed that blood flow restriction training had a good effect on improving aerobic capacity. However, only VO_{2max} was used to evaluate the aerobic capacity, the application of above conclusions required to be further verified.

6. Conclusions

The blood flow restriction training had a significant effect on the improvement of aerobic capacity. Blood flow restriction training had a low exercise intensity. A good intervention effect was achieved with an exercise cycle of 2–4 weeks. The training frequency of 12 times a week was better than the frequency of 2–4 training per week. A daily 6–30-min blood flow restriction training had a significant effect on improving aerobic capacity. Only VO_{2max} was used to evaluate the aerobic capacity, the application of above conclusions required caution and further confirmation.

Author contributions

QY put forward the theme of the paper, analyzed the statistical data and wrote the paper; XNS verified the statistical results, carried out statistical analysis and wrote the paper; JXH, ZYZ and HWZ conducted literature research and collected statistical data; GXL and SCD conducted literature quality evaluation; DYL designed the framework, reviewed, and guided the revision of the thesis, and applied for research projects; JS designed the paper framework, organized the paper discussion, reviewed and guided the revision of the paper.

Ethics approval and consent to participate

Not applicable.

Acknowledgment

Not applicable.

Funding

The National Social Science Fund of China (20FTYB008).

Conflict of interest

The authors declare no conflict of interest.

References

- [1] Abe T, Loenneke JP, Fabs CA, Rossow LM, Thiebaud RS, Bemben MG. Exercise intensity and muscle hypertrophy in blood flow-restricted limbs and non-restricted muscles: a brief review. *Clinical Physiology and Functional Imaging*. 2012; 32: 247–252.
- [2] Wortman RJ, Brown SM, Savage-Elliott I, Finley ZJ, Mulcahey MK. Blood Flow Restriction Training for Athletes: a Systematic Review. *The American Journal of Sports Medicine*. 2021; 49: 1938–1944.
- [3] Krzysztofik M, Wilk M, Wojdała G, Golaś A. Maximizing Muscle Hypertrophy: A Systematic Review of Advanced Resistance Training Techniques and Methods. *International Journal of Environmental Research and Public Health*. 2019; 16: 4897.
- [4] Silva JCG, Pereira Neto EA, Pfeiffer PAS, Neto GR, Rodrigues AS, Bemben MG, *et al.* Acute and Chronic Responses of Aerobic Exercise with Blood Flow Restriction: A Systematic Review. *Frontiers in Physiology*. 2019; 10: 1239.
- [5] Tomlin DL, Wenger HA. The Relationship between Aerobic Fitness and Recovery from High Intensity Intermittent Exercise. *Sports Medicine*. 2001; 31: 1–11.
- [6] Madarame H, Neya M, Ochi E, Nakazato K, Sato Y, Ishii N. Cross-Transfer Effects of Resistance Training with Blood Flow Restriction. *Medicine & Science in Sports & Exercise*. 2008; 40: 258–263.
- [7] Martín-Hernández J, Marín PJ, Menéndez H, Ferrero C, Loenneke JP, Herrero AJ. Muscular adaptations after two different volumes of blood flow-restricted training. *Scandinavian Journal of Medicine & Science in Sports*. 2013; 23: e114–e120.
- [8] Slys JT, Burr JF. The Effects of Blood Flow Restricted Electrostimulation on Strength and Hypertrophy. *Journal of Sport Rehabilitation*. 2018; 27: 257–262.
- [9] Yasuda T, Ogasawara R, Sakamaki M, Ozaki H, Sato Y, Abe T. Combined effects of low-intensity blood flow restriction training and high-intensity resistance training on muscle strength and size. *European Journal of Applied Physiology*. 2011; 111: 2525–2533.
- [10] Wei J, Li B, Yang W, Wang X, Feng S, Li Y. The Effects and Mechanisms of Blood Flow Restriction Training. *China Sport Science*. 2019; 39: 71–80. (In Chinese)
- [11] Abe T, Kearns CF, Fujita S, Sakamaki M, Sato Y, Brechue WF. Skeletal muscle size and strength are increased following walk training with restricted leg muscle blood flow: implications for training duration and frequency. *International Journal of KAATSU Training Research*. 2009; 5: 9–15.
- [12] Abe T, Sakamaki M, Fujita S, Ozaki H, Sugaya M, Sato Y, *et al.* Effects of low-intensity walk training with restricted leg blood flow on muscle strength and aerobic capacity in older adults. *Journal of Geriatric Physical Therapy*. 2010; 33: 34–40.
- [13] Manari D, Manara M, Zurini A, Tortorella G, Vaccarezza M, Prandelli N, *et al.* VO2Max and VO2AT: athletic performance and field role of elite soccer players. *Sport Sciences for Health*. 2016; 12: 221–226.
- [14] Keramidis ME, Kounalakis SN, Geladas ND. The effect of interval training combined with thigh cuffs pressure on maximal and submaximal exercise performance. *Clinical Physiology and Functional Imaging*. 2012; 32: 205–213.
- [15] Park S, Kim JK, Choi HM, Kim HG, Beekley MD, Nho H. Increase in maximal oxygen uptake following 2-week walk training with blood flow occlusion in athletes. *European Journal of Applied Physiology*. 2010; 109: 591–600.
- [16] Paton CD, Addis SM, Taylor LA. The effects of muscle blood flow restriction during running training on measures of aerobic capacity and run time to exhaustion. *European Journal of Applied Physiology*. 2017; 117: 2579–2585.
- [17] Clarkson MJ, Conway L, Warmington SA. Blood flow restriction walking and physical function in older adults: a randomized control trial. *Journal of Science and Medicine in Sport*. 2017; 20: 1041–1046.
- [18] Abe T, Fujita S, Nakajima T, Sakamaki M, Ozaki H, Ogasawara R, *et al.* Effects of Low-Intensity Cycle Training with Restricted Leg Blood Flow on Thigh Muscle Volume and VO2MAX in Young Men. *Journal of Sports Science & Medicine*. 2010; 9: 452–458.
- [19] Salvador AF, Schubert KR, Cruz RS, Corvino RB, Pereira KL, Caputo F, *et al.* Bilateral muscle strength symmetry and performance are improved following walk training with restricted blood flow in an elite paralympic sprint runner: Case study. *Physical Therapy in Sport*. 2016; 20: 1–6.
- [20] Amani AR, Sadeghi H, Afsharnezhad T. Interval Training with Blood Flow Restriction on Aerobic Performance among Young Soccer Players at Transition Phase. *Montenegrin Journal of Sports Science and Medicine*. 2018; 7: 5.
- [21] Conceição MS, Junior EMM, Telles GD, Libardi CA, Castro A, Andrade ALL, *et al.* Augmented Anabolic Responses after 8-

- wk Cycling with Blood Flow Restriction. *Medicine & Science in Sports & Exercise*. 2019; 51: 84–93.
- [22] de Oliveira MF, Caputo F, Corvino RB, Denadai BS. Short-term low-intensity blood flow restricted interval training improves both aerobic fitness and muscle strength. *Scandinavian Journal of Medicine & Science in Sports*. 2016; 26: 1017–1025.
- [23] Corvino RB, Oliveira MFM, Denadai BS, Rossiter HB, Caputo F. Speeding of oxygen uptake kinetics is not different following low-intensity blood-flow-restricted and high-intensity interval training. *Experimental Physiology*. 2019; 104: 1858–1867.
- [24] Lu JM, Liu SY, Sun P, Li WL, Lian ZQ. Effects of low intensity resistance training of blood flow restriction with different occlusion pressure on lower limb muscle and cardiopulmonary function of college students. *Chinese Journal of Applied Physiology*. 2020; 36: 595–599. (In Chinese)
- [25] Eikens F, Lay D, Behringer M, Predel H. Influence of blood flow restriction training on post exercise hypotension in hypertensive subjects -a randomized controlled trial. *Hypertension*. 2018; 3: 42.
- [26] Held S, Behringer M, Donath L. Low intensity rowing with blood flow restriction over 5 weeks increases $\dot{V}O_{2\max}$ in elite rowers: a randomized controlled trial. *Journal of Science and Medicine in Sport*. 2020; 23: 304–308.
- [27] Johnson BD, Babcock MA, Suman OE, Dempsey JA. Exercise-induced diaphragmatic fatigue in healthy humans. *The Journal of Physiology*. 1993; 460: 385–405.
- [28] Aaron EA, Johnson BD, Seow CK, Dempsey JA. Oxygen cost of exercise hyperpnea: measurement. *Journal of Applied Physiology*. 1992; 72: 1810–1817.
- [29] Wu Y, Li Q, Bao D. The Effects of KAATSU Training on the Lower Limb: A Meta-analysis. *China Sport Science and Technology*. 2019; 55: 20–26. (In Chinese)
- [30] Evans HJ, Ferrar KE, Smith AE, Parfitt G, Eston RG. A systematic review of methods to predict maximal oxygen uptake from submaximal, open circuit spirometry in healthy adults. *Journal of Science and Medicine in Sport*. 2015; 18: 183–188.
- [31] Scott BR, Loenneke JP, Slattery KM, Dascombe BJ. Exercise with Blood Flow Restriction: an Updated Evidence-Based Approach for Enhanced Muscular Development. *Sports Medicine*. 2015; 45: 313–325.
- [32] Pardo Albiach J, Mir-Jimenez M, Hueso Moreno V, Nácher Moltó I, Martínez-Gramage J. The Relationship between $\dot{V}O_{2\max}$, Power Management, and Increased Running Speed: Towards Gait Pattern Recognition through Clustering Analysis. *Sensors*. 2021; 21: 2422.
- [33] Wei W, Sun K, Zhao Z, Ding M, Wang M, Xiao Z. Effects of Different Pressure of Blood Flow Restriction on Cardiopulmonary Endurance during Incremental Intensity Running. *China Sport Science and Technology*. 2019; 55: 8–13. (In Chinese)
- [34] Renzi CP, Tanaka H, Sugawara J. Effects of Leg Blood Flow Restriction during Walking on Cardiovascular Function. *Medicine & Science in Sports & Exercise*. 2010; 42: 726–732.
- [35] di Prampero PE, Ferretti G. Factors limiting maximal oxygen consumption in humans. *Respiration Physiology*. 1990; 80: 113–128.
- [36] Zhao Z, Cheng J, Wei W, Sun K, Wang M. KAATSU Training and Traditional Muscle Hypertrophy Training on Some Hormones and Bioactive Factors of Elite Male Handball Players. *China Sport Science and Technology*. 2019; 55: 20–29. (In Chinese)
- [37] Barcelos LC, Nunes PRP, de Souza LRMF, de Oliveira AA, Furlanetto R, Marocolo M, *et al.* Low-load resistance training promotes muscular adaptation regardless of vascular occlusion, load, or volume. *European Journal of Applied Physiology*. 2015; 115: 1559–1568.
- [38] Kim LJ. Changes of Compound Muscle Action Potential after Low-Intensity Exercise with Transient Restriction of Blood Flow: A Randomized, Placebo-Controlled Trial. *Journal of Physical Therapy Science*. 2009; 21: 361–366.
- [39] Scott BR, Loenneke JP, Slattery KM, Dascombe BJ. Blood flow restricted exercise for athletes: a review of available evidence. *Journal of Science and Medicine in Sport*. 2016; 19: 360–367.
- [40] Lixandrão ME, Roschel H, Ugrinowitsch C, Miquelini M, Alvarez IF, Libardi CA. Blood-Flow Restriction Resistance Exercise Promotes Lower Pain and Ratings of Perceived Exertion Compared with either High- or Low-Intensity Resistance Exercise Performed to Muscular Failure. *Journal of Sport Rehabilitation*. 2019; 28: 706–710.