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

Qun Yang¹,†, Duan Ying Li¹,†, Jia Xin He¹, Zhi Yong Zhang¹, Hong Wei Zhu¹, Guo Xing Li², Shi Cong Ding³, Xiao Ning Sun²,*,†, Jian Sun¹,*,†

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.
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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, CINHAL, 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), I² = 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 (VO₂max); Meta-analysis

1. Introduction

Blood flow restriction training (also known as 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 interventions, 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, CINHAL, 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
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$_{2\text{max}}$). 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 $a = 0.1$), 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% VO2max), 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 VO2max.

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 (VO2peak 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), I2 = 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 (I2 = 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, I2 = 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, I2 = 0%). The intervention effect size gradually decreased with the extension of exercise time. The improvement effect of the blood flow restriction training on the VO2max 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, I2 = 53.4%), followed by

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**Fig. 2. Flow of studies within the review process.**
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$_{2\text{max}}$ 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$_{2\text{max}}$, 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$_{2\text{max}}$ | 3 times/week      | 8 weeks           | Pressure belt: 5 cm  
Applied pressure: 160–210 mmHg  
Compression duration: 18 min |
| Abel 2010 [18]              | 20.3 ± 1.7 | 9:10               | Cycling        | 40% VO$_{2\text{max}}$ | 3 times/week      | 8 weeks           | Pressure belt: 5 cm  
Applied pressure: 160–200 mmHg  
Compression duration: 23 min |
| Park 2010 [15]              | 20.1 ± 1.2 | 5:7                | Walking        | 40% VO$_{2\text{max}}$ | 12 times/week     | 2 weeks           | Pressure belt: 11 cm  
Applied pressure: 160–210 mmHg  
Compression duration: 19 min |
| Corvino 2019 [23]           | 25 ± 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 1 2019 [23]         | 25 ± 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 ± 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 ± 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 ± 4   | 7:10               | Cycling        | 30% VO$_{2\text{max}}$ | 3 times/week      | 4 weeks           | Pressure belt: 5 cm  
Applied pressure: +90 mmHg  
Compression duration: 8 min |
| Amani 2018 [20]             | 23.89 ± 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 ± 3     | 10:10              | Jogging        | 30% VO$_{2\text{max}}$ | 4 times/week      | 8 weeks           | Pressure belt: 5 cm  
Applied pressure: 80% pressure  
Compression duration: 30 min |
| Eikens 2018 [25]            | 58.1 ± 10.4 | 17:17            | Cycling        | 40% VO$_{2\text{max}}$ | 3 times/week      | 6 weeks           | Pressure belt: 5 cm  
Applied pressure: 140 mmHg  
Compression duration: * |
| Held 2020 [26]              | 21.9 ± 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 ± 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 |
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].

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: impact 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\textsubscript{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 insignificant.
Table 2. Table showing the subgroup analysis characteristics.

| Research characteristics | Index classification | Sample size | SMD     | 95% CI | p  | I² (%) | p 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.

Studies have shown that the blood oxygen-carrying capacity is closely related to $\text{VO}_{2\text{max}}$ \[35\]. 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$_{2\text{max}}$. Like the increase in muscle strength, the increase in VO$_{2\text{max}}$ 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$_{2\text{max}}$ 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$_{2\text{max}}$ [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$_{2\text{max}}$, both groups completed 80% heart rate (HR) and 30-second incremental training. The results were 6.3 ± 3.5% and 4.0 ± 3.3% in the blood flow restriction training group and the control group, respectively. The improvement in the VO$_{2\text{max}}$ 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$_{2\text{max}}$ 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$_{2\text{max}}$ 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$_{2\text{max}}$ 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$_{2\text{max}}$ 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, and collected statistical data; JXH, ZYZ and HWZ conducted literature research and wrote the paper; XNS verified the statistical data and wrote the paper; KRW, GZ and YC conducted literature research.

Ethics approval and consent to participate

Not applicable.

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Conflict of interest

The authors declare no conflict of interest.

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