Huang et al. BMC Sports Science, Medicine and Rehabilitation (2025) 17:46
https://doi.org/10.1186/s13102-025-01084-8

BMC Sports Science, Medicine and Rehabilitation

RESEARCH Open Access

Hemodynamic analysis of blood flow restriction training: a systematic review

Ruifeng Huang[1,2], Yong Ma[1,3,4*], Zizhe Yang[1,2], Zhikun Wang[1,2], Canyi Zeng[1,2], Yazhou Qin[1,2] and Mengyao Jia[1,2*]

Abstract
Blood Flow Restriction Training (BFRT) is a low-load training technique that involves applying pressure to partially restrict arterial blood flow while occluding venous return. Despite its growing popularity, there is still no consensus on how combining BFRT with resistance or aerobic training influences hemodynamic responses, or on the safest and most effective methods for implementing it. This review aims to systematically identify the effects of BFRT on hemodynamic parameters. A systematic review was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) Statement guidelines. The Chinese literature search was performed in the China National Knowledge Infrastructure (CNKI) database. English literature search was conducted in the Web of Science, PubMed, and Google Scholar databases. The studies included human subjects, the outcome indicators included hemodynamic evaluation indicators, and only randomized controlled trials and randomized crossover trials were considered. Non-Chinese or English literature, duplicate studies, and those with missing data were excluded. The adapted STROBE checklist was used to assess the risk of bias, 44 articles were included in this review. Results indicated that BFRT has increased heart rate and blood lactate levels, while its effect on blood oxygen saturation varies. Additionally, BFRT significantly enhances cardiac output but may either have no significant effect or cause a decrease in stroke volume. Furthermore, BFRT improves pulse wave velocity from the femur to the posterior tibia, suggesting a positive influence on cardiovascular function. BFRT induces changes in arterial structure and function, with these indicators interacting to produce both positive and negative effects on cardiovascular health. The primary mechanisms by which BFRT influences hemodynamics include the activation of the sympathetic and vagus nerves, as well as the regulation of chemical mediators in body fluids that modulate cardiovascular function. Convenient, economical, non-invasive, and easily measurable hemodynamic indicators are expected to become an efficient tool for evaluating the effects of exercise training. Further research is needed to establish the optimal compression thresholds and durations for different populations and exercise types, as well as to assess the long-term impact of BFRT on hemodynamic parameters.

Clinical trial number
Not applicable.

Keywords BFRT, Blood pressure, Heart rate, Blood lactate, Blood oxygen saturation

*Correspondence:
Yong Ma
mayong@whsu.edu.cn
Mengyao Jia
jmy15737132785@163.com
[1]School of Intelligent Sports Engineering, Wuhan Sports University, Wuhan 430079, P.R. China
[2]Key Laboratory of Sports Engineering of General Administration of Sports of China, Wuhan Sports University, Wuhan 430079, P.R. China
[3]Specialised Research Centre for High-Quality Development of Competitive Sports, Wuhan Sports University, Wuhan 430079, P.R. China
[4]Engineering Research Center of Sports Health Intelligent Equipment of Hubei Province, Wuhan Sports University, Wuhan 430079, P.R. China

Introduction

The American College of Sports Medicine recommends a strength training at an intensity of 70% of one repetition maximum (1RM) to promote muscle hypertrophy and strength gains [1]. However, this training method requires heavy loads, which may increase the stress on muscles and joints, thereby elevating the risk of injury and placing an additional burden on the cardiovascular system. Blood Flow Restriction Training (BFRT) offers similar results to high-intensity resistance training while utilizing lower weight loads. Developed by Dr. Yoshiaki Sato in 1983 [2], BFRT involves applying pressure to partially restrict blood flow. This method promotes muscle hypertrophy, increases strength, and enhances endurance.

BFRT uses specialized devices to apply pressure to the upper or lower limbs of the human body during exercise [3], and occluding certain blood vessels in the limbs and reducing venous return from the limb's proximal end. Typically, there are two methods of pressurization, one involves applying a fixed pressure, ranging from 100-240mmHg. The other method measures the user's arterial occlusion pressure (AOP) or limb occlusion pressure (LOP), and then select 40 -80% AOP or LOP as the compression amount, based on the individual's condition. BFRT can affect the cardiovascular system, leading to changes in hemodynamic indicators [4]. Clinically, these indicators are often used to assess physiological or pathological changes in the body [5]. When evaluating the effects of exercise training, objective and quantitative hemodynamic measurements are expected to become an effective tool for indirect evaluation [6]. During exercise, Blood flow within vessels directly interacts with endothelial cells, subjecting them to hemodynamic stimuli [7]. Endothelial cells can sense various types of hemodynamic stimuli and transmit these signals, triggering cellular responses. These responses include changes in cell morphology, function, and gene expression, as well as the release of vasoactive substances such as nitric oxide (NO, a vasodilator) and endothelin-1 (ET-1, a vasoconstrictor) [8]. These processes are referred to as the mechanobiological effects of vascular endothelial cells. The biomechanical effects have both short-term and long-term impacts. In the short term, they are closely related to changes in vascular volume and local blood pressure, which are regulated by vascular smooth muscle. Over time, these effects contribute to vascular remodeling and structural reshaping. Blood pressure is the most fundamental hemodynamic monitoring indicator. It is closely linked to blood circulation in tissues and organs, the body's oxygen supply, and microcirculation. Exercise has a protective effect on blood pressure, reducing the risk of hypertension [9–12]. Heart rate (HR) serves as an important indicator of cardiac function, and it is crucial to maintain heart rate within an optimal range to achieve desired outcomes [13]. Excessive training can lead to the accumulation of blood lactate (BLa) and a subsequent decrease in pH, which can result in delayed onset muscle soreness and impair physical performance in daily activities [14], this can result in delayed onset muscle soreness and impair physical performance in daily activities [15], Blood oxygen saturation refers to the concentration of oxygen in the blood and includes pulse oxygen saturation (SpO2), tissue oxygen saturation (StO2, also known as tissue saturation index, TSI), and muscle oxygen saturation (SmO2), which reflex the oxygen saturation of hemoglobin in muscle tissue. Cardiac output (CO) refers to the volume of blood ejected from one ventricle per minute and should be adjusted according to the body's metabolic demands. Stroke volume (SV) is defined as the amount of blood ejected by one ventricle with each contraction. The combination of these two indicators can be used to assess whether the heart's pumping function is negatively affected. Pulse wave velocity (PWV) refers to the speed at which pressure waves travel along the walls of major arteries with each heartbeat. It can indirectly reflect vascular damage caused by various risk factors. In clinical practice, hemodynamic monitoring includes additional indicators, such as mean velocity, plasma volume, shear rate (SR), oscillatory shear index (OSI), total peripheral resistance (TPR) [6, 16–18]. However, research on these indicators is currently relatively limited.

The above indicators are essential for evaluating cardiovascular function, and cardiovascular health, which is closely related to a variety of chronic diseases (such as hypertension, coronary heart disease, heart failure). Understanding the effects of BFRT on these parameters can help better assess its safety in both rehabilitation and training. This is important not only for patients with cardiovascular diseases or high-risk groups, but also for healthy individuals considering BFRT. Additionally, while BFRT is a low-load training method known to promote muscle hypertrophy and strength gains, its potential effects on the cardiovascular system are not yet fully understood. Clarifying the hemodynamic effects of BFRT will help optimize training programs for healthy individuals and provide a theoretical foundation for clinical rehabilitation, such as its application in postoperative recovery, exercise interventions for the elderly, and treatments for patients with cardiovascular conditions. Therefore, this study reviews and summarizes the existing relevant literature, examining the effects and mechanisms of BFRT on human hemodynamic parameters under various conditions. It also analyzes current issues and research prospects based on existing findings.

Methods

Information sources and search strategy

This systematic review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) Statement guidelines, and it was registered on PROSPERO (CRD42025630210). A systematic search was undertaken to identify all relevant studies assessing the effect of BFRT on hemodynamics parameters. The Chinese literature search was performed in the China National Knowledge Infrastructure (CNKI) database. English literature search was performed in the Web of Science, PubMed, and Google Scholar databases. The following keywords and terms were used: ("Blood Flow Restriction Training" OR "BFRT") AND ("KAATSU training" OR "Hemodynamics" OR "Blood Pressure" OR "Heart Rate" OR "Blood Lactate" OR "Cardiac Output" OR "Stroke Volume" OR "oxygen saturation" OR "pulse wave velocity"). The time span of the search was from the inception of the databases to January 31, 2025.

Eligibility criteria

Inclusion criteria

(1) The research subjects are humans, all subjects are ≥ 18 years old, with no gender restriction. There were no significant difference in the baseline characteristics of the subjects; (2) BFRT was the primary training regimen; (3) The study included a control group; (4) The outcome indicators of the study include hemodynamic evaluation indicators; (5) The study design consisted of randomized controlled trials and randomized crossover trials, and was not limited to acute or chronic studies.

Exclusion criteria

(1) The research subjects were not humans; (2) BFRT was not the primary training regimen, or it was used in combination with other training interventions; (3) Literature that was not in Chinese or English, duplicated literature, or literature for which the full text was unavailable were excluded; (4) Research results with missing data were excluded.

Study selection

Two authors (R.H. and Z.Y.) independently conducted all literature searches to determine if the studies met inclusion criteria. Duplicates were then removed, followed by screening of titles and abstracts. Any discrepancies were resolved by discussion and consultation with third author (Y.M). For eligibility criteria. Articles were excluded based on the analysis of outcome indicators, and only studies meeting the eligibility criteria were included in the systematic review.

Risk of bias and quality assessment

This systematic review used adapted verison of Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) to assess the risk of bias and quality of the studies that met the inclusion criteria [19, 20]. Each study was scored for the six aspects, with 1 point if it met the criteria and 0 points if it did not. The following are the specific questions: (1) Did the study describe the participant eligibility criteria? (2) Were the participants randomly selected? (3) Did the study provide information on the sources and details of the procedure used to measure the hemodynamics outcomes of BFRT and whether the instrument was reliable? (4) Did the study report the sources and details of assessment of potential benefits on hemodynamics and did all of the methods have acceptable reliability? (5) Did the study report a power calculation and was the study adequately powered to detect hypothesized relationships? (6) Is the study' s total number of participants account for at least 80% of the total sample? Studies that scored 0–2 were regarded as low quality studies, studies that scored 3–4 were classified as medium quality and those that scored 5–6 were classified as high quality (see supplement file).

Data extraction

The following data were extracted: subjects types and numbers, study design, types of training sessions, cuff location, cuff pressure, hemodynamics outcomes (e.g., Blood Pressure, Heart Rate, Blood Lactate, Cardiac Output, Stroke Volume, oxygen saturation, pulse wave velocity and other study-specific measured indicators). The data are presented in Table 1.

Results

The results of the search strategy and criteria are shown in Fig. 1. During the systematic literature search, 1372 articles were identified through online database searches. After removing duplicate articles, 343 articles remained. Based on the inclusion criteria, 219 articles were excluded again after reading the titles and abstracts. Subsequently, 80 articles were excluded based on the exclusion criteria. Finally, 44 articles were included in this review. These studies examined the effects of BFRT on both chronic and acute outcomes. For acute effects, the BFRT duration in different studies ranged from 3 min to 25 min [49, 22]. For chronic effects, the BFRT interventions varied between 2 weeks and 12 weeks, with a minimum of 2 training sessions and a maximum of 10 sessions per week, and a single BFRT duration ranging from 5 min to 30 min [16, 32]. Most studies used BFRT cuff sizes ranging from 5 to 7 cm [50, 21].

Table 1 Effects of BFRT on changes in blood pressure and heart rate

Author Year	*N*	Subjects	BFRT position	BFRT pressure	Training Session	Outcomes
Takano et al. [21]	11	Healthy adults	proximal end of thighs	130%SBP	20%1RM leg extension	SBP↑DBP↑MBP↑ HR↑
Karabulut et al. [22]	34	Healthy adults	proximal end of thighs	40mmHg or 60mmHg, then increase to 120mmHg	21 min cycling ergometer with load of 1kp	SBP↑ DBP↑ HR↑
Cohen et al. [16]	31	Healthy adults	N/A	220 ± 112mmHg	walk with crutch	SBP↓DBP↓MAP↓
Suga et al. [23]	16	Healthy adults	proximal end of thighs	200mmHg	30、15、15、15 reps' 20%1RM knee extension	MAP↑ HR↑↑
Kojima et al. [17]	17	Healthy adults	proximal end of thighs	140mmHg	Repeated sprints, 40s rest	HR↑↑
Silva et al. [14]	22	Healthy adults	proximal end of thighs	50AOP%	18 minutes' 40% VO_2max running	HR↓
Sieland et al., [24]	18	Healthy adults	proximal end of thighs	300mmHg	walk session with 5.0Km/h, 7.5% slope	HR↑
Yamada et al. [25]	14	Healthy adults	proximal end of thighs	N/A	15 minutes' walk with 5.6Km/h	HR↑
Winchester et al. [26]	15	Healthy adults	proximal end of thighs	Traditional BFR equipment: 50%LOP; BFR band: 150% length, 150%width	3 sets with 20 reps maximum knee extension	HR↑
Zheng et al. [27]	17	Healthy adults	proximal end of arms	80%LOP	4 sets of 15 reps of 20%1RM Biceps Curl	SBP→DBP→ HR↑
Jacob et al. [28]	56	Healthy adults	proximal end of thighs	60%LOP	4 sets of 20%1RM leg extension until exhaustion	SBP→DBP→MAP→ HR↑
Shi [29]	20	Healthy adults	proximal end of thighs	130%SBP	single-leg standing for 10 min	right leg: HR↓ left leg: SBP→DBP→
Liu [30]	31	healthy adults	proximal end of thighs and arms	LBFRT:60mmHgfor arms,160mmHg for thighs; MBFRT:90mmHg for arms,220mmHg for thighs	arms: 30、15、15、15 reps' 35%1RM arm extension thighs: 30、15、15、15reps' 35%1RM deep squat	SBP↓ MAP↓
Vieira et al. [31]	27	15 healthy adults、12 elderly people	proximal end of arms	120mmHg	30%1RM biceps curl for 3 min	SBP↑DBP↑ MBP↑HR↑
Kim et al. [32]	27	8 healthy adults 19 elderly people	proximal end of arms	130%SBP	3 sets 20%MVC grip, with 1 min rest	MAP→
Ferreira et al. [33]	21	elderly people	proximal end of thighs	63.9 ± 5.5mmHg	40%VO2max walk for 20 min	SBP↓DBP→MBP→
Patterson et al. [34]	10	elderly people	proximal end of thighs	110mmHg	25%1RM ankle plantar flexion, 20%1RM ankle dorisflexion	SBP→ DBP→
Sardeli et al. [18]	24	elderly people	proximal end of thighs	50AOP%	30、15、15、15 reps' 30%1RM leg press	SBP→DBP→MBP→HR↑
Barili et al. [35]	16	the elderly at 60–75 years old	proximal end of thighs	130%SBP	walking on treadmill	SBP→DBP→HR↑
Amorim et al. [36]	17	elderly people aged 65 and above	proximal end of thighs	150-260mmHg	15reps of 3 sets' leg lifting and extension, with 20s rest.	DBP→HR↑
Zhao et al. [37]	45	the elderly at 55–70 years old	proximal end of thighs	30%SBP	12 weeks, 3 sessions every week, 5 sets every session, with 30%1RM leg extension for 20 reps	SBP↓DBP→HR→
Curty et al. [38]	9	physically active adults	proximal end of arms	Dominant side: 120 ± 8mmHg Non-dominant side:121 ± 9mmHg	3 sets 10 reps' 30%1RM arm extension	SBP→MBP→HR↑↑

Table 1 (continued)

Author Year	N	Subjects	BFRT position	BFRT pressure	Training Session	Outcomes
Tai et al. [39]	23	physically active adults	proximal end of thighs and arms	40%AOP	30、15、15、15 reps' 30%1RM pull down、bench press、leg extension	lower body BFR: SBP↑↑HR↑ upper body BFR: DBP↑HR↑
Esen et al. [40]	14	physically active adults	proximal end of thighs	220mmHg	8 min knee isometric contraction	SBP↓MAP↓DBP→
Walden et al. [41]	16	physically active adults	proximal end of thighs	60%AOP	10 min 6Km/h walk, 10 min 7.2Km/h walk, 10 min 9 km/h jogging	SBP↑ HR↑↑
Beak et al. [42]	29	physically active adults	proximal end of thighs	160-240mmHg	5 sets 2 min jogging, 1 min rest	SBP→ DBP→
Neto et al. [43]	24	physically active adults	proximal end of thighs and arms	arm: 93.75 ± 12.09mmHg thigh: 108.75 ± 11.53mmHg	20%1RM biceps curl and triceps extension, leg extension and flexion	HR↑
Sun et al. [44]	40	physically active adults	proximal end of thighs	200mmHg	15 min 8.4 km/ h running on treadmill	HR↑↑
Wei et al. [45]	21	physically active adults	proximal end of thighs	40%, 50%, 60%, 70% and 80% AOP	5 min cycling ergometer with 70-80RPM	HR↑
Christiansen et al. [46]	8	physically active adults	proximal end of thighs	175mmHg	9 sets 2 min 105%lactate threshold running	HR↑↑
Moreno et al. [47]	40	physically active adults	proximal end of arms	80%AOP	30%1RM biceps curl until exhaustion	SBP↑DBP↑
Grey et al. [48]	30	physically active adults	proximal end of thighs	40%AOP and 60%AOP	30、15、15、15 reps 30%1RM leg extension	MAP↑

Note: AOP, arterial occlusive pressure; SBP, systolic blood pressure; DBP, diastolic blood pressure, MAP, mean artery pressure, MBP, mean blood pressure, LOP, limb occlusive pressure, Kp, kilopound, MVC, maximum voluntary contraction, RPM, revolutions per minute, ↓, decrease, ↑, increase, →, unchanged, ↑↑ significant increase

Basic vital signs indicators

Basic vital signs include blood pressure and pulse, both of which are essential for maintaining normal bodily functions. Since pulse and HR are consistent in healthy individuals, HR is also considered a fundamental vital sign. The results of the effect of BFRT on blood pressure and heart rate are shown in Table 1.

Blood pressure

Nineteen studies investigated the effects of BFRT on blood pressure. Five studies found that BFRT led to lower blood pressure. Current research shows that after 2 to 4 weeks or up to 12 weeks of BFRT, when combined with 35% 1RM lower limb resistance training, systolic blood pressure (SBP), diastolic blood pressure (DBP), and mean arterial pressure (MAP) in healthy adults or elderly individuals were significantly reduced [16, 30, 37] The low-intensity BFRT group showed a greater reduction in SBP compared to the moderate-intensity BFRT group, although the latter may require a longer duration to observe similar effects [30]. And after conducting a single session of upper body BFRT combined with 30% 1RM whole-body resistance training on physically active subjects, it found a significant reduce in aortic DBP [39]. When the elderly subjects completed BFRT with 40% VO2max walking, SBP was significantly reduced compared to pre-exercise levels [33]. Six studie reported that after a single session of BFRT combined with 20-30% 1RM knee extension or biceps curl training, or cycling exercise, the healthy subjects or physcially active subjects generally experience increases in SBP, DBP, mean blood pressure (MBP), or MAP within 30 min of blood pressure measurement [22, 39, 31–35]. However, eight studies report findings that contradict these results. For example, Studies showed that after healthy adults completed 20%1RM knee extension or biceps curl training with a BFRT, the acute response of SBP, DBP, MAP or MBP was not significant [27–29]. Elderly participants performed 20%1RM lower limb resistance training or 40%VO2max walk exercise with BFRT, there was no significant change in DBP or MBP in the BFR group after a single intervention [33, 36]. Some studies indicated that Long-term BFRT has no significant effect on blood pressure in physcially active individuals or elderly adults [32, 42, 34], whether their training regimen is jogging or 20–25% 1RM biceps curl or ankle dorsiflexion resistance training.

Heart rate

Sixteen studies investigated the effects of BFRT on blood pressure. Studies conducted a single low-intensity BFRT combined with 20% 1RM knee extension or biceps curl training, or aerobic training, such as walking and jogging on healthy adults and found a significant increase in heart rate in the BFR group after training [17, 21, 31, 23, 27, 28, 26]. For physically active adults, heart rate

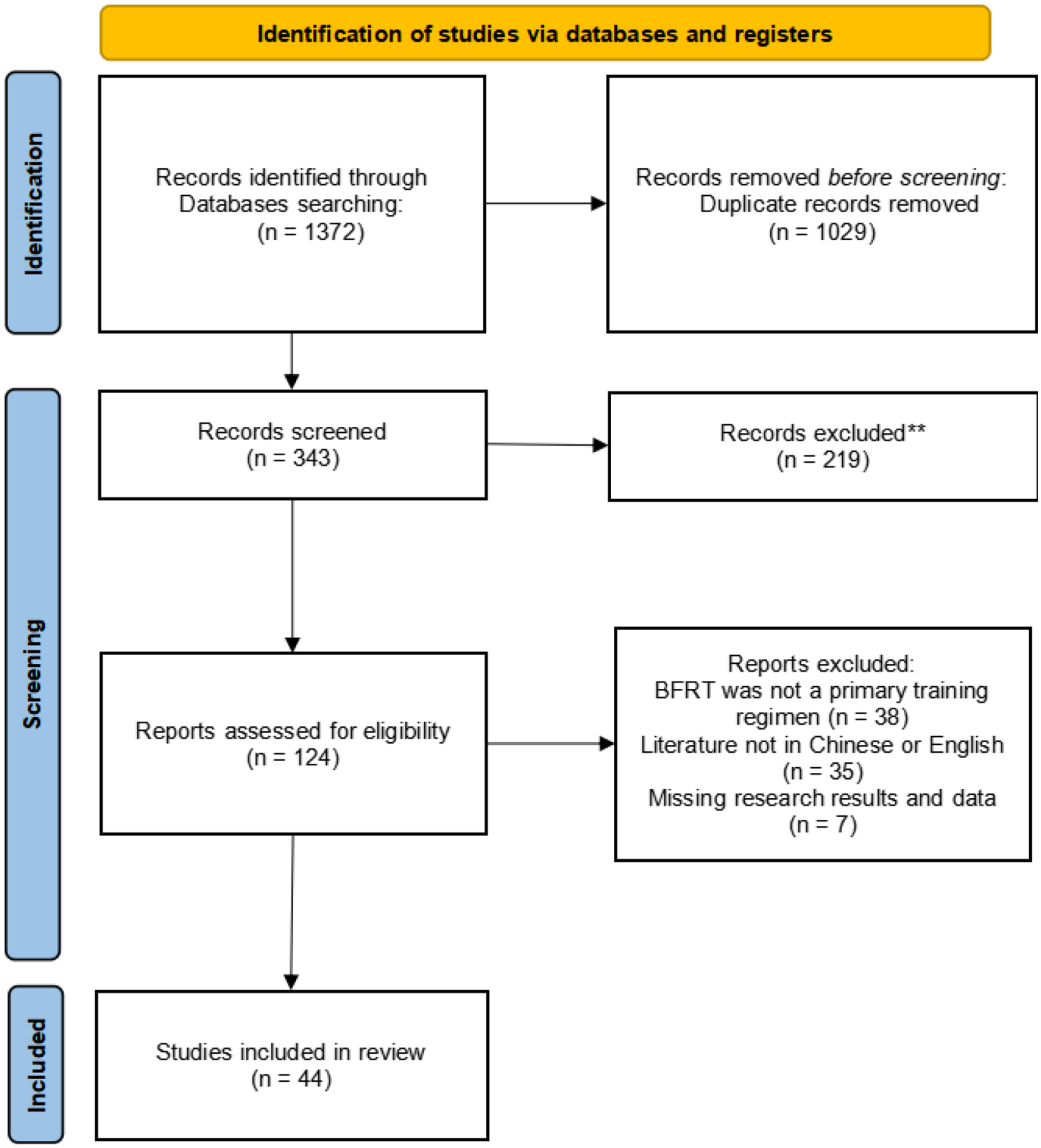

Fig. 1 PRISMA flow chart of the study selection process

changes are more pronounced with higher indensity lower limb resistance training or cycling [38, 43, 45, 46]. When applying BFRT, safety is a primary concern particularly for the elderly. Several studies have investigated the short-term effects of BFRT combined with low-intensity upper limb resistance training [31], only lower limb resistance training, and aerobic exercise on heart rate in elderly individuals [18, 36, 35]. These studies have shown that different low-intensity exercise training programs, along with the size and location of compression, can significantly increase the heart rate of elderly participants, though it remains within a safe range. Zhao et al. Further investigated the effect of long-term BFRT combined with low-intensity resistance training on heart rate in elderly individuals. Their results showed that heart rate recovery in the BFR group was significantly faster [37].

Tissue perfusion and oxygenation indicators

According to the theory of oxygen delivery and metabolism, the clinical significance of BLa primarily lies in its association with increased anaerobic metabolism in tissues. By combining BLa levels with blood oxygen saturation indicators, tissue perfusion can be effectively assessed. This approach allows for the analysis of human hemodynamics, helping to determine whether they are within the normal range of physiological function.

Blood lactate

Eight studies investigated the effects of BFRT on BLa. Several studies found that a single session of BFRT combined with 20% 1RM knee extension training or walking in healthy adults increased BLa levels in the BFRT group [23, 24, 51]. However, Kojima et al.'s study showed different results, with both BFRT group and control group showing significant increases in BLa concentration after completing 5 sets of full sprint runs, but no significant difference between the groups [17]. Among physically active adults undergoing BFRT, the BLa levels in the BFR group were higher than in the control group but lower than in the high-intensity group, across different pressure levels. However, the inter group differences between different pressure levels were not significant [45]. However, Kilgas et al.'s study reported different findings, with varying compression schemes leading to an increase in BLa levels, and higher compression amount resulting in higher the BLa concentrations [52]. For long term BFRT studies, Teixeira et al. selected physically active adults for a study in which they underwent a 8-week BFRT session combined with 70% 1RM lower limb resistance training [53]. BLa concentration was quantified using earlobe blood samples, and the results showed that all groups exhibited a significant increase in BLa levels compared to baseline values after completing the training program. Cintineo et al. observed similar results in a 6-week study of BFRT combined with resistance training for soldiers [54]. However, the intermittent BFRT group showed a more substantial increase in BLa concentration compared to the continuous BFR group. Throughout the study, the RMS-EMG (Root Mean Square Electromyography) values of muscle activation were approximately equal, suggesting that while different compression methods may have varying effects on BLa levels, they do not significantly influence the effectiveness of BFRT.

Oxygenation indicators

Seven studies investigated the effects of BFRT on Oxygenation indicators. Salzmann et al. conducted a study on healthy individuals using an ergometer bicycle at a power output of 60 W. The results showed that two different pressure levels (40% and 50% AOP) significantly reduced the TSI of the subjects, although the difference between the two groups was not significant [55]. Additionally, during full sprint running and rest periods, the StO2 of the BFRT group was 20% lower than that of the control group, while the average output power remained unaffected [17]. BFRT also affects blood oxygen levels in physically active adults. Neto et al.'s research shows that low-intensity resistance training reduces the blood oxygen saturation of subjects with training experience, with this decrease being more pronounced when combined with BFRT [43]. The combination of moderate-intensity aerobic training and BFR has a similar effect on TSI as high-intensity training, independent of changes in BFR pressure [45]. Sun et al. reported that 15 min of steady-state running combined with BFRT significantly reduced the SpO2 of athletes [44]. However, Bielitzki et al.'s research suggests that combining balance training with BFRT can reduce in SmO2 in subjects with training experience, with 80% AOP leads to a greater decrease in SmO2 than of 40% AOP[21]. Kilgas et al.'s research demonstrated that combining ergometer cycling training with different compression schemes led to a decrease in TSI, with the rate of decrease accelerating as compression intensity increases [52].

Flow volume indicators

Five studies investigated the effects of BFRT on SV and CO. Takano et al. conducted a study using 20% 1RM sitting leg flexion and extension training on 19 healthy adults. The study found that the CO of the BFR group increased significantly, while the SV decreased significantly [21]. Borges et al. reported that the use of BFR during moderate-intensity cycling in healthy adults resulted in an acute and transient decrease in CO kinetics, which means a slower growth rate of increase in CO during exercise [56]. Walden et al. conducted a 10-minute jog training session on physically active adults and found that, during the BFR combined with aerobic training, CO was higher in the BFR group compared to the control group [41]. Additionally, moderate-intensity BFRT resulted in a greater CO compared to low-intensity BFRT. The impact of BFRT on cardiovascular indicators in elderly individuals has also attracted research interest. Sardeli et al. found that after resistance training, CO in elderly individuals was higher than in the control group but lower than in the high-intensity training group, while SV did not show significant changes [18]. However, Ferreira et al. reported that walking training with 40% VO2max combined with BFRT resulted in a significant decrease in SV in both the BFR group and the control group, and CO did not show significant changes [33].

Pulse wave velocity

Six studies investigated the effects of BFRT on PWV. After healthy adults conducted jogging training with an intensity at 40% VO2max intensity and physically active adults completed upper limb resistance training, studies found that BFRT improved PWV from femur to posterior tibia [16, 39, 57, 58]. However, there are discrepancies in some studies. Beak et al.'s study showed that 8-week BFRT combined with aerobic training had no significant effect on arm-ankle PWV in physically active adults [42].

Similarly, after completing 20% 1RM lower limb resistance training with a single session BFRT, no significant change in PWV was observed in the BFR group using smart devices [36, 59].

Other indicators

Four Studies investigated the effects of BFRT on shear rates (SR), oscillatory shear index (OSI), shear forces, TPR, plasma volume and blood flow velocity. Cohen et al. found that there was no change in in femoral artery flow, suggesting that vascular conduction remained unaffected; The average, anterograde, and retrograde shear rates were also not affected by experimental conditions. The oscillatory shear index, which describes the effect of anterograde and retrograde shear forces, showed a non-significant reduction following fixation [16]. In analysis of the blood flow velocity curve, it was observed that after pressurization, the retrograde blood flow velocity decreases, while the anterograde blood flow velocity remained unchanged, which may contribute to maintaining stable baseline blood flow levels. Winchester et al. have shown that pressurization caused a significant decrease in tibial artery flow, while the average flow velocity remained relatively unchanged [26]. Thompson et al. investigated the effects of different training regimens for 4 and 6 weeks combined with BFR on plasma volume. The results showed that plasma volume remained unchanged across the various training regimens [60]. Additionally, several studies have also examined the effect of BFR on TPR. These results revealed that vascular TPR was not significantly affected by BFRT in either the elderly or healthy populations [21, 33].

Discussion

The effects of BFRT on hemodynamics, both short-term and long-term, are influenced by the specific training regimen and the target population. Under consistent training programs and populations, changes in blood pressure indicators generally align with the typical effects of exercise on blood pressure. BFRT can induce heart rate alterations within a safe range, making it a useful indicator for assessing exercise intensity. Additionally, BFRT leads to an increase in BLa levels, but when combined with an appropriate pressure regimen and low-intensity training, it does not cause metabolic disturbances. While BFRT can reduce oxygenation index levels, higher pressures and longer training durations result in more pronounced decreases. The effects of BFRT on CO and SV vary across populations, but these changes remain within safe limits and do not negatively affect cardiac pumping function. When the intervention period is insufficient, BFRT does not significantly influence PWV. Overall, BFRT appears to modulate blood vessel function and structure without causing adverse cardiovascular reactions. BFRT affects the human body primarily by restricting arterial and venous blood flow, inducing a state of relative hypoxia and ischemia in the upper or lower limbs [61]. During exercise, blood plays important roles in oxygen transport, nutrient supply, and hormone transmission [62]. BFRT applies mechanical stimulation to blood vessels, causing traction on the inner walls of blood vessels and altering partial pressure, which subsequently affects endothelial cell function. To maintain normal blood function, the body initiates a series of physiological regulatory measures, during which hemodynamic parameters also change. Therefore, various researches have discussed the mechanisms by which BFR influences hemodynamics from different perspectives, involving neural regulation, fluid regulation, and the interactions between hemodynamic parameters.

The regulation of the human cardiovascular system primarily occurs through the activities of the sympathetic and vagus nerves. Research suggests that changes in blood pressure caused by BFRT may be related to neuromodulation. In this context, low-frequency power (LF) serves as an indicator of sympathetic nerve regulation, while high-frequency power (HF) represents vagal nerve regulation [37]. Studies have shown that BFRT significantly increases both LF and HF, indicating heightened excitability of sympathetic and parasympathetic nerves [63]. During BFRT, sympathetic nerve activity decreases while parasympathetic nerve activity increases, which may lead to a reduction in blood pressure [30]. Nitric oxide (NO) is a potent vasodilator known to mobilize large volumes of blood [64, 65]. One study has shown that supplementing foods containing nitrates, which can be converted into NO during BFRT, also increases the bioavailability of NO and lowers blood pressure [40]. In addition, vascular endothelial growth factor (VEGF) plays a crucial role in inducing angiogenesis and increasing vascular permeability [30]. During BFRT, the compression of blood vessels reduces blood flow. Once the restriction is released, the previously compressed vessels undergo congestion, leading to increased shear stress on the blood vessels and endothelial cells. This heightened shear stress promotes the expression of VEGF, its receptors, and endothelial nitric oxide synthase (eNOS) [66–68]. Studies have shown that the increased eNOS and VEGF facilitate the generation of new capillaries, which enhances blood circulation. The density of capillaries is a key indicator of effective blood flow, and these processes improve cardiac function, reduce cardiac load, and contribute to a decrease in blood pressure [69, 70].

However, other studies have reported opposite results. The increase in blood pressure may result from heightened cardiac contractility due to sympathetic nerve stimulation or from sympathetic nerve-induced vasoconstriction of vascular smooth muscle, raising blood pressure in the vessels [22], However, during the increase in blood pressure caused by BFRT, vagal nerve recovery is not delayed. Regardless of whether higher pressure and muscle contraction stimulation occurred during exercise, it takes approximately 30 min for these factors to significantly affect the autonomic recovery of the cardiac vagus nerve [18]. Studies have also shown that the hemodynamic changes caused by BFRT are related to an increase in catecholamines [71]. As neurotransmitters of the sympathetic nervous system, catecholamines can regulate heart rate and blood pressure by activating sympathetic pathways [72]. Catecholamines can also stimulate the release of adrenaline, thereby affecting the contraction of vascular smooth muscle, blood flow and blood pressure [73]. The cardiovascular response to BFRT may also involve the action of renin [74]. Renin can stimulate angiotensin II and antidiuretic hormone through the renin-aldosterone-blood regulation system, which helps regulate fluid balance and blood pressure [75].

Additionally, some studies have reported that blood pressure changes are not significant, which may be due to low-intensity BFRT failing to induce reactive hyperemia, resulting in minimal blood pressure alterations [27]. One study also observed that blood pressure changes in the lower limbs were less pronounced than in the upper limbs. This may be due to the fact that, under normal conditions, the blood pressure in the lower limbs is generally higher than than in the upper limbs, making the effect of BFRT on restricting venous outflow and arterial inflow in the lower limbs less noticeable [29]. Another explanation is the use of smart BFR devices, which monitored blood pressure in training and adjusted the applied pressure to help maintain a constant overall pressure on the human vascular system. BFRT leads to an increase in heart rate, with neuromodulation being one of the primary factors responsible for these changes. During BFRT application, a hypoxic environment is created [14], leading to an increase in heart rate to ensure oxygen delivery to the working muscles. This process primarily driven by increased sympathetic nervous system activity and elevated pressure, which together reduce venous return by restricting blood flow [22]. Increased training intensity also significantly elevates heart rate due to the higher demands placed on cardiovascular capacity and muscle endurance. Repeated low-resistance exercises may increase the demands on muscle endurance and cardiovascular capacity, thereby raising heart rate [43]. Heart rate recovery following the post-exercise period is more pronounced in regimens incorporating BFRT in some studies, likely due to enhanced parasympathetic reactivation during BFRT [33].Similar results were found in the BFRT group of elderly individuals, suggesting that long-term BFRT combined with low-intensity resistance training can enhance cardiovascular adaptability and potentially reduce cardiovascular risk [37]. Indicating that using smart devices can improve the safety of BFRT compared to using elastic bands.

Our results showed that BFRT induced an increase in BLa concentration, although this increase was not significantly different from that observed in the control group. Elevated BLa concentration were observed in BFRT group after subjects completed sprints, which could be attributed to the high intensity of the exercise, demanding more energy and leading to increased glycolysis and a gradual rise in BLa concentration [17]. Other studies suggest that BLa concentrations are influenced by the specific training protocols used, but these increases do not negatively affect healthy adults or increase the risk of metabolic disorders [23, 24, 51].

BFRT can cause a decrease with blood oxygen saturation. This effect can be attributed to high-intensity exercise, which may lead to an imbalance between oxygen delivery and utilization, prompting a shift toward anaerobic metabolism to compensate for the oxygen deficit. But varying levels of pressure do not affect the reduction of TSI [55]. One study had similar findings, indicating that moderate-intensity resistance training with BFR can induce local hypoxia similar to that experienced during high-intensity training. Thus, for individuals unable to perform high-intensity exercise, using BFRT with moderate-intensity workouts may serve as an effective alternative. However, this study estimated AOP based on thigh circumference, which could contribute to variations in TSI measurements. Specifically, differences in fat thickness at the same thigh circumference may influence the near-infrared spectroscopy (NIRS) signal [76]. Another study indicate that appropriate amount of BFRT pressure can induce local hypoxia in working muscles, and moderate hypoxic stimulation can promote muscle adaptation to low-oxygen environments and enhance aerobic metabolism. However, excessive hypoxia from BFRT can decrease hemoglobin and red blood cell counts, leading to anemia and impairing the body's ability to move [77]. Therefore, when applying BFRT, it is necessary to carefully control the amount of pressure and the duration of BFRT during aerobic training to prevent excessively low blood oxygen saturation. In addition, BFRT leads to an increase in hypoxia, ischemia, and acid accumulation, which are closely related to the increase in vascular resistance caused by BFRT during exercise [78]. The conditions of hypoxia, ischemia-reperfusion, and acid accumulation can induce heat shock proteins that protect myocardial cells from ischemia-reperfusion injury [79].

Some studies found that BFRT had no significant effect on PWV. This may be attributed to the long exercise history of the subjects prior to the study, which may have limited the ability of the blood vessels to respond significantly [42]. One study suggested that this may be related to the selection of PWV measurement position, as the the placement of BFR device was placed near the thigh and the measurement site was located at the femoral artery might have influenced the results [59]. This lack of change can also be attributed to the short duration of the exercise, which may be insufficient to induce long-term vascular adaptation [80]. When the intervention duration is too short, BFRT does not significantly impact PWV, nor does it affect the PWV of physically fit individuals. However, the increased vascular wall shear stress caused by BFRT may promote the release of NO, resulting in vasodilation in the lower limbs and an improvement in PWV along the lower limb, from the femur to the posterior tibia [57].

There is limited research of the effects of BFRT on blood flow, blood flow velocity, TPR and other related indicators. There is still variability in the interpretation of the results and mechanisms of BFRT on these indicators. The decrease of the arterial cross-sectional area may be due to the use of elastic band as BFR equipment, which covers a relatively large area on the thigh, leading to the compression of more blood vessels [26]. Therefore, both the amount of compression and its position need to be carefully considered when designing a BFRT program to avoid adverse effects on the cardiovascular system. Sympathetic vasoconstrictor nerves and decompression reflexes primarily regulate changes in TPR. A reduction in sympathetic vasoconstrictor tone can lead to arteriolar dilation and a decrease in TPR [18]. Vagus nerve regulation can also reduce in TPR, promote angiogenesis, or induce volume expansion, thereby improving endothelial function [81]. However, some studies suggest that TPR does not change after BFRT application. This may be because the decompression reflex regulates the cardiac sympathetic center and the sympathetic vasoconstrictor center, preventing excessive cardiac activity and maintaining stable TPR [21]. Plasma volume remained unchanged across the various training regimens, this outcome may be affected by the test duration, as factors such as sweating and body fluid shifts during exercise can lead to a loss of plasma volume [60].

Another explanation for the mechanism of BFRT involves the interaction between hemodynamic parameters. Reduced oxygen delivery to exercising muscles can lead to increased muscle acidosis, which has been shown to be closely associated with an increase in calf vascular resistance during exercise [14]. Regarding the relationship between blood pressure and TPR, Queiroz et al. suggested that the reduction in blood pressure may be explained by a reduction in TPR, this is because BFRT triggers a mechanical reflex that stimulates the synthesis of NO synthase, promoting vasodilation and reducing TPR [82]. Additionally, blood pressure changes resulting from BFRT may also be influenced by the combined effects of CO, SV, and HR, as well as by metabolite accumulation and vascular compression [83]. The reduction in post-exercise hypertension caused by BFRT can be attributed to the reduction in SV and HR, which can also contribute to a reduction in CO [84, 85]. Variation in HR are often associated with changes in CO and SV. This may be due to the impaired blood return to the heart after BFRT, resulting in a smaller SV compared to conditions without BFR. As exercise progresses, HR will continue to increase, and the combined effect of this and a reduced SV slows the increase in stroke volume [56]. If HR increases too rapidly, the diastolic phase is shortened, leading to insufficient filling time for the ventricles. This results in decreased filling volume and SV, ultimately reducing CO [77]. Additionally, sympathetic nerve excitation can reduce ventricular volume at the end of systole. When coupled with increased cardiac contractility, this significantly elevates SV, supplying more oxygen-rich blood during the diastolic phase [77]. However, after BFRT is applied, blood flow return to the heart becomes impaired, resulting in a smaller SV in the BFR group compared to the group without BFR.

Limitations

While this study aimed to provide a comprehensive overview of the hemodynamic impact of BFRT by examining a wide range of parameters, the broad scope may have limited the depth of discussion for individual parameters. Since the selected studies were highly heterogeneous, the BFRT training regimens, measurement methods, and subject characteristics varied greatly among the studies. Although meta-analysis can provide more quantitative evidence, this study is unable to use it as it may increase the risk of statistical error. In future studies, meta-analysis could be performed on a certain type of subjects (e.g. elderly people or type 2 diabetics and people with an ABI index below 7.5) hemodynamic parameters (e.g. post-occlusive reactions hyperemia), or training regimens (e.g. BFRT at 100% AOP) to explore their mechanisms and practical implications in greater detail.

Conclusion and prospect

The evaluation of hemodynamic indicators is essential for monitoring the physiological status of the human body and preventing cardiovascular diseases. These indicators serve as effective measures for assessing the efficacy of BFRT. Research has demonstrated that BFRT can lead to changes in heart rate and blood pressure within a safe range, although the specific trends are influenced by the training program and the characteristics of the subjects. BFRT combined with various training programs can increase in BLa concentration without causing metabolic disorders. Additionally, it may decrease oxygen levels in muscles, resulting in a degree of partial hypoxia while enhancing aerobic metabolic capacity. While low-intensity exercise combined with BFRT produces varying effects on CO and SV, the magnitude of these changes is generally less than those observed with high-intensity exercise. Exercises of sufficient intensity, when paired with BFRT, can improve PWV in untrained individuals, affecting other metrics such as vascular area, blood flow, and OSI to some extent. BFRT causes changes in arterial structure and function indicators, and the indicators influencing each other to produce either positive or negative effects on cardiovascular health. BFR mainly affects the hemodynamic indexes of the human body by restricting the blood flow in arteries and veins. Its mechanisms involve the activation of the sympathetic nerves and vagus nerves, and the regulation of cardiovascular activity by chemical substances in body fluids (NO, VEGF, etc.). These mechanisms collectively make BFRT a promising exercise intervention for improving cardiovascular function through hemodynamic regulation.

Given the current state of research, the following prospects are proposed: (1) Most studies on BFRT and hemodynamics focus on healthy adults, physically active individuals, and the elderly. There is a notable lack of research on specific populations, such as patients with cardiovascular conditions or professional athletes. To better understand whether BFRT has adverse effects on the cardiovascular system, empirical research should encompass a broader range of participants. (2) In the selection of training programs for BFRT and hemodynamic studies, although the research programs vary, they mainly focus on several aerobic exercises, such as cycling, repeated sprint running, walking, etc. It is still necessary to systematically explore the effects of other types of aerobic exercise and resistance training combined with BFRT on hemodynamic indicators. (3) Most studies focus on measuring hemodynamic indicators during exercise, immediately after exercise, or within 30 min after exercise. Consequently, the focus is predominantly on the short-term effects of BFRT on these indicators. The long-term effects of BFRT on hemodynamics warrant further investigation.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s13102-025-01084-8.

Supplementary Material 1

Supplementary Material 2

Acknowledgements

Thanks to all authors for their contributions.

Author contributions

RH—original draft preparation, visualization. YM: supervision, funding acquisition project administration. RH and YM: Conceptualization, methodology, writing, review and editing. ZY, ZW, CC, YQ and MJ: investigation. All authors reviewed the manuscript and agreed to the published version of the manuscript.

Funding

This study was supported by the Science and Technology Team Foundation of Wuhan Sports University under Grant [21KT02] (funded by Wuhan Sports University), the East Lake Scholars Sponsorship Program of WHSU (funded by Wuhan Sports University), and the 14th Five-Year-Plan Advantageous and Characteristic Disciplines (Groups) of Colleges and Universities in Hubei Province under Grant [2021.05] (funded by Department of Education of Hubei Province).

Data availability

All data generated or analyzed during this study are included in this published article.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

Received: 10 December 2024 / Accepted: 17 February 2025
Published online: 12 March 2025

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