Effects of aerobic exercise with blood flow restriction on aerobic capacity and hemoglobin in male university athletes

Efectos del ejercicio aeróbico con restricción del flujo sanguíneo sobre la capacidad aeróbica y la concentración de hemoglobina en atletas universitarios masculinos

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Abstract

Introduction: Aerobic exercise remains a primary strategy for improving cardiorespiratory function. Recently, aerobic exercise combined with blood flow restriction has emerged as a low-load training approach with potential benefits for enhancing aerobic capacity and hemoglobinmediated oxygen transport in male university athletes.
Objective: To investigate and compare the effects of aerobic exercise combined with blood flow restriction on aerobic capacity and hemoglobin concentration in male university athletes.
Methods: Twenty-four male team-sport athletes (mean age: 20.33 ± 1.09 years) were randomly assigned to an aerobic exercise group (AE; n = 12) or an aerobic exercise with blood flow restriction group (AE+BFR; n = 12). Both groups performed stationary cycling three times per week for six weeks under controlled laboratory conditions. The AE+BFR group trained with pneumatic cuffs applied to the proximal thighs at 60% of arterial occlusion pressure. Maximal oxygen consumption (VO_2max) and hemoglobin concentration were assessed before and after the intervention.
Results: After the intervention, both groups demonstrated improvements in aerobic capacity and hemoglobin concentration. However, the AE+BFR group exhibited significantly greater increases in VO_2max compared with the AE group ($p = 0.005$). Hemoglobin concentration tended to increase to a greater extent in the AE+BFR group than in the AE group, although the between-group difference was not statistically significant.
Conclusion: Aerobic exercise combined with blood flow restriction is an effective and time- efficient training modality for enhancing aerobic capacity and may provide additional benefits for hemoglobin-related oxygen transport in male university athletes.

Keywords

Aerobic exercise; blood flow restriction; hemoglobin; maximum oxygen consumption; university athletes.

Resumen

Introducción: El ejercicio aeróbico es una estrategia clave para mejorar la función cardiorrespiratoria, y su combinación con la restricción del flujo sanguíneo representa un enfoque de baja carga con potencial para mejorar la capacidad aeróbica y el transporte de oxígeno mediado por la hemoglobina en atletas universitarios masculinos.
Objetivo: Investigar y comparar los efectos del ejercicio aeróbico combinado con la restricción del flujo sanguíneo sobre la capacidad aeróbica y la concentración de hemoglobina en atletas universitarios masculinos.
Metodología: Veinticuatro atletas universitarios masculinos de deportes de equipo (edad media: 20,33 ± 1,09 años) fueron asignados aleatoriamente a un grupo de ejercicio aeróbico (AE; n = 12) o a un grupo de ejercicio aeróbico con restricción del flujo sanguíneo (AE+BFR; n = 12). Ambos grupos realizaron ciclismo estacionario tres veces por semana durante seis semanas en condiciones controladas. El grupo AE+BFR entrenó con manguitos neumáticos en la región proximal de los muslos al 60 % de la presión de oclusión arterial. El consumo máximo de oxígeno (VO_2max) y la concentración de hemoglobina se evaluaron antes y después de la intervención.
Resultados: Tras la intervención, ambos grupos mejoraron la capacidad aeróbica y la concentración de hemoglobina; sin embargo, el grupo AE+BFR mostró incrementos significativamente mayores en el VO_2max ($p = 0{,}005$), mientras que el aumento de la hemoglobina no difirió significativamente entre grupos.
Conclusiones: El ejercicio aeróbico con restricción del flujo sanguíneo es una estrategia eficaz y eficiente para mejorar la capacidad aeróbica y el transporte de oxígeno mediado por la hemoglobina en atletas universitarios masculinos.

Palabras clave

Ejercicio aeróbico; restricción del flujo sanguíneo; hemoglobina; consumo máximo de oxígeno; atletas universitarios.

Introduction

In the modern era of sports science, the enhancement of aerobic fitness has become a central focus of athletic training, particularly among university students, who represent a crucial developmental stage for improving both physical performance and cardiorespiratory capacity. Aerobic exercise (AE) is widely recognized as a fundamental and effective approach for optimizing cardiovascular efficiency, oxygen transport capacity, and metabolic adaptations within the body (Silva et al., 2021). However, moderate- to high-intensity aerobic training can impose excessive musculoskeletal and cardiovascular strain, especially during pre-competition or rehabilitation phases (Rolnick & Schoenfeld, 2020). Consequently, sports scientists have increasingly explored alternative modalities capable of eliciting comparable physiological adaptations at lower intensities, thereby improving safety, reducing mechanical stress, and enhancing training efficiency. One scientifically validated method attracting growing attention is blood flow restriction (BFR) training, which involves the partial restriction of venous return from working muscles by applying pneumatic cuffs or elastic bands around the proximal limbs to induce localized hypoxia during exercise (Fitschen et al., 2014; Silva et al., 2021). This transient hypoxic stimulus promotes several physiological adaptations, including elevated secretion of growth hormone (GH) and insulin-like growth factor-1 (IGF-1), augmented muscle protein synthesis, and angiogenesis-mechanisms that collectively enhance oxygen delivery and utilization at the cellular level (Smith et al., 2022; Yinghao et al., 2021). Based on these mechanisms, aerobic exercise combined with blood flow restriction has been shown to improve aerobic performance even at low intensities (~40% VO_2max), producing greater increases in VO_2max than conventional AE performed at equivalent workloads. Consequently, AE+BFR is increasingly acknowledged as a safe, time-efficient, and physiologically effective training method capable of producing adaptations akin to those generated by high-intensity exercise (Abe et al., 2010; Formiga et al., 2020; Kuhn et al., 2024; Miller et al., 2021; Yang et al., 2022). Recent evidence indicates that metabolically stressful conditions induced by blood flow restriction or hypoxia can elicit meaningful neuromuscular and morphological adaptations despite low mechanical loading, underscoring hypoxic stress as a potent stimulus for physiological adaptation independent of high-intensity exercise (Buttichak et al., 2025). Blood flow restriction exercise induces localized hypoxia and metabolic stress comparable to that observed during systemic hypoxic training by partially restricting venous return, thereby reducing oxygen availability within active skeletal muscle, accelerating anaerobic metabolism, and activating hypoxia-sensitive signaling pathways. Evidence from low-load resistance training performed under hypoxia or venous occlusion further demonstrates that improvements in muscle performance may occur independently of sustained elevations in resting growth hormone levels, suggesting that chronic adaptations are predominantly mediated by metabolic stress and hypoxia-induced vascular remodeling rather than endocrine responses alone (La-bantao et al., 2025; Laurentino et al., 2022). Importantly, these physiological mechanisms are transferable to aerobic exercise, as aerobic training combined with BFR imposes a sustained ischemic-hypoxic stimulus that enhances peripheral oxygen extraction and hematological demand at reduced workloads, thereby providing a clear mechanistic rationale for investigating its effects on aerobic capacity and hemoglobin concentration in male university athletes.

A growing body of literature further supports the efficacy of AE+BFR in enhancing aerobic performance among young adults and university athletes. Paton et al. 2017 demonstrated that running with BFR at 80% of maximal speed led to a 6.3% greater improvement in VO_2max and a 27% longer time to exhaustion compared with conventional training. Similarly, Silva et al. 2021 reported that AE+BFR elicited significantly higher oxygen consumption and heart rate responses than standard AE, while perceived exertion remained comparable to that observed during high-intensity interval exercise (HIIE), despite requiring less training time and energy expenditure-underscoring its efficiency and practicality. Bennett & Slattery. 2019 observed VO_2max improvements of 6-10% within 6-8 weeks, particularly when cuff pressures were maintained between 50-70% of arterial occlusion pressure. More recently, a meta-analysis by Dong et al. 2025 involving 221 athletes confirmed that AE+BFR significantly improved VO_2max and lower-limb strength without adverse effects on cardiac function or anaerobic performance. Collectively, these findings reinforce AE+BFR as a safe and effective training modality for improving aerobic fitness in university-aged populations.

From a hematological perspective, AE+BFR has also demonstrated pronounced systemic adaptations. Smith et al. 2022 reported significant increases in hemoglobin mass, stroke volume, and red blood cell volume following AE+BFR, contributing to enhanced oxygen transport efficiency and potential applications in cardiac rehabilitation for individuals unable to tolerate high-intensity exercise. Likewise, Pignanelli et al. 2021 found superior improvements in oxygen-carrying capacity and capillary perfusion compared with conventional AE, reflecting its effectiveness in stimulating peripheral circulatory adaptations. In contrast, Kostrzewa-Nowak et al. 2015 noted that traditional AE improved VO_2max and reduced body fat percentage but did not significantly affect hemoglobin concentration. These findings suggest that integrating BFR into aerobic training programs can facilitate greater hematological and muscular adaptations, particularly among male university athletes aiming to optimize endurance performance and recovery.

Despite growing evidence supporting the effectiveness of aerobic exercise combined with blood flow restriction (AE+BFR) in enhancing aerobic performance and hematological adaptations, existing research has primarily focused on elite or international athlete populations. Consequently, empirical evidence examining comprehensive physiological and hematological responses to AE+BFR in university-aged male athletes—a critical developmental stage for optimizing athletic performance—remains limited. Therefore, the present study aimed to investigate the effects of aerobic exercise combined with blood flow restriction on aerobic performance, hemoglobin concentration, and maximal oxygen consumption in male university athletes. The findings are expected to inform the development of safe, efficient, and evidence-based training protocols to enhance aerobic capacity and performance in collegiate-level athletes.

Method

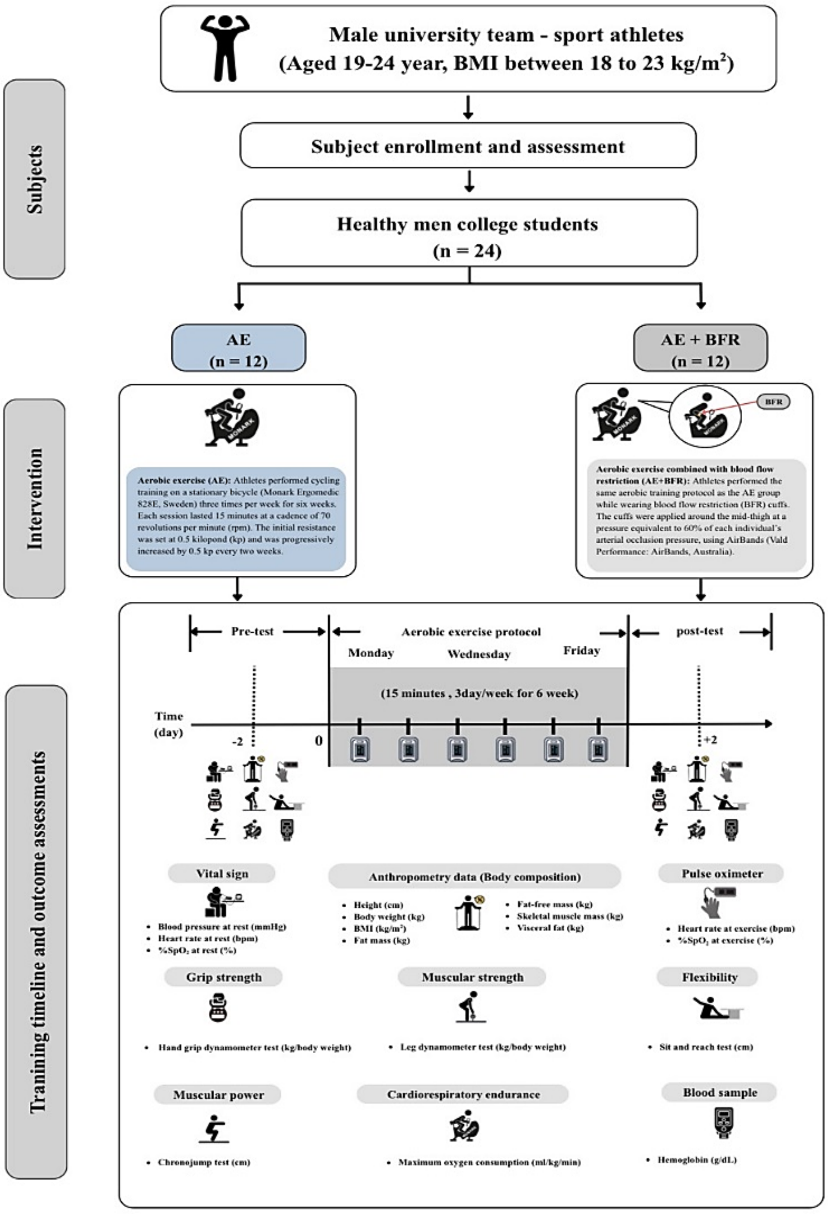
Participants

Twenty-four male university team-sport athletes from Ubon Ratchathani Rajabhat University (mean age: 20.33 ± 1.09 years; soccer = 8, futsal = 10, volleyball = 3, basketball = 3) volunteered for this study. The participants were selected to represent their sport at the University Games in Thailand and were consequently well-trained. All participants satisfied the inclusion criteria: they reported no exposure to altitudes exceeding 1,000 m in the preceding three months, no history of severe acute mountain sickness, no contraindicated health problems or drugs, and no aerobic exercise regimen in the past three months. The exclusion criteria encompassed individuals who missed over 20% of the program and those with health difficulties, including respiratory disorders, allergies, asthma, hypertension, or any other conditions that could impair participation, such as dizziness, lightheadedness, or chest pain during exercise. Informed consent was acquired from all participants after they were thoroughly briefed on the study's aims, protocols, and pertinent details. The research utilized an experimental design and received approval from the Sisaket Rajabhat University Human Ethics Committee (Ref. No. UE681025, Thailand), adhering to the standards of the Declaration of Helsinki.

Procedure

The required sample size was determined a priori using G*Power version 3.1 (Heinrich Heine University, Düsseldorf, Germany). The power analysis targeted a medium effect size ($f = 0.25$), as reported in a previous investigation on low-intensity aerobic exercise combined with blood flow restriction (Beak et al., 2022), with the statistical power ($1-\beta$) set at 0.80 and the significance level (α) established at 0.05. The analysis indicated that a total of 24 participants would provide sufficient power to detect significant main and interaction effects. Participants were recruited using a simple random sampling method and were subsequently randomly assigned to one of two experimental groups based on the prescribed occlusion pressure. The first group performed aerobic exercise (AE; n = 12), whereas the second group performed aerobic exercise combined with blood flow restriction (AE + BFR; 60% of arterial occlusion pressure; n = 12). All participants completed baseline and post-training evaluations conducted 2–3 days before and after the six-week training intervention (Figure 1).

Figure 1. Outline the training and testing schedule. Abbreviations: HR, heart rate; SpO_2, resting arterial oxygen saturation.



Aerobic exercise (AE): Athletes performed cycling training on a stationary bicycle (Monark Ergomedic 828E, Sweden) three times per week for six weeks. Each session lasted 15 minutes at a cadence of 70 revolutions per minute (rpm). The initial resistance was set at 0.5 kilopond (kp) and was progressively increased by 0.5 kp every two weeks.

Aerobic exercise combined with blood flow restriction (AE+BFR): Athletes performed the same aerobic training protocol as the AE group while wearing blood flow restriction (BFR) cuffs. The cuffs were applied around the mid-thigh at a pressure equivalent to 60% of each individual's arterial occlusion pressure, using AirBands (Vald Performance: AirBands, Australia).

Training program

All participants underwent an aerobic exercise intervention utilizing a stationary cycle ergometer (Monark Ergomedic 828E, Sweden) under controlled laboratory conditions. Participants in the aerobic exercise (AE) group cycled three times a week for six weeks in a row. Each session lasted 15 minutes and had a cadence of 70 revolutions per minute (rpm). The training intensity was initially set at 0.5 kilopond (kp) and was progressively increased by 0.5 kp every two weeks to promote gradual physiological adaptation. Participants in the aerobic exercise combined with blood flow restriction (AE+BFR) group completed an identical training protocol while wearing pneumatic blood flow restriction cuffs applied around the proximal thighs. Arterial occlusion pressure (AOP) was individually determined using an automated pneumatic system (AirBands, VALD Performance, Australia), and blood flow restriction was applied at 60% of each participant's measured AOP throughout the training sessions. Throughout the intervention period, physiological variables were closely monitored to ensure participant safety and training efficacy; oxygen saturation (SpO_2) was continuously assessed using a finger pulse oximeter (Beurer PO30, Germany), while heart rate was measured and recorded during each session with a heart rate sensor (Polar H10, Finland) to verify adherence to the prescribed exercise intensity. The six-week aerobic training program was validated by five experts in exercise physiology and sports science, yielding an index of item-objective congruence (IOC) value of 0.90, indicating a high level of content validity and methodological rigor.

Outcome measurements

Body composition measurement

Body composition, including body weight, body mass index (BMI), body fat mass, lean body mass, skeletal muscle mass, and visceral adipose tissue, was assessed using a multi-frequency bioelectrical impedance analyzer (Seca mBCA, Hamburg, Germany). Participants stood barefoot on the analyzer platform for approximately 10 minutes in an upright position to ensure optimal electrode contact and reliable readings.

Muscular strength measurement

Muscular strength was evaluated for both upper and lower limbs using standardized dynamometric assessments. Upper limb strength was measured using a handgrip dynamometer (Grip-D, Takei Physical Fitness Test; T.K.K. 5401, Japan), while lower limb strength was assessed with a back and leg dynamometer (Back-A, Takei Physical Fitness Test; T.K.K. 5002, Japan). Participants were instructed to perform maximal voluntary contractions following the manufacturer's testing procedures, with the highest value from two trials recorded for analysis.

Flexibility measurement

Flexibility of the hamstring and lower back muscles was assessed using the sit-and-reach test (Takei Physical Fitness Test; T.K.K. 5403, Japan). Participants were seated on the floor with legs fully extended, feet placed flat against the testing box, and hands positioned one over the other. They were instructed to slowly reach forward as far as possible without bending the knees and to hold the final position for approximately two seconds. The distance reached by the fingertips beyond the toes was measured in centimeters, and the highest value from two trials was recorded for analysis.

Muscular power measurement

Lower limb muscular power was evaluated using a contact platform system (Chronojump Contact Platform Kit, Barcelona, Spain), which determined jump height and power output from flight time during a vertical jump. Participants performed the countermovement jump (CMJ) after a standardized warm-up, standing barefoot on the platform with feet shoulder-width apart and hands on the hips to minimize arm swing. They executed two maximal jumps, and the highest value was used for analysis. All tests were performed under controlled laboratory conditions, and data were analyzed using Chronojump software to ensure measurement accuracy and reliability.

Maximum oxygen consumption measurement

Cardiorespiratory endurance was evaluated using a submaximal cycle ergometer test based on the Åstrand–Rhyming protocol. The evaluation was conducted on a mechanically braked cycle ergometer (Monark Ergomedic 828E, Vansbro, Sweden) to ascertain maximal oxygen consumption as a measure of aerobic fitness. Participants maintained a steady pedaling rate throughout the test, while workload and heart rate responses were monitored to predict VO_{2max} indirectly according to the Åstrand - Rhyming nomogram. Although indirect, this protocol has been widely validated and demonstrated acceptable reliability for estimating VO_2max in young and physically active populations.

Hemoglobin concentration measurement

To evaluate arterial hemoglobin concentration, fingertip capillary blood samples were collected from all participants both before and after the 6-week training intervention. Prior to blood sampling, participants were instructed to remain seated at rest for at least 10 minutes to ensure hemodynamic stability. The fingertip was then disinfected with 70% alcohol and allowed to dry completely before being punctured using a sterile, single-use lancet. The initial drop of blood was discarded to avert contamination with interstitial fluid, while subsequent drops were utilized for analysis. Hemoglobin concentration was measured immediately using a portable hemoglobin analyzer (CERA-CHEK 3 in 1 GHL, Korea), which displayed results in grams per deciliter (g/dL). All measurements were performed by trained personnel under controlled laboratory conditions to ensure the accuracy, reliability, and consistency of the data.

Heart rate and S_pO_2 monitoring

During the entire training intervention, physiological parameters, such as resting heart rate and arterial hemoglobin oxygen saturation (SpO_2), were systematically monitored to thoroughly assess the cardiovascular and respiratory responses to exercise. Baseline measurements were recorded daily prior to each training session, followed by continuous assessments of SpO_2 and heart rate at 5-minute intervals during aerobic exercise until the completion of each 15-minute session. Furthermore, post-exercise measurements were immediately obtained upon training cessation to capture acute physiological changes. All evaluations were performed across all groups using a pulse oximeter (Beurer PO30, USA) and a heart rate monitor (Polar H10, Finland), ensuring precise monitoring of physiological adaptations and verifying both the safety and efficacy of the training protocol.

Data analysis

All statistical analyses were performed using IBM SPSS Statistics for Windows, Version 27.0 (IBM Corp., Armonk, NY, USA). Data are presented as mean ± standard deviation (SD). The normality of the distribution was verified using the Shapiro–Wilk test. Paired t-tests were employed to compare pre- and post-intervention values within groups, while independent t-tests were used to compare the differences from baseline between groups. A p-value of less than 0.05 was considered statistically significant.

Results

The participants' characteristics and baseline measurements for the two training groups are presented in Table 1. There were no significant differences between the aerobic exercise (AE) and aerobic exercise combined with blood flow restriction (AE+BFR) groups in any of the measured variables, indicating that both groups were comparable at baseline before the intervention.

Table 1. Participant characteristics in the two training groups.

Characteristics	AE (n = 12)	AE+BFR (n = 12)
Age (years)	20.25 ± 1.22	20.42 ± 1.00
Weight (kg)	65.38 ± 4.63	66.49 ± 9.16
Height (cm)	172.17 ± 5.29	173.58 ± 5.55
BMI (kg/m^2)	21.54 ± 1.87	21.66 ± 2.03
Resting heart rate (b/m)	74.75 ± 5.42	72.60 ± 8.10
S_pO_2 (%)	98.42 ± 0.67	98.50 ± 0.52
SBP (mmHg)	119.55 ± 5.28	118.73 ± 4.80
DBP (mmHg)	74.10 ± 7.91	73.00 ± 6.25

Note: Values are mean ± SD. AE; aerobic exercise, AE+BFR; aerobic exercise combined with blood flow restriction, BMI; body mass index; S_pO_2 = resting arterial oxygen saturation; SBP = systolic blood pressure; DBP = diastolic blood pressure.

After six weeks of training, both groups demonstrated favorable improvements in body composition parameters. The aerobic exercise combined with blood flow restriction (AE+BFR) group showed a significant increase in skeletal muscle mass and a significant reduction in body mass index (BMI) compared with pre-training values ($p < 0.05$). These findings indicate that the AE+BFR intervention induced beneficial adaptations in body composition (Table 2).

With regard to physical performance, both groups exhibited improvements in most measured variables following the training period. Notably, the AE+BFR group demonstrated significant improvements in handgrip strength, flexibility (sit and reach), and maximal oxygen consumption compared with pre-training levels ($p < 0.05$). The AE+BFR group achieved a 16.68% increase in VO_2max, which was significantly greater than the 5.66% improvement observed in the AE group ($p = 0.005$).

Hemoglobin concentration significantly increased from pre- to post-training within the AE+BFR group ($p < 0.05$), with a 19.36% increase, compared with a 6.53% increase observed in the AE group. Between-group comparisons indicated a greater increase in hemoglobin concentration in the AE+BFR group; however, this difference did not reach statistical significance ($p = 0.058$). Overall, these results suggest that AE+BFR training elicited greater physiological and hematological responses, contributing to enhanced oxygen transport capacity and aerobic performance in male university athletes (Table 3).

Table 2. Mean changes in body composition parameters in the two training groups after six weeks of training.

Body composition	AE (*n* = 12)			AE+BFR (*n* = 12)			P-value
	Pre-test	Post-test	%change	Pre-test	Post-test	%change	
Weight (kg)	65.38 ± 4.63	65.29 ± 4.19	0.07	66.49 ± 9.16	65.80 ±8.40	0.92	0.416
BMI (kg/m^2)	21.54 ± 1.87	21.48 ± 2.00	0.02	21.66 ± 2.03	21.40 ±1.92	1.16*	0.400
Fat-Free mass (kg)	55.09 ± 4.97	54.99 ± 3.74	0.01	57.40 ± 4.68	59.25 ±6.22	3.25	0.295
Fat mass (%)	14.83 ± 4.26	15.33 ± 4.16	4.06	14.76 ± 6.12	14.35 ±5.91	1.36	0.273
Skeletal muscle mass (kg)	26.29 ± 1.62	26.29 ± 1.46	1.06	26.79 ± 2.17	27.41 ±1.90	2.44*	0.262
Skeletal muscle mass of right leg (kg)	5.85 ± 0.62	5.86 ± 0.53	0.42	6.04 ± 0.55	6.06 ± 0.51	0.45	0.982
Skeletal muscle mass of left leg (kg)	5.78 ± 0.05	5.79 ± 0.42	0.26	5.97 ± 0.62	5.98 ± 0.58	0.38	0.924
Visceral adipose tissue (L)	1.30 ± 0.26	1.26 ± 0.18	1.91	1.29 ± 0.25	1.24 ± 0.32	4.55	0.513

Note: Values are mean ± SD. *Significant p<0.05 pre-test vs post-test, $^{\#}$Significant p<0.05 AE vs. AE+BFR

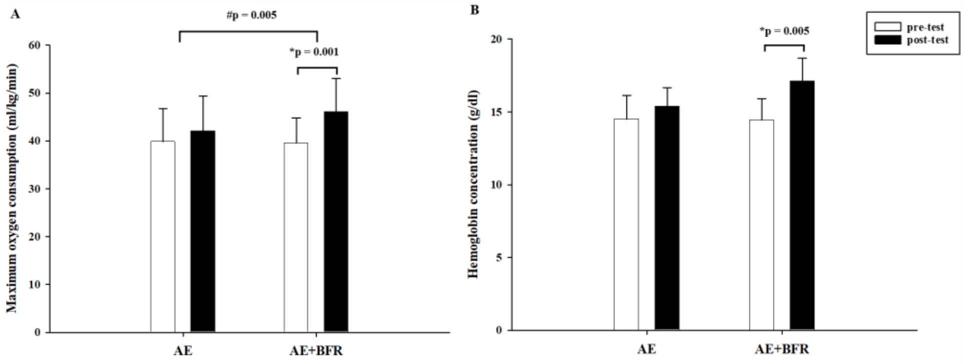
Table 3. Mean changes in physical performance and hemoglobin concentration in the two training groups after six weeks of training.

Variables	AE (*n* = 12)			AE+BFR (*n* = 12)			P-value
	Pre-test	Post-test	%change	Pre-test	Post-test	%change	
Muscular strength							
Hand grip strength (kg/body weight)	0.65 ± 0.14	0.67 ± 0.12	3.63	0.68 ± 0.11	0.73 ± 0.13	7.68*	0.097
Leg strength (kg/body weight)	2.38 ± 0.62	2.45 ± 0.68	3.62	2.45 ± 0.43	2.55 ± 0.55	3.84	0.972
Flexibility							
Sit and reach test (cm)	17.55 ± 4.37	18.47 ± 5.05	5.01	17.96 ± 3.88	19.07 ± 4.50	5.92*	0.796
Muscular power							
Countermovement jump test (cm)	38.09 ± 4.96	38.37 ± 3.93	1.12	37.49 ± 4.78	38.37 ± 3.93	8.74	0.202
Cardiorespiratory endurance							
VO$_{2max}$ (ml/kg/min)	39.80 ± 6.89	42.01 ± 7.36	5.66	39.49 ± 5.32	46.03 ± 6.97	16.68*	0.005$^{\#}$
Blood parameter							
Hemoglobin concentration (g/dl)	14.50 ± 1.64	15.36 ± 1.31	6.53	14.45 ± 1.47	17.11 ± 1.59	19.36*	0.058

Note: Values are mean ± SD. VO$_{2max}$; Maximum oxygen consumption, *Significant p<0.05 pre-test vs post-test, $^{\#}$Significant p<0.05 AE vs. AE+BFR

Figure 2 illustrates the changes in maximal oxygen consumption and hemoglobin concentration before and after six weeks of training. Both groups exhibited upward trends in these parameters following the intervention. The aerobic exercise combined with blood flow restriction (AE+BFR) group demonstrated significant increases in both VO$_2$max and hemoglobin concentration compared with pre-training values ($p < 0.05$). A significantly greater improvement in VO$_2$max was observed in the AE+BFR group compared with the AE group ($p < 0.05$). Hemoglobin concentration increased in both groups, with a greater numerical increase observed in the AE+BFR group; however, the between-group difference did not reach statistical significance. Collectively, these findings suggest that AE+BFR training may promote favorable cardiovascular and hematological responses, contributing to enhanced oxygen transport capacity and aerobic performance in male university athletes.

Figure 2. Changes in (A) maximum consumption and (B) hemoglobin concentration before and after 6-week of the training period. Values are present as mean ± SD. *Significant p<0.05 pre-test vs post-test, $^{\#}$Significant p<0.05 AE vs. AE+BFR



Discussion

This study demonstrated that aerobic exercise combined with blood flow restriction (AE+BFR) effectively induced physiological and hematological adaptations in male university athletes. The intervention resulted in notable improvements in skeletal muscle mass, maximal oxygen consumption and hemoglobin concentration, reflecting integrated central and peripheral cardiovascular adaptations.

The localized hypoxia induced during BFR exercise plays a key role in stimulating the expression of angiogenic growth factors, particularly hypoxia-inducible factor-1 (HIF-1). This transcription factor triggers capillary formation through hypoxia-induced cellular signaling pathways (Taylor et al., 2016), facilitating skeletal muscle remodeling and increased capillary density within the muscle. These vascular adaptations enhance oxygen and nutrient delivery to myocytes and promote oxidative metabolism, even under lower workloads than conventional training. Such findings are consistent with those of Yang et al. 2022, who reported significant increases in VO_{2max} following AE+BFR, and Chen et al. 2022, who demonstrated that eight weeks of running combined with BFR significantly improved aerobic performance in endurance athletes. Similar adaptations have also been observed in university populations (Amani-Shalamzari et al., 2019; Paton et al., 2017). Slysz & Burr. 2019 discovered that university students exhibited a more rapid VO_{2max} response to BFR training than well-trained athletes, suggesting enhanced cardiovascular responsiveness in individuals with less training.

The metabolic stress caused by restricted blood flow further elevates anaerobic energy metabolism, resulting in increased lactate and hydrogen ion (H^+) accumulation within skeletal muscles (Kon et al., 2012; Morley et al., 2021). This metabolic acidosis stimulates the secretion of anabolic hormones, such as growth hormone (GH) and insulin-like growth factor-1 (IGF-1), both of which activate the mTOR signaling pathway to enhance muscle protein synthesis and satellite cell activation (Frost & Lang, 2012; Wu & Storey, 2021; Yinghao et al., 2021). Consequently, AE+BFR promotes muscle hypertrophy and improvements in body composition, aligning with previous findings by Abe et al. 2010 and Formiga et al. 2020 demonstrating the efficacy of AE+BFR in enhancing muscle mass and physical performance. In contrast to the findings of Formiga et al. 2020, the current study demonstrated more significant enhancements in VO_{2max}, potentially attributable to prolonged cuff exposure and elevated arterial occlusion pressure (AOP). Furthermore, the application of BFR following sprint interval training at 60% of AOP has been associated with increases in total and oxygenated hemoglobin, indicating reduced venous return and improved muscle oxygen delivery and recovery efficiency (Solsona et al., 2021).

At the hematological level, the elevated hemoglobin concentration observed in AE+BFR participants may be attributed to erythropoietin (EPO)-mediated erythropoiesis under hypoxic conditions and the influence of shear stress within capillaries. These findings are consistent with previous evidence indicating that hypoxic and ischemic stimuli associated with blood flow restriction may promote erythropoietic and oxygen transport–related adaptations. Although the between-group difference in hemoglobin concentration did not reach statistical significance, the AE+BFR group demonstrated a greater increase, suggesting a potential hematological benefit associated with blood flow restriction training. Shear stress stimulates endothelial nitric oxide synthase (eNOS) activity, leading to increased nitric oxide (NO) production, which enhances endothelial function and promotes vasodilation (Green & Smith, 2018). Similarly, Barjaste et al. 2021 reported that BFR exercise at 40% VO_2max increased both hypoxia-inducible factor-1α (HIF-1α) and vascular endothelial growth factor (VEGF) protein expression compared with control conditions, supporting the role of shear stress and NO in vascular adaptations. These mechanisms collectively contribute to enhanced erythropoiesis, greater hemoglobin mass, and improved oxygen-carrying capacity. Correspondingly, Smith et al. 2022 and Pignanelli et al., 2021 found that AE+BFR significantly increased hemoglobin mass, stroke volume, and red blood cell volume without adverse cardiac effects.

Peripheral adaptations induced by BFR training include increased capillarization, mitochondrial density, and oxidative enzyme activity (Conceição & Ugrinowitsch, 2019), while central adaptations such as enhanced stroke volume (Abe et al., 2010) and cardiac output (Mitchell et al., 2019; Tangchaisuriya et al., 2022) further contribute to improved aerobic performance. A recent meta-analysis by Dong et al., 2025 confirmed that AE+BFR enhances VO_{2max} and lower-limb muscle strength without impairing anaerobic performance. These results collectively suggest that AE+BFR is a safe, time-efficient, and physiologically effective training method, suitable for university athletes who face time constraints or limited tolerance to high mechanical loads.

Nevertheless, this study presents some limitations. The small, homogenous sample size of male participants from a single institution may limit generalizability. Additionally, the six-week training period may not fully capture long-term physiological adaptations. Molecular and hormonal markers such as EPO, GH, IGF-1, and VEGF were not assessed, which restricts the mechanistic interpretation of the observed adaptations. Future research should therefore include larger, more diverse samples; incorporate both male and female athletes from different sports; extend the training duration; and examine molecular and endocrine responses to better elucidate the physiological mechanisms underlying AE+BFR adaptations.

Conclusions

Aerobic exercise combined with blood flow restriction represents a promising and evidence-based training modality for enhancing body composition, aerobic performance, and hematological adaptations. This hybrid method effectively replicates the physiological benefits of high-intensity training while operating under substantially reduced workloads, thereby minimizing mechanical strain and cardiovascular stress. AE+BFR is a safe, effective, and scientifically sound way for college athletes to improve their aerobic fitness. Moreover, this training strategy holds practical value for developing low-load aerobic conditioning protocols in collegiate athletic settings or rehabilitation programs, where optimizing physiological adaptations while reducing mechanical load is essential for both performance enhancement and injury prevention.

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Conflict of interest

The authors declare that they have no conflict of interest.

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