

Acute effects of high-intensity interval exercise combined with different blood flow restrictions on hemodynamic and muscle oxygenation responses in junior rowers

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Published online: September 30, 2025

Accepted for publication: September 15, 2025

DOI:10.7752/jpes.2025.09208

Abstract:

Introduction: High-intensity interval training (HIIT) is known to improve endurance performance, yet the physiological effects of combining high-intensity interval exercise (HIIE) with blood flow restriction (BFR) are not fully understood. This study aimed to identify the optimal HIIE+BFR protocol for enhancing hemodynamic and muscle oxygenation responses in young rowers. **Methods:** Fourteen junior rowers (11 males, 3 females) completed four HIIE sessions on a rowing ergometer with different arterial occlusion pressures (AOPs): HIIE alone, HIIE+40%AOP, HIIE+50%AOP, and HIIE+60%AOP, following a randomized crossover design. Each session included four 2-min rowing bouts at 90% $\dot{V}O_{2max}$, separated by 2 min of passive recovery, with trials spaced 7 days apart. Cardiac output (CO), stroke volume (SV), heart rate (HR), muscle oxygen saturation (SmO_2), rating of perceived exertion (RPE), and pain were continuously monitored throughout each session. **Results and Discussion:** Overall, mean SmO_{2max} increased with higher AOPs (%AOP) across sets. Mean SmO_{2min} differed significantly between conditions, with the lowest value observed at 50% AOP compared to other BFR conditions. The mean ΔSmO_{2diff} in the HIIE-alone condition did not change across sets, whereas in all BFR conditions, ΔSmO_{2diff} progressively increased across sets (all, $p < 0.05$). Mean SV, CO, and HR gradually increased from set 1 to set 2 and slightly declined from set 3 to set 4, regardless of BFR condition. RPE values increased from set 1 to set 4 across all conditions (all, $p < 0.05$). In contrast, pain scores were significantly higher in all BFR conditions compared to HIIE alone ($p = 0.00$), with the highest values observed in HIIE+60%AOP, exceeding those in HIIE+50%AOP and HIIE+40%BFR (all, $p < 0.05$). **Conclusion:** Combining HIIE with BFR at 50% AOP appears effective in promoting muscle deoxygenation while remaining more tolerable for junior rowers. Thus, this BFR training approach can be used to enhance peripheral adaptations and improve physical performance in rowers.

Keywords: occlusion training, aerobic training, rowing, NIRS

Introduction

Rowing is a strength–endurance sport, with competitive events requiring an all-out effort lasting 6–7 min. Performance in rowing primarily depends on the aerobic energy system, contributing approximately 70%–80% of total energy expenditure, while anaerobic metabolism accounts for the remainder (Hagerman, Connors, Gault, Hagerman, & Polinski, 1978; Treff, Winkert, & Steinacker, 2021). The aerobic system dominates throughout most of the race, whereas the anaerobic pathway is particularly important during the initial sprint and final phases (Akca & Aras, 2015). Therefore, rowers require a high cardiac output (CO) (Wasfy et al., 2015) and proportion of type I muscle fiber (approximately 70%–80%) (Larsson & Forsberg, 1980) to attain a high level of $\dot{V}O_{2max}$ (Nolte, 2011). To improve aerobic capacity and endurance performance, various training modalities—including strength training, moderate-intensity continuous training (MICT), and high-intensity interval training (HIIT)—can be used (Volianitis et al., 2020). Among these methods, HIIT has gained popularity in recent years owing to its time-efficient nature. High-intensity interval exercise (HIIE) involves short bouts of near-maximal effort, typically lasting 30 s to ~5 min, interspersed with brief recovery periods. HIIT has been shown to improve both aerobic and anaerobic performance in healthy and endurance-trained athletes (Hoshino, Kitaoka, & Hatta, 2016; MacInnis & Gibala, 2017). Moreover, mixed-modality training combining HIIT and MICT has been effective in improving oxygen consumption at the lactate threshold ($\dot{V}O_{2@LT}$) in adolescent rowers (Panasci et al., 2025). However, a recent study reported that 11 HIIT sessions over 6 weeks did not result in significant performance improvements in highly trained rowers (Mujika et al., 2023). Collectively, these findings suggest that novel training strategies may be needed to provide additional stimuli to enhance adaptive responses to HIIT, particularly in young rowers.

Blood flow restriction (BFR) is a novel training strategy that involves restricting blood flow to and from the working muscles using pneumatic tourniquets or cuffs applied around the proximal portion of a limb (Cerqueira et al., 2021; Ferguson et al., 2021; Werasirirat & Yimlamai, 2022). The ischemic and hypoxic environment created during BFR is thought to generate high levels of metabolic stress and mechanical tension

when combined with exercise. Physiologically, this stimulus can activate key transcriptional factors—such as HIF-1 α , PGC-1 α , and AMPK pathways—which regulate mitochondrial biogenesis, angiogenesis, and skeletal muscle hypertrophy (de Freitas et al., 2017; Ferguson et al., 2021).

Near-infrared spectroscopy (NIRS) has been widely used to monitor changes in muscle oxygenation across various sports and exercise interventions (Perrey & Ferrari, 2018). NIRS provides real-time measurements of local muscle oxygen saturation (SmO₂), reflecting the balance between oxygen delivery and utilization during exercise. An increase in SmO₂ indicates that oxygen delivery exceeds extraction, whereas a decrease in SmO₂ suggests that oxygen extraction exceeds delivery (Ferrari, Muthalib, & Quaresima, 2011). SmO₂ has also been reported to be associated with exercise intensity, with supramaximal exercise inducing lower SmO₂ values compared to high-intensity exercise (Nemoto et al., 2024; Paquette et al., 2019). In world-class rowers, SmO₂ gradually decreased during incremental exercise, indicating that SmO₂ monitoring can be useful for guiding aerobic training programs (Klusiewicz et al., 2021). Notably, changes in SmO_{2min} (i.e., muscle deoxygenation), rather than VO_{2max}, during exercise testing were strongly correlated with time–trial performance in highly trained canoe–kayakers (Paquette, Bieuzen, & Billaut, 2018).

To date, there is no consensus on the BFR training strategy that elicits the most robust muscle hypoxia, which is necessary to provide optimal stimuli for central and peripheral adaptations during aerobic or endurance exercise (Perrey, 2022; Wizenberg et al., 2023; Wu, Song, & Xu, 2015; Chua, Sim, & Burns, 2022). Moreover, most BFR research has used arbitrary pressures (practical BFR) or fixed systolic blood pressure values rather than a relative percentage of arterial occlusion pressure (AOP) for each individual, which is considered the gold standard for BFR training (Reis et al., 2019). These methodological inconsistencies can lead to variability in physiological adaptations among subjects and hinder controlled comparisons between studies, potentially limiting peak performance outcomes. Importantly, excessively high AOP may adversely affect cardiovascular function, increase participant discomfort, and increase the risk of injury (Cherouveim et al., 2023; Geladas, 2010). Therefore, the purpose of this pilot study was to find out an optimal BFR protocol combined with HIIE that would induce greater ischemia while minimizing a decrement in performance, particularly during rowing exercise. Considering previous research reported that relative blood flow during resistance exercise with BFR was significantly reduced from 50% to 60 % of AOP at rest when compared with baseline (Hornikel et al., 2023), with no further change observed between 60% and 80% of AOP, and very little is known about the physiological effects of combined HIIE and BFR in young rowers, which may respond differently to BFR compared to adult athletes. Hence, this study was designed to investigate the acute effects of HIIE combined with various BFR conditions (i.e. 40% to 60% of AOP) on muscle oxygenation, cardiovascular responses, and rowing performance in young rowers. We hypothesized that the addition of 60% AOP to HIIE is more effective to elicit greater physiological responses compared to other BFR and non-BFR conditions. This information is valuable for coaches and sports practitioners seeking to develop effective BFR training strategies to further improve endurance performance in young rowers.

Materials and methods

Participants

Fourteen young rowers (11 males and 3 females) from the Rowing and Canoeing Association of Thailand and the Rowing Club of the Marine Training Center, each with at least one year of training experience, participated in this study. All participants were free of musculoskeletal or cardiovascular disorders and provided informed consent after being fully briefed on the procedures, potential risks, and benefits. The experimental protocol was approved by the Human Research Ethics Committee of Chulalongkorn University (Protocol number 670015). Sample size was determined based on a previous study (Hornikel et al., 2023) using G*Power version 3.0.10 (Heinrich-Heine university düsseldorf, Germany) with an effect size of 1.22, $\alpha = 0.05$, and statistical power of 0.80, resulting in a minimum requirement of 12 participants. Accounting for a 10% dropout rate, 14 participants were recruited.

Study design

This study used a randomized, counterbalanced crossover design. Participants visited the laboratory on five occasions, each separated by at least 7 days. The first visit included body composition assessment, AOP measurement, and a VO_{2max} test to confirm eligibility (VO_{2max} ≥ 45 mL kg⁻¹ min⁻¹). Visits 2–5 involved four experimental conditions: HIIE, HIIE+40%AOP, HIIE+50%AOP, and HIIE+60%AOP (Figure 1). The order of conditions was randomized, and all trials were performed at the same time of day to minimize circadian effects. Throughout each trial, hemodynamic responses, muscle oxygenation, ratings of perceived exertion (RPEs), and pain scores were continuously monitored. All testing procedures were performed under the supervision of the principal investigator.

Experimental trials

Each participant completed one of the four experimental conditions on a Concept 2 Model D rowing ergometer in a randomized order. Following a standardized 10-min warm-up, participants performed four sets of HIIE, consisting of 2-min rowing bouts at a power output corresponding to 90%VO_{2max}, interspersed with 2–5 min of passive recovery, as described in a previous study (Faelli et al., 2022). For the BFR interventions, a pneumatic cuff (10.5 cm width; Grand Marketing, Thailand) was placed around the proximal thigh of both legs

and inflated to the target pressure 30 s before starting the exercise. During the recovery periods, the cuffs were deflated and then re-inflated 30 s before the start of the subsequent exercise bout.

Outcome measures

Participants visited the laboratory on five occasions, each separated by one week. During the first visit, baseline measurements were collected, including body composition (TANITA MC-780, MA, USA; S/N 14040018), AOP, and maximal oxygen uptake ($\text{VO}_{2\text{max}}$).

Arterial occlusion pressure (AOP) measurement

AOP was measured using an ultrasound imaging device (Aloka ARIETTA Prologue, Hitachi, Japan) with participants in the prone position. After resting in the prone position for 20 min, a pneumatic cuff (Grand Marketing, Thailand) was placed around the proximal thigh of the dominant leg. The ultrasound probe was positioned over the popliteal region in duplex mode to locate the popliteal artery. Pulse-wave mode was then used to visualize the arterial pulse. The cuff pressure was gradually increased every 30 s until the pulse wave was no longer detectable. The highest pressure at which the pulse wave disappeared was recorded as 100% AOP (Corvino et al. 2017).

Maximal oxygen uptake ($\text{VO}_{2\text{max}}$) test

An incremental exercise test was performed to determine $\text{VO}_{2\text{max}}$ on a rowing ergometer (Concept 2, Model D, Morrisville, VT, USA) using an ergospirometer (MES $\text{VO}_{2\text{max}}$ Tracker, USA). Following a 10-min warm-up, the $\text{VO}_{2\text{max}}$ test began at an initial power output of 100 W for 2 min, with increments of 30 W every 2 min until volitional exhaustion or until participants could no longer maintain the target intensity (Papadakis, Etchebaster, & Garcia-Retortillo, 2022).

$\text{VO}_{2\text{max}}$ was considered achieved when at least three of the following criteria were met: (1) a plateau in VO_2 (change < 150 mL/min), (2) a respiratory exchange ratio (RER) exceeding 1.15, (3) visible signs of exhaustion, and (4) HR at the end of exercise (HR_{max}) within 10 bpm of the predicted maximum [$210 - (0.65 \times \text{age})$]. The lowest power output required to elicit $\text{VO}_{2\text{max}}$ was defined as P_{max} (Faelli et al., 2022).

Muscle oxygenation measurement

A commercial NIRS device (Moxy Monitor, Fortiori Designs LLC, MN, USA) was used to monitor real-time SmO_2 of the vastus lateralis (VL) muscle on the dominant leg. The sensor was positioned on the distal three-fourths of the VL, approximately 5 cm lateral from the midline between the anterior superior iliac spine (ASIS) and posterior superior iliac spine (PSIS). The device uses four continuous wavelengths (680, 720, 760, and 800 nm) to measure light absorbance using a modified Beer–Lambert approach, providing a relative SmO_2 value ranging from 0% to 100% (Feldmann et al., 2019). SmO_2 was calculated using the following equation: $\text{SmO}_2 = (\text{O}_2\text{Hb} + \text{O}_2\text{Mb}) / [(\text{O}_2\text{Hb} + \text{O}_2\text{Mb}) + (\text{HHb} + \text{HMb})]$. The device was secured to cleaned skin with adhesive tape and covered with a dark bandage to minimize light interference. The Moxy monitor position was marked on the participants' skin to ensure consistent placement across all exercise conditions. SmO_2 values were recorded every 2 s during exercise. Maximum SmO_2 ($\text{SmO}_{2\text{max}}$) was defined as the highest SmO_2 value recorded at the beginning of exercise, whereas minimum SmO_2 ($\text{SmO}_{2\text{min}}$) was defined as the lowest value, typically occurring at the end of exercise. The maximal oxygen desaturation ($\Delta\text{SmO}_{2\text{diff}}$) was calculated as the difference between $\text{SmO}_{2\text{max}}$ and $\text{SmO}_{2\text{min}}$ during the exercise session (Ferrari et al., 2011). The mean values of $\text{SmO}_{2\text{max}}$, $\text{SmO}_{2\text{min}}$, and $\Delta\text{SmO}_{2\text{diff}}$ were used for further analysis.

Hemodynamic measurement

Cardiac output (CO), stroke volume (SV), and heart rate (HR) were measured using thoracic electrical bioimpedance (PhysioFlow® Enduro™, France). The device was calibrated according to the manufacturer's guidelines prior to testing. All parameters were recorded on a beat-by-beat basis and averaged over the course of the exercise session.

Perception measurement

RPE was assessed using Borg's category ratio scale (CR10), where 0 indicates no exertion and 10 represents maximal exertion (Foster et al., 2001). Pain was evaluated using a visual analogue scale (VAS, 0–10) (Lee, Hicks, & Nino-Murcia, 1991). Participants rated their exertion and pain immediately after each set. Prior to the study, all subjects were familiarized with the scales and the anchoring procedures.

Rowing performance

Total rowing distance (TD) and mean power output (MPO) were determined as previously described (Faelli et al., 2022). TD was defined as the cumulative distance completed across the four sets of simulated rowing exercise, while MPO was defined as the average power output achieved during the exercise session.

Statistical analysis

All data were analyzed using IBM SPSS Statistics version 23. Participant characteristics and outcome measures are presented as mean $\pm$ standard deviation. The Shapiro–Wilk test was used to assess the normality of all data. For normally distributed data, a two-way repeated measures ANOVA (condition $\times$ set) was used to evaluate the main effects and interactions of condition and set on hemodynamic variables, muscle oxygenation and perceptual response. One-way repeated measures ANOVA, followed by least significant difference (LSD) post hoc test was used to compare mean differences of rowing performance among conditions. For non-normally distributed data, the Friedman test was applied, and multiple comparisons were performed using the Wilcoxon signed-rank test. Statistical significance was set at $p < 0.05$.

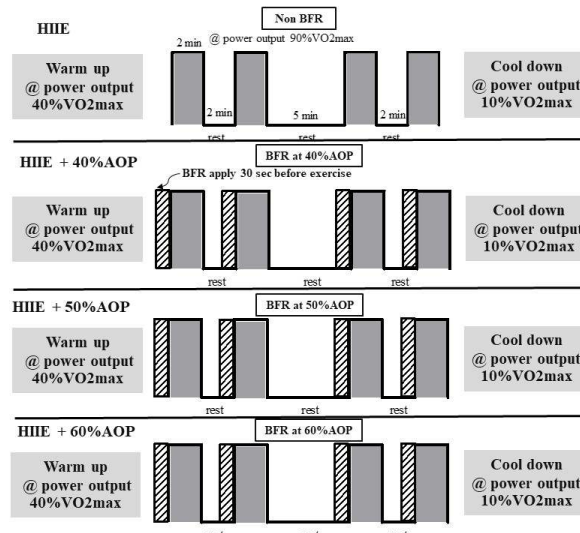


Figure 1. Experimental procedure

Results

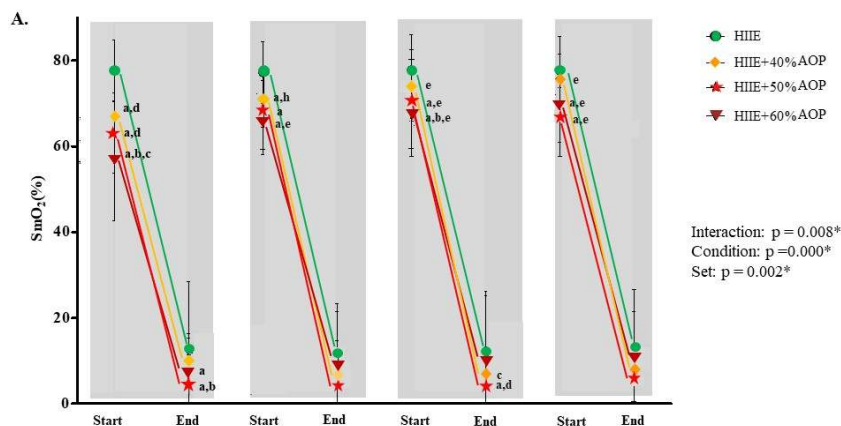
Table 1 summarizes the characteristics of the study participants. On average, participants were 15.80 ± 1.12 years old, with a body weight of 64.69 ± 9.26 kg, a height of 172.29 ± 5.85 cm, a $\text{VO}_{2\text{max}}$ of 50.12 ± 9.48 mL $\text{kg}^{-1} \text{min}^{-1}$, and a peak power output (PPO) of 230.71 ± 36.47 W. The participants had an average training experience of 2.44 ± 1.80 years and trained 6.29 ± 0.47 days per week, including rowing (on-water and ergometer), resistance training, and athletic conditioning.

Table 1. Participant characteristics

(Male = 11, Female = 3)	Mean $\pm$ SD
Age (years)	15.80 ± 1.12
Weight (kg)	64.69 ± 9.26
Height (cm)	172.29 ± 5.85
$\text{VO}_{2\text{max}}$ (mL $\text{kg}^{-1} \text{min}^{-1}$)	50.12 ± 9.48
Peak power output (W)	230.71 ± 36.47
Rowing experience (years)	2.44 ± 1.80
Training frequency (days week^{-1})	6.29 ± 0.47

Muscle oxygenation responses

A two-way repeated measures ANOVA revealed significant effects of condition ($p = 0.000$, $\eta^2 = 0.495$), set ($p = 0.000$, $\eta^2 = 0.392$), and condition $\times$ set interaction ($p = 0.008$, $\eta^2 = 0.168$) on $\text{SmO}_{2\text{max}}$. Overall, the mean $\text{SmO}_{2\text{max}}$ was highest during HIIE alone, followed by HIIE+40%AOP, HIIE+50%AOP, and HIIE+60%AOP across all sets (Figure 2). $\text{SmO}_{2\text{max}}$ values were higher in HIIE compared with all BFR conditions during sets 1 and 2. No significant differences in $\text{SmO}_{2\text{max}}$ were observed between the BFR conditions in set 2 and 4. The mean $\text{SmO}_{2\text{min}}$ was lower in HIIE+50%AOP compared with HIIE (sets 1 and 3), HIIE+40%AOP (set 1), and HIIE+60%AOP (set 3). Interestingly, $\text{SmO}_{2\text{min}}$ was also lower in HIIE+60%AOP (set 1) compared with HIIE. Significant effects of condition ($p = 0.028$, $\eta^2 = 0.206$) and set ($p = 0.000$, $\eta^2 = 0.425$) were observed on $\Delta\text{SmO}_{2\text{diff}}$. The mean $\Delta\text{SmO}_{2\text{diff}}$ in HIIE+60%AOP was significantly lower than in HIIE (sets 1, 2, and 4), HIIE+40%AOP (sets 3 and 4), and HIIE+50%AOP (sets 1 and 4). While $\Delta\text{SmO}_{2\text{diff}}$ values in HIIE did not differ across sets, values in HIIE+40%AOP (sets 3 and 4) and HIIE+60%AOP (set 4) were higher than in set 1 (all, $p < 0.05$). Similarly, $\Delta\text{SmO}_{2\text{diff}}$ in HIIE+50%AOP (sets 2 and 4) was higher than in set 1 (all, $p < 0.05$).



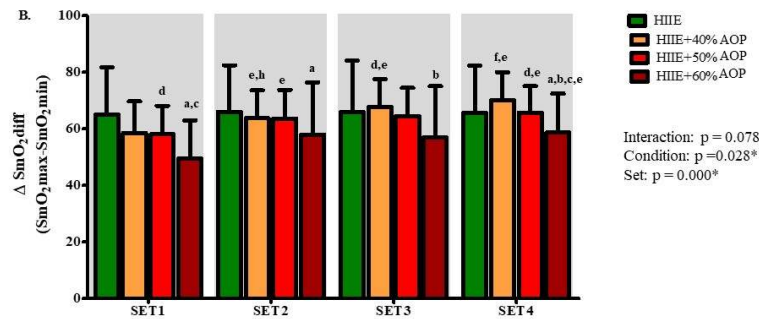


Figure 2. Changes in vastus lateralis muscle oxygenation during high-intensity interval exercise (HIIE) under different arterial occlusion pressures (AOPs)

(A: SmO_{2max} and SmO_{2min} during exercise, B: ΔSmO_{2diff} during exercise)

a = significantly different from HIIE, b = significantly different from HIIE+40%AOP, c = significantly different from HIIE+50%AOP, d = significantly different from HIIE+60%AOP, e = significantly different from set 1, f = significantly different from set 2, g = significantly different from set 3, h = significantly different from set 4, * = $p < 0.05$

Acute hemodynamic response

Significant effects of set and condition $\times$ set interaction were observed for SV ($p = 0.000$, $\eta^2 = 0.429$), CO ($p = 0.000$, $\eta^2 = 0.638$), and HR ($p = 0.000$, $\eta^2 = 0.877$), whereas no effect of condition was found for any hemodynamic variable (all $p > 0.05$). Mean SV values in HIIE and HIIE+40%AOP during sets 2–4 were significantly higher than in set 1 (all $p < 0.05$). Additionally, SV in HIIE+50%AOP was significantly higher in sets 3 and 4 compared with set 1, and SV in HIIE+50%BFR at set 4 was also significantly higher than in sets 2–3 (all $p < 0.05$). No significant changes in mean SV were observed across sets in HIIE+60%AOP.

Similarly, mean CO in all BFR conditions was significantly higher in sets 2–4 compared with set 1 (all $p < 0.05$), with CO in HIIE+50%AOP being higher in set 4 than in set 3 ($p = 0.019$). Likewise, mean HR in all BFR conditions increased significantly from set 2 to set 4 compared with set 1 (all $p = 0.000$). Furthermore, mean HR values in HIIE, HIIE+40%AOP, and HIIE+50%AOP during set 4 were significantly higher than in sets 2 and 3 (all $p < 0.01$).

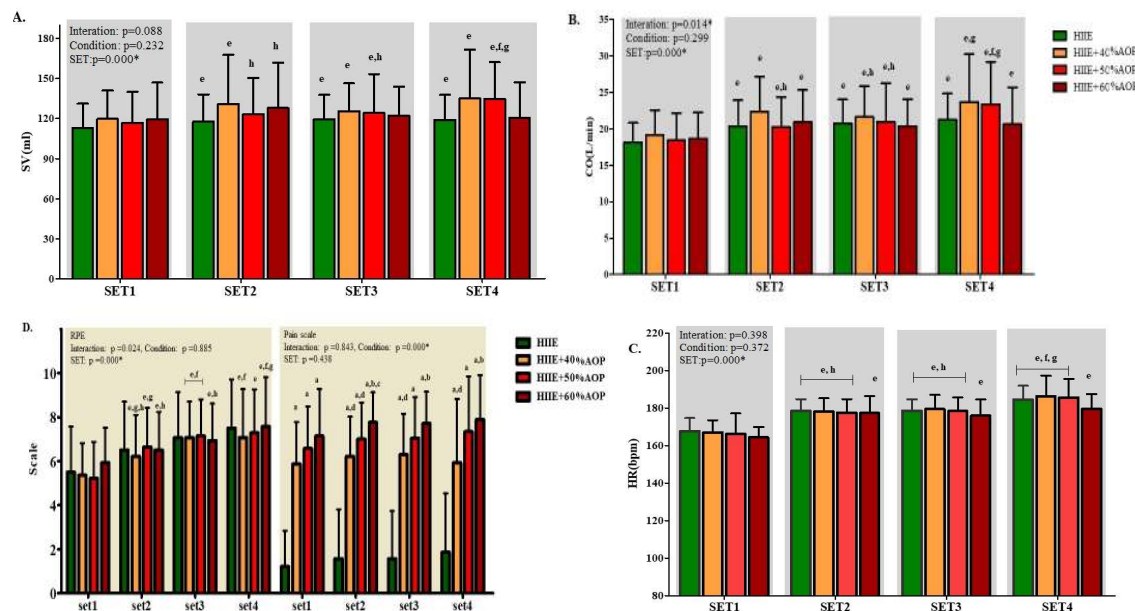


Figure 3. Hemodynamic and perceptual responses during high-intensity interval rowing exercise (HIIE) under different arterial occlusion pressures (AOPs)

a = significantly different from HIIE, b = significantly different from HIIE+40%AOP, c = significantly different from HIIE+50%AOP, d = significantly different from HIIE+60%AOP, e = significantly different from set 1, f = significantly different from set 2, g = significantly different from set 3, h = significantly different from set 4, * = $p < 0.05$

Perceptual response

As shown in Figure 3, no significant effect of condition was observed for RPE ($p = 0.885$, $\eta^2 = 0.016$), whereas significant effects of set ($p = 0.000$, $\eta^2 = 0.572$) and a condition $\times$ set interaction ($p = 0.024$, $\eta^2 = 0.147$) were found. Overall, RPE values increased from set 1 through set 4, regardless of BFR condition (all $p < 0.05$). In contrast, a significant effect of condition was observed for pain scale ($p = 0.000$, $\eta^2 = 0.786$), but no significant effects of set ($p = 0.438$, $\eta^2 = 0.052$) or condition $\times$ set interaction ($p = 0.843$, $\eta^2 = 0.026$) were found. Pain scores were significantly higher in all BFR conditions compared with HIIE alone across all sets ($p = 0.000$). Notably, pain was significantly higher in HIIE+60%AOP than in HIIE+50%AOP (set 2) and HIIE+40%AOP (sets 2 and 3) (all $p < 0.05$).

Rowing performance

In the present study, MPO and TD, indicators of rowing performance, differed significantly between conditions (both $p = 0.000$). Specifically, mean MPO in HIIE+60%BFR was significantly lower than in HIIE ($p = 0.001$), HIIE+40%AOP ($p = 0.007$), and HIIE+50%AOP ($p = 0.025$) (Table 2). Similarly, TD in HIIE+60%AOP was significantly lower than in HIIE ($p = 0.001$), HIIE+40%AOP ($p = 0.006$), and HIIE+50%AOP ($p = 0.021$). No significant differences were observed among the BFR conditions themselves.

Table 2. Rowing performance

Rowing performance	HIIE	HIIE+40%AOP	HIIE+50%AOP	HIIE+60%AOP
MPO (W)	217.14 $\pm$ 34.29 ^d	211.57 $\pm$ 33.68 ^d	210.50 $\pm$ 32.05 ^d	199.79 $\pm$ 40.89 ^{a,b,c}
Total distance (m)	2040.64 $\pm$ 111.24 ^d	2023.71 $\pm$ 111.35 ^d	2020.43 $\pm$ 108.44 ^d	1981.50 $\pm$ 141.66 ^{a,b,c}

a = Significantly different from HIIE, b = Significantly different from 40%AOP, c = Significantly different from 50%AOP, d = Significantly different from 60%AOP

Discussion

The aim of this study was to identify an optimal BFR combined with the HIIE protocol to improve central and peripheral adaptive responses in young rowers. Our findings showed that VL SmO₂ was lowest at 50% AOP compared with other BFR conditions and did not support our hypothesis. Although SV, HR, and CO gradually increased across sets, no significant differences were observed between BFR conditions. Lastly, RPE and pain scores gradually increased across sets, with the highest pain observed at 60% AOP compared to 40% AOP, 50% AOP, and non-BFR conditions. Overall, these findings suggest that adding BFR at 50% AOP to HIIE provides a more effective training regimen, reducing SmO₂ without negatively affecting cardiovascular function during rowing exercise.

In this study, NIRS monitoring was used to assess changes in VL muscle oxygenation as an indicator of peripheral adaptive responses to BFR training. Typically, three phases characterize the SmO₂ response during HIIE on a rowing ergometer. Initially, SmO₂ remains stable at rest (phase 1, SmO_{2max}). It then rapidly declines at the beginning of exercise (phase 2, fast desaturation) until a new equilibrium is reached, where oxygenation is lower but relatively consistent, typically occurring at the end of each exercise session (phase 3, SmO_{2min}). During recovery, SmO₂ rapidly returns to baseline (fast reoxygenation) (Gasser et al., 2022). In this study, we found that while SmO_{2max} during HIIE remained relatively unchanged across sets, SmO_{2min} was lowest in HIIE+50%AOP compared with HIIE+40%AOP and HIIE+60%AOP (Figure 1). This finding was unexpected because previous studies have reported that SmO_{2min} typically decreases with increasing AOP (Salzmann et al., 2021). The mechanism underlying this observation remains unclear. One possible explanation is that the relatively higher SmO_{2min} in HIIE+60%AOP may be due to a reduction in power output during exercise (Perrey, 2022). Changes in SmO₂ during exercise are influenced by multiple factors, including exercise intensity and duration (Chaug et al., 2002; Nioka et al., 1998), as well as the aerobic fitness and endurance capacity of the individual (Hoppeler et al., 1985). Therefore, in this study, Δ SmO_{2diff} rather than the absolute SmO_{2min} was used as a proxy for skeletal muscle oxygenation (Buchheit & Ufland, 2011). We observed that the mean Δ SmO_{2diff} values for HIIE, HIIE+40%AOP, and HIIE+50%AOP were not significantly different, whereas the Δ SmO_{2diff} value for HIIE+60%AOP was significantly lower compared to the other BFR and non-BFR conditions. Collectively, these findings suggest that incorporating 50% AOP into HIIT may elicit the most robust acute muscle oxygenation response, with 60% AOP providing no additional benefit.

Given that central factors (CO and SV) play a major contribution in limiting VO_{2max} in highly trained endurance athletes (Saltin & Calbet, 2006), to quantify the impact of different AOP levels on central cardiovascular function, hemodynamic variables (SV, CO, and HR) were continuously measured during exercise. Overall, all hemodynamic variables increased significantly across sets (from set 1 to 4), but no differences were observed between BFR and non-BFR conditions. This finding contrasts with previous studies. For example, Ozaki et al. (2010) and Cherouveim et al. (2023) reported that continuous BFR protocols with high occlusion pressures (120–140 mmHg) reduced SV, CO, and HR during exercise and impaired performance. Theoretically, the increase in SV during exercise is primarily attributed to enhanced venous return and increased ventricular contractility, while HR typically increases owing to elevated sympathetic nervous system activity and circulating catecholamines (e.g., epinephrine and norepinephrine) (Kenney, Wilmore, & Costill, 2012). Thus, the

observed increase in CO in this study is likely attributed to concurrent increases in both SV and HR, regardless of BFR condition. Because no differences in hemodynamic variables were observed across BFR conditions, these results suggest that cardiovascular function is not compromised during BFR training. This finding aligns with previous reports showing that cardiovascular responses increase during HIIT sessions (Neves, Gasparini-Neto, Leite, & Carletti, 2023). To further evaluate the feasibility and safety of BFR training, RPE and pain scale were assessed during the simulated rowing trials. Interestingly, even though RPE values tended to be higher in all BFR conditions compared to non-BFR conditions, no statistically significant differences were detected between conditions. In contrast, the pain scale was highest at 60% AOP compared to 40% and 50% AOP, likely owing to increased accumulation of metabolites (e.g., hydrogen ion (H^+) and phosphate (P_i)), which may contribute to discomfort and fatigue during exercise. This observation is supported by rowing performance data showing that both MPO and TD were lowest at 60% AOP compared to the other BFR and non-BFR conditions.

Limitation

This study has several limitations. First, the sample size was relatively small, and future studies with larger cohorts are needed to further validate these findings. Second, only young rowers were included. Thus, the results may not be directly generalizable to other athletic populations. Third, both male and female rowers participated, but the study did not examine potential sex-related differences in physiological responses to BFR exercise. Future research should explore this aspect to determine whether sex influences the effectiveness of BFR training.

Conclusion

In conclusion, the addition of 50% AOP BFR to traditional HIIE is feasible and more effective in inducing muscle deoxygenation without adversely affecting cardiovascular function, compared to other BFR conditions. These findings suggest that incorporating BFR at 50% AOP into high-intensity interval rowing exercise is a promising strategy to further improve endurance performance in junior rowers, whereas higher occlusion pressures (e.g., 60% AOP) provide no additional benefits and may potentially impair performance. Future studies are needed to investigate the long-term or chronic effects of combined HIIE and BFR on VO_{2max} and rowing performance in young rowers.

Acknowledgments The authors gratefully acknowledge the Rowing and Canoeing Association of Thailand for permitting all rowers to participate in this study and for providing the necessary facilities.

Conflicts of interest The authors declare no conflicts of interest.

Funding No funding was received for this study.

Declaration of generative AI and AI-assisted technologies in the writing process

The authors confirm that no artificial intelligence tools were used in performing this study, and all ideas, data, and results presented are the work of the researchers.

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