©Journal of Sports Science and Medicine (2025) **24,** 696-706
http://www.jssm.org DOI: https://doi.org/10.52082/jssm.2025.696

Research article

Effects of Acute and Repeated Ischemic Preconditioning on Recovery from Muscle Fatigue after High-Intensity Swim Training in Male Amateur Swimmers

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Abstract
This study investigated the effects of acute and repeated ischemic preconditioning (IPC) on recovery following high-intensity swim training. Thirty male amateur freestyle swimmers (21 ± 1 years, with at least 2 years of training experience) were randomly assigned to one of three groups: sham IPC (SHAM, n = 10, 4×5 min, 20 mmHg), acute IPC (AIPC, n = 10, 4×5 min, 220 mmHg), or repeated IPC (RIPC, n = 10, 7 days×4×5 min, 220 mmHg). A 7×200m swim incremental load training was conducted 20 minutes after the intervention. External load measures (grip strength, upper limb work, lower limb relative peak torque, average power) and internal load measures [limb circumferences, creatine kinase (CK), malondialdehyde (MDA), glutathione (GSH), superoxide dismutase (SOD), total antioxidant capacity (T-AOC), interleukin-6 (IL-6), C-reactive protein (CRP)] were recorded at baseline, immediately, 24h and 48h post exercise. For external load, RIPC exhibited higher upper limb total work and average power than SHAM at all post-training points ($P < 0.05$), while AIPC exceeded SHAM at 48h ($P < 0.05$). For internal load, immediately post-training, RIPC had higher T-AOC, lower MDA and IL-6 than the other two groups ($P < 0.05$); AIPC showed lower MDA than SHAM ($P < 0.05$). At 24h, RIPC had higher T-AOC than the other two groups; both RIPC and AIPC had lower MDA and IL-6 than SHAM ($P < 0.05$). Moreover, RIPC had lower CK than SHAM at 24h and 48h ($P < 0.05$). Findings indicated that both AIPC and RIPC, compared to SHAM, promoted internal and external recovery following intensive swim training, with RIPC being more effective. These results suggest that incorporating repeated IPC sessions into athletes' training routines could be a practical strategy to optimize recovery and improve subsequent performance.

Key words: Ischemic preconditioning, freestyle swimming, fatigue recovery, anti-inflammatory, antioxidant.

Introduction

Swimming is a high-intensity, full-body endurance sport that demands significant muscle strength, endurance, and aerobic capacity from athletes. During high-intensity swimming training, due to the limited breathing rhythm, the entire body must frequently coordinate muscle efforts, leading to the rapid accumulation of metabolic by-products and hypoxia (Aujouannet et al., 2006). These factors cause muscle fatigue and exhaustion, accompanied by increased oxidative damage and inflammatory responses (Sanderson et al., 2020). Effective fatigue recovery not only directly influences an athlete's short-term performance but also impacts their long-term competitive state and overall health. Therefore, improving recovery efficiency after intense training is a key challenge in swimming training. Currently, external recovery methods used following high-intensity swimming training include low-intensity swimming (40% - 60% of maximum intensity), stretching, massage, foam rolling, and the use of fascia guns (Toubekis et al., 2011). While these methods help relax muscles to varying degrees, they fail to address the primary causes of skeletal muscle fatigue after intense swimming, which are energy depletion, oxidative stress, and inflammation. These relaxation techniques primarily improve physical aspects, such as muscle stiffness and joint mobility, but do not induce internal physiological changes. Cold Water Immersion (CWI), as a swim-specific intervention to facilitate endogenous recovery, has been demonstrated to effectively mitigate muscle fatigue and inflammatory responses (Xiao et al., 2023). However, its application often requires sophisticated equipment and specialized facilities, thereby limiting its widespread adoption. Therefore, exploring endogenous methods that are simple to implement and promote fatigue recovery is expected to offer a promising new direction for accelerating recovery.

Ischemic preconditioning (IPC) is a relatively new recovery method, initially introduced for cardiovascular protection (Przyklenk et al., 1993). IPC involves brief cycles of ischemia and reperfusion in the limbs or heart, inducing local tissue tolerance and reducing damage from subsequent ischemic events. This process activates endogenous protective mechanisms, including the activation of antioxidant enzymes, increased antioxidants production, and modulation of cellular signaling pathways, which help reduce oxidative stress and inflammation associated with ischemia-reperfusion (Downey et al., 2007). Based on these mechanisms, IPC has gradually been extended to the protection of skeletal muscles, particularly in exercise contexts. Studies have shown that IPC can increase VO_2 max by 3% before cycling exercises (De Groot et al., 2010) and improve 100m swimming performance by 0.7s (Jean-St-Michel et al., 2011). In recent years, IPC's effectiveness in promoting post-exercise recovery has gained increasing attention. Research indicated that IPC can reduce inflammation in low- to moderate-level marathon runners (Mieszkowski et al., 2020), promote recovery after 5km cycling time trials (Paradis-Deschenes et al., 2020), aid in recovery from upper and lower limb exercise-induced muscle damage (Franz et al., 2018; Patterson et al., 2021), and facilitate recovery after simulated tennis matches (Xin et

Received: 27 February 2025 / Accepted: 05 August 2025 / Published (online): 01 September 2025

al., 2024). Unlike traditional post-exercise recovery methods, IPC serves as a pre-exercise intervention that establishes a "pre-conditioning" state in muscles through repeated ischemia-reperfusion cycles, enhancing fatigue resistance during high-intensity exercise and accelerating post-exercise recovery. Additionally, the effect of IPC on post-exercise fatigue recovery seems to be dose-dependent (Patterson et al., 2021). Both AIPC and repeated ischemic preconditioning (RIPC) have been shown to promote the recovery of maximal voluntary contraction strength in the lower limbs after eccentric exercise, with RIPC demonstrating a faster recovery rate (101.5%) at 48 hours post-exercise compared to AIPC (92.6%). This suggests that RIPC may be more effective than AIPC in promoting the recovery of maximal strength in the lower limbs following eccentric exercise (Patterson et al., 2021).

While the benefits of IPC have been demonstrated in various land-based sports such as cycling and running, it is essential to consider the unique physiological demands of swimming that may modulate IPC's efficacy. Unlike upright endurance activities, swimming is performed in a horizontal posture, which alters cardiovascular loading and venous return. Moreover, swimmers experience intermittent hypoxia due to breath-hold cycles and restricted ventilatory patterns during stroke execution (Arce-Álvarez et al., 2021). These characteristics create distinct systemic and muscular oxygenation challenges, potentially enhancing the relevance of IPC, which mimics hypoxic stimuli to induce endogenous protective responses. Therefore, investigating IPC within the context of swimming is not only scientifically justified but also essential for understanding its sport-specific recovery and performance benefits. Although previous studies have explored the effects of IPC on the athletic performance of swimmers (Ferreira et al., 2016; Jean-St-Michel et al., 2011; Williams et al., 2021), no research has yet explored the effects of IPC on fatigue recovery following high-intensity swim training. During swimming competitions, athletes are exposed to high training demands, intensive schedules, and prolonged pre-race waiting periods. These factors can significantly impact fatigue levels and recovery efficiency. IPC offers a potential strategy to alleviate fatigue and enhance recovery outcomes. Therefore, this study aimed to investigate whether IPC, as a preconditioning strategy, can effectively accelerate recovery after intensive swim training. Specifically, the study compared the effects of AIPC and RIPC applied over 7 consecutive days. The hypothesis was that RIPC will be more beneficial for fatigue recovery following high-intensity training in swimmers, compared to AIPC and SHAM. This hypothesis is supported by previous studies showing that RIPC can improve fatigue recovery more effectively than AIPC (Patterson et al., 2021).

Methods

Participants

Thirty male university students specializing in swimming participated in this study. All eligible participants were enrolled, and none dropped out. The inclusion criteria for participants were as follows: 1) participants must have at least two years of training experience and have trained at least three times per week; 2) Participants were national level-2 swimmers, with 200-meter freestyle completion times ranging from 2minutes 3 seconds to 2 minutes and 23 seconds, currently in their regular training phase. 3) no history of cardiovascular diseases, sports injuries, or other contraindications for participation; 4) no consumption of alcohol, coffee, strong tea, or nutritional supplements was allowed within the two months prior to the experiment; 5) Participants had never used ischemic preconditioning. Prior to the experiment, participants were informed of the study procedures, risks, and requirements by the principal investigator and signed an informed consent form. During the study, participants were instructed to refrain from intense physical activity, avoid other exercise interventions, and abstain from alcohol, caffeinated drinks, and other supplements aimed at promoting fatigue recovery. They were also asked to maintain a normal diet and daily routine and record their dietary intake. The study was approved by the Ethics Committee (approval number: 2022182H), and all procedures followed the ethical standards of the 2013 revision of the Helsinki Declaration. The sample size was determined using G*Power with the following parameters: effect size (f) = 0.25 (based on Beaven et al. (2012), who reported a moderate effect of IPC on repeated sprint performance), significance level (α) = 0.05, and desired statistical power (1-β) = 0.80. Considering the three groups and four measurement time points, with a correlation of 0.5 between repeated measures and assuming sphericity (ε = 1), the minimum required sample size was calculated to be 30 participants (10 per group). Table 1 shows the basic characteristics of the participants. There were no significant differences in age, height, weight, body mass index (BMI), or years of training among the groups ($P > 0.05$).

Study design

Thirty participants were randomly assigned to one of three groups: SHAM, AIPC, or RIPC. The randomization was achieved by generating a random numerical sequence on the website (www.randomization.com, accessed on September 26, 2022). Ten days before the intervention, venous blood samples were collected from all participants, and limb circumference and exercise performance tests were conducted. Five days prior to the intervention, participants performed a 200-meter freestyle test between 9:00 and

Table 1. Physical characteristics of the participants.

Group	SHAM (n = 10)	AIPC (n = 10)	RIPC (n = 10)	P value
Age (y)	20.6 ± 1.2	20.7 ± 0.7	20.6 ± 1.2	0.969
Training years (y)	2.4 ± 0.5	2.3 ± 0.5	2.2 ± 0.4	0.647
Training frequency (times/week)	2.3 ± 0.5	2.4 ± 0.5	2.2 ± 0.4	0.589
Height (cm)	179.2 ± 3.6	181.2 ± 3.9	179.2 ± 3.6	0.498
Weight (kg)	70.4 ± 7.6	77.9 ± 7.1	75.6 ± 11.1	0.167
BMI	21.9 ± 1.7	23.7 ± 1.8	23.5 ± 2.8	0.160

Values are presented as mean ± SD.

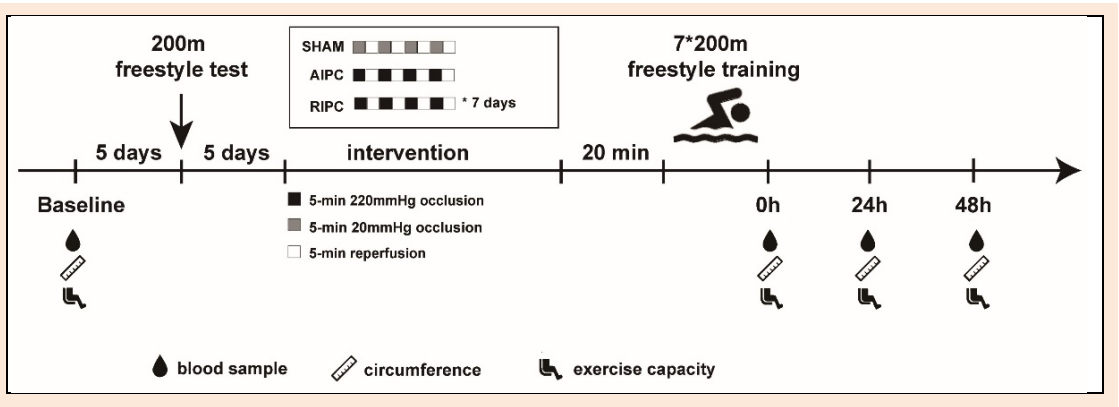

Figure 1. Study design. The interventions for the three groups of participants were conducted in separate rooms.

10:00 AM to establish their baseline performance level for high-intensity training. The RIPC group underwent a continuous 7-day intervention, while the AIPC and SHAM groups received a single-day intervention. Twenty minutes after the intervention, all participants completed a 7×200m incremental high-intensity swimming training session between 9:00 and 10:00 AM. To control for circadian variation, all measurements—including venous blood sampling, limb circumference, and exercise performance tests—were conducted between 10:00 and 11:00 AM at baseline, and at 0-, 24-, and 48-hours post-training (Patterson et al., 2021). The overall experimental procedure is shown in Figure 1.

200m freestyle test protocol

The 200m freestyle test was performed only once to determine individualized training intensity. Our 200m freestyle test protocol was based on the method described by Gurton et al. (Gurton et al., 2025). The test was conducted in a standard 50-meter swimming pool, with water temperature controlled between 26 - 28°C to ensure environmental stability. According to the facility's environmental control system, the ambient air temperature during the study period was maintained at approximately 26 - 28 °C, with relative humidity around 55 - 65%. Participants rested for 10 - 15 minutes prior to the test to ensure they were fully energized (Neiva et al., 2017). Each participant swam 200 meters at maximum effort, with the time taken recorded. After the test, participants were given 5-10 minutes of light recovery swimming at 40 - 60% intensity.

Intervention protocol

Participants in the SHAM and AIPC groups underwent a single intervention, while those in the RIPC group underwent a continuous 7-day intervention. The 7-day duration of RIPC intervention was selected based on existing literature suggesting a dose–response relationship of IPC (Patterson et al., 2021; Xin et al., 2024), where longer or repeated protocols may induce more pronounced and sustained recovery effects. Furthermore, a 7-day protocol aligns well with the typical weekly microcycle of swim training, enhancing both feasibility and participant compliance. The interventions for the three groups of participants were conducted in separate rooms. During the intervention, participants lay in a supine position, with cuffs (Yuwell Medical Equipment, China, width: 15 cm) placed on the proximal thighs. A 5 minutes blood flow occlusion was followed by 5 minutes of reperfusion, repeated 4 times for a total duration of 40 minutes. The occlusion pressure for the AIPC and RIPC groups was set to 220 mmHg, while for the SHAM group, it was set to 20 mmHg. Previous studies have shown that 4 cycles of 5-minute occlusion at 220 mmHg is safe for swimmers (Ferreira et al., 2016) and has been shown to effectively block blood flow and promote fatigue recovery (Griffin et al., 2018; Marocolo et al., 2016). We used color Doppler ultrasound (LOGIQ E9, General Electric, Boston) to monitor the blood flow occlusion. At a 220-mmHg occlusion pressure, the blood flow in the anterior tibial artery was completely blocked, while at a 20-mmHg pressure, the blood flow in the anterior tibial artery was not blocked. All ultrasound operations were conducted by physicians trained in ultrasound imaging.

Training protocol

The training protocol used in this study was adapted from the submaximal intensity swimming protocol used by Jean-St-Michel et al.(2011), with further details provided in Table 2. The target time for each 200m swim during training was calculated based on each participant's individual 200m freestyle performance, ensuring that the exercise intensity and workload were as consistent as possible across all participants. The target time for the first 200m was set to each participant's personal best time plus 35 seconds. Subsequently, the target time for each subsequent 200m swim was reduced by 5 seconds per set, with the 7th set aimed at the personal best time plus 5 seconds. Rest intervals and exercise duration were kept constant across all groups.

Table 2. Training protocol.

Training Part	Specific Content
Warm-up	300 freestyle swim 2 * 50m freestyle swim (25m kicking / 25m relaxed swim) 4 * 50m freestyle swim (15m kicking / 35m relaxed swim)
Main Training	7 * 200m freestyle swim (progressive load training)
Cool-down	300m relaxed freestyle swim Static stretching of deltoids, pectoralis major, quadriceps, gluteus maximus, and hamstring group

To ensure the adherence and performance of participants during the training process, completion status was systematically monitored using two key metrics: completion time and exercise heart rate. Completion time was designated as the primary evaluation criterion. Tasks completed within the predefined time frame were considered satisfactory. For tasks exceeding the prescribed time limit, exercise heart rate was employed as an auxiliary assessment parameter. Specifically, if the exercise heart rate reached or exceeded 80% of the participant's maximum heart rate, the task was likewise deemed to meet the established standards. The maximum heart rate was estimated using the commonly applied formula HRmax = 208 - 0.7 × age (Tanaka et al., 2001).

Limb circumference

Measurements were taken for the circumference of the upper arms, shoulders, and thighs on both sides. The upper arm circumference was measured during maximum contraction of the biceps muscle. Participants raised their arms diagonally at approximately a 45-degree angle with palms facing up while flexing their elbows. The examiner wrapped a measuring tape around the “muscle peak” of the biceps and kept it in place as the participant slowly straightened their arm, ensuring the tape was in full contact with the skin surface. Shoulder circumference was measured with the participant in the standard anatomical position. A measuring tape was placed around the upper chest, passing over the highest points of the deltoid muscles on both shoulders. For thigh circumference, in the standard anatomical position, the midpoint between the greater trochanter and the lateral epicondyle of the femur was identified, and the tape was wrapped around this midpoint. All readings were recorded to one decimal place. To ensure consistency across the four measurement sessions, semi-permanent markers were used to mark the measurement sites. A single examiner performed all measurements throughout the experiment.

Grip strength

Grip strength was assessed using a handgrip dynamometer (CAMRY EH101, USA). Before testing, participants adjusted the grip width to fit their hand size, allowing for maximum force exertion. Participants stood upright with their feet naturally apart, holding the dynamometer without it touching their body or clothing, keeping the device as steady as possible. Testing started with the right hand followed by the left hand without a break between sides. After the left-hand test, participants rested for 30 seconds before repeating the test, with each hand being tested three times. The same standardized verbal encouragement was provided to all participants during all performance tests to ensure consistency and maximize effort. The average of the three trials was recorded. The testing procedure was based on a previously published protocol (Xin et al., 2024).

Upper limb total work

Upper limb total work was assessed using a swimming isokinetic ergometer (JIEYI ISE-III, China). The swimming isokinetic ergometer is a specialized apparatus designed for the assessment of sport-specific strength and technical execution in swimmers (Nordsborg et al., 2021). It facilitates the simulation of stroke mechanics and enables precise measurement of force output under controlled isokinetic conditions. Participants lay prone on the ergometer with their face down, performing a full range of arm movements from complete extension to full flexion. Prior to testing, participants warmed up for 5 minutes, which included two sets of 2-minute light pulling exercises, followed by a 1-minute rest. Participants then completed a 10-second maximal pulling test at a resistance level of 5, with the total work completed during the 10 seconds recorded.

Lower limb isokinetic test

Knee isokinetic muscle strength was measured by an isokinetic muscle strength testing system (Biodex System 4, USA). Participants were seated with their hips and trunk stabilized using straps to prevent compensatory movements. The seat was adjusted so that the back of the participant’s knee was about a fist-width away from the front edge of the chair. The seat height was aligned so that the axis of the dynamometer matched the lateral epicondyle of the femur. Range of motion was set to 0-80°, and the limb weight was measured for gravity compensation. Testing started with the right leg performing 5 repetitions at an angular velocity of 60°/s, followed by a 1-minute rest, and then 25 repetitions at 240°/s. After a 2-minute rest, the left leg underwent the same testing protocol. Record the relative peak torque of the quadriceps during the 5 repetitions of knee flexion and extension performed at an angular velocity of 60°/s, and the average power of the quadriceps during the 25 repetitions of knee flexion and extension performed at an angular velocity of 240°/s. The testing procedure was based on a previously published protocol (Zihan et al., 2024).

Blood sampling

Blood samples were collected at four time points: pre-intervention, immediately post-training, 24 hours post-training, and 48 hours post-training. All samples were collected between 1:00 PM and 3:00 PM to control for potential circadian variation. Fasting venous blood (5 mL) was drawn from the elbow and immediately centrifuged at 3,500 rpm for 10 minutes at 4°C. The processed serum samples were stored at -80°C for further analysis. Serum MDA levels were determined using a thiobarbituric acid (TBA) assay kit (Nanjing Jiancheng Bioengineering Institute, China). Serum SOD activity was measured using a hydroxylamine oxidation method kit (Nanjing Jiancheng Bioengineering Institute, China). Total antioxidant capacity (T-AOC) was assessed using the ABTS method with a commercial kit (Nanjing Jiancheng Bioengineering Institute, China). Serum GSH levels were determined using a microplate method kit (Nanjing Jiancheng Bioengineering Institute, China). Serum CRP and IL-6 levels were measured by enzyme-linked immunosorbent assay (ELISA) kits (Jianglai Bio, Shanghai, China). Serum CK levels were analyzed using an automated biochemical analyzer (UniCel DxC 600 Synchron, Beckman Coulter, USA).

Statistical analysis

Basic demographic data between groups were analyzed using one-way ANOVA. Prior to ANOVA, the normality of the data was assessed using the Shapiro–Wilk test, and the

homogeneity of variances was examined using Levene's test. External and internal load indicators were analyzed using a two-way repeated measures ANOVA (factors: group, time). If a significant interaction effect was found, simple effects analysis was performed for each factor; if no interaction effect was detected, only main effects were analyzed. Statistical significance was set at $P < 0.05$. The effect size (ES) for main effects and interactions was determined using partial η^2, categorized as small (0.01 - 0.059), medium (0.06 - 0.137), and large (> 0.137) (Richardson, 2011). For significant interactions, Bonferroni post hoc comparisons were conducted. The sphericity assumption was tested using Mauchly's test. In cases where the sphericity assumption was violated, Greenhouse-Geisser corrections were applied. Effect sizes for pairwise comparisons were determined using Cohen's d, categorized as large (d > 0.8), medium (d between 0.8 and 0.5), small (d between 0.49 and 0.20), and very small (d < 0.2). Statistical analyses were conducted using IBM SPSS 27.0 (SPSS, Chicago, IL, USA), with data presented as mean ± standard deviation (mean ± SD).

Results

No significant interaction effects were found for bilateral upper arm circumferences (all $P > 0.05$). However, significant main effects of time were observed (left: $P < 0.001$, $\eta^2 = 0.335$; right: $P < 0.001$, $\eta^2 = 0.336$). The circumferences of both arms were significantly greater immediately after training and at 24 hours post-training compared to baseline (left: $P < 0.001$, $P = 0.040$; right: $P < 0.001$, $P = 0.024$). Similarly, for bilateral thigh circumferences, no significant interaction effects were found (all $P > 0.05$), but significant main effects of time were identified (left: $P < 0.001$, $\eta^2 = 0.264$; right: $P < 0.001$, $\eta^2 = 0.342$). Both thighs showed significantly greater circumferences immediately after training and at 24 hours post-training compared to baseline (all $P < 0.001$). For shoulder circumference, there were no significant interaction effects ($P > 0.05$), but a significant main effect of time was detected ($P < 0.001$, $\eta^2 = 0.333$). The shoulder circumference was significantly greater immediately post-training compared to the baseline ($P < 0.001$).

Figures 2A-C illustrate changes in upper limb exercise performance. Significant interaction effects were observed for total upper limb work ($P < 0.001$, F=9.778, $\eta^2 = 0.420$). Across all post-training time points, the RIPC group demonstrated significantly higher total work compared to the SHAM group ($P = 0.029$, Cohen's d = 1.14, 95% CI [0.13, 2.15]; $P = 0.033$, Cohen's d = 1.05, 95% CI [0.05, 2.05]; $P = 0.043$, Cohen's d = 1.04, 95% CI [0.04, 2.04]). Additionally, at 48 hours post-training, the AIPC group showed significantly higher total work than the SHAM group ($P = 0.045$, Cohen's d = 1.16, 95% CI [0.15, 2.18]). However, for bilateral grip strength, no significant interaction effects were found (all $P > 0.05$), but significant main effects of time were identified (left: $P < 0.001$, $\eta^2 = 0.376$; right: $P < 0.001$, $\eta^2 = 0.409$). Bilateral hands showed significantly lower grip strength immediately after training and at 24 hours post-training compared to baseline (all $P < 0.001$).

Figures 2D-G present changes in lower limb exercise performance. There was no significant interaction effect on the relative peak torque of bilateral quadriceps (all $P > 0.05$), only a main effect of time (Left: $P < 0.001$, $\eta^2 = 0.394$; Right: $P < 0.001$, $\eta^2 = 0.404$). Immediately after training and at 24 hours post-training, the relative peak torque of bilateral quadriceps was significantly higher than baseline values (all $P < 0.001$). Significant interaction effects were found for mean power of bilateral quadriceps (left: $P = 0.040$, F = 2.331, $\eta^2 = 0.147$; right: $P = 0.048$, F = 2.236, $\eta^2 = 0.142$). At all post-training time points, mean quadriceps power were significantly higher in the RIPC group than in the SHAM group (left: $P = 0.037$, Cohen's d = 1.11, 95% CI [0.10, 2.12]; $P = 0.007$, Cohen's d = 1.97, 95% CI [0.83, 3.12]; $P = 0.015$, Cohen's d = 1.81, 95% CI [0.69, 2.92]; right: $P = 0.036$, Cohen's d = 1.12, 95% CI [0.11, 2.13]; $P = 0.004$, Cohen's d = 2.10, 95% CI [0.93, 3.28]; $P = 0.017$, Cohen's d = 1.81, 95% CI [0.70, 2.93]). At 48 hours post-training, the AIPC group's mean quadriceps power was also significantly higher than that of the SHAM group (left: $P = 0.017$, Cohen's d = 1.29, 95% CI [0.25, 2.32]; right: $P = 0.028$, Cohen's d = 1.18, 95% CI [0.16, 2.19]).

Figure 3A illustrates the changes in muscle damage markers, showing a significant interaction effect for CK levels ($P = 0.038$, F = 2.650, $\eta^2 = 0.164$). At 24 hours post-exercise, CK levels in the RIPC group were significantly lower than those in the SHAM group ($P < 0.001$, Cohen's d = -1.44, 95% CI [-2.50, -0.39]), and this difference persisted at 48 hours post-exercise ($P = 0.008$, Cohen's d = -1.51, 95% CI [-2.58, -0.45]).

Figures 3B-C illustrate the changes in inflammatory markers. For CRP levels, no significant interaction effect was found ($P > 0.05$). However, a main effect of time was observed ($P = 0.012$, $\eta^2 = 0.161$), with CRP levels immediately post-exercise being significantly higher than baseline ($P = 0.011$). IL-6 levels showed a significant interaction effect ($P = 0.008$, F=3.153, $\eta^2 = 0.189$). Immediately post-exercise, IL-6 levels in the RIPC group were significantly lower than those in the AIPC and SHAM groups (RIPC vs. AIPC: $P = 0.024$, Cohen's d = -1.52, 95% CI [-2.59, -0.46]; RIPC vs. SHAM: $P < 0.001$, Cohen's d = -1.96, 95% CI [-3.10, -0.82]). At 24 hours post-exercise, IL-6 levels in both the AIPC and RIPC groups remained significantly lower than in the SHAM group (AIPC vs. SHAM: $P = 0.041$, Cohen's d = -1.50, 95% CI [-2.56, -0.43]; RIPC vs. SHAM: $P < 0.001$, Cohen's d = -1.87, 95% CI [-3.0, -0.75]).

Figures 4A-D display the changes in oxidative and antioxidative markers. SOD levels did not show a significant interaction effect ($P > 0.05$, $\eta^2 = 0.037$), but there was a main effect of time ($P < 0.001$, $\eta^2 = 0.037$), with SOD levels immediately post-exercise and at 24 hours post-exercise being significantly higher than baseline (all $P < 0.05$). T-AOC levels exhibited a significant interaction effect ($P = 0.041$, F = 2.581, $\eta^2 = 0.174$). Immediately post-exercise and at 24 hours post-exercise, T-AOC levels in the RIPC group were significantly higher than those in both the AIPC and SHAM groups (RIPC vs. AIPC: $P = 0.021$, Cohen's d = 1.19, 95% CI [0.17, 2.21]; $P = 0.030$, Cohen's d = 1.12, 95% CI [0.11, 2.13]; RIPC vs. SHAM: $P = 0.001$,

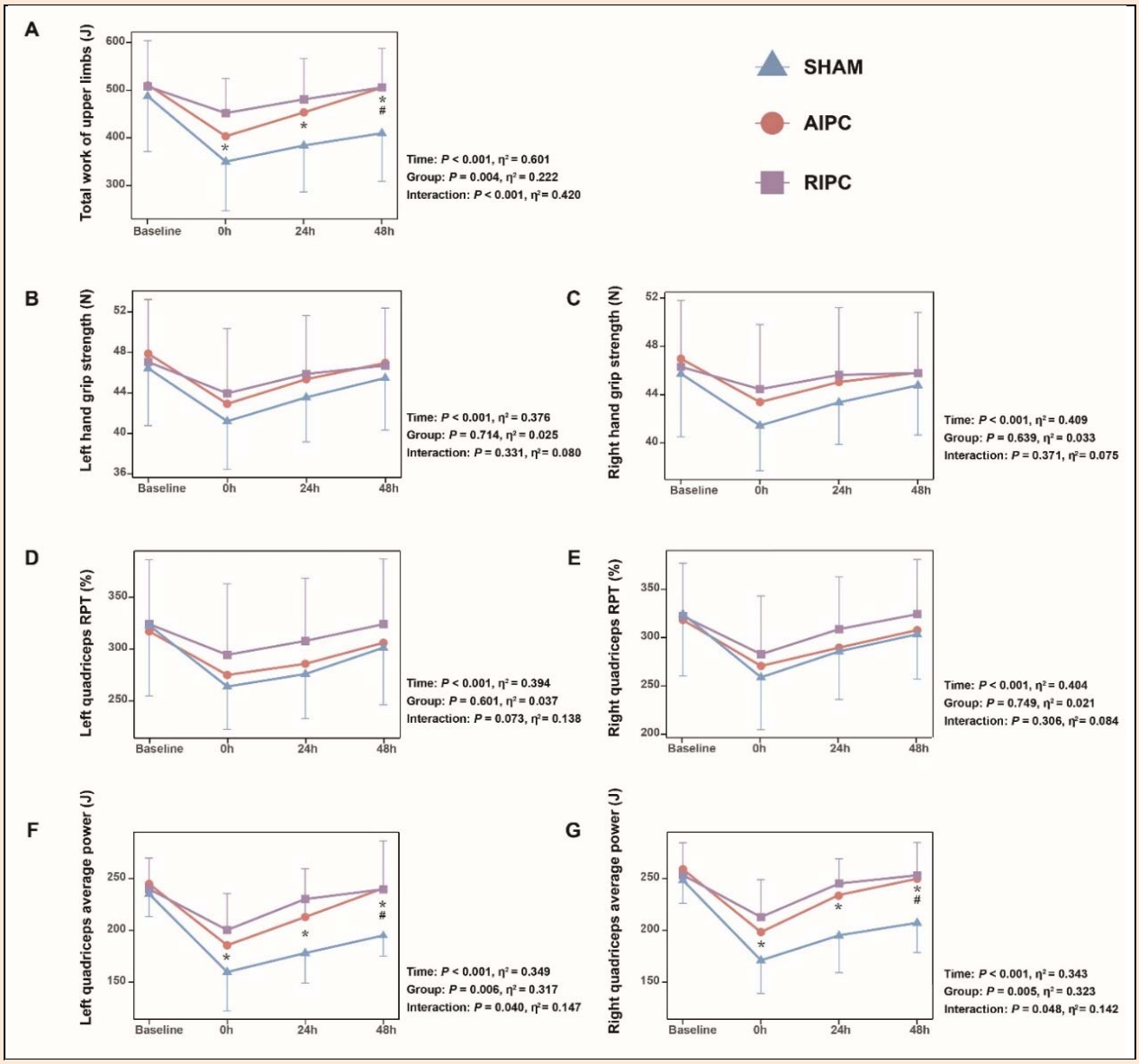

Figure 2. Changes in exercise capacity. RPT: relative peak torque. * Indicates a significant difference between RIPC and SHAM. # indicates a significant difference between AIPC and SHAM.

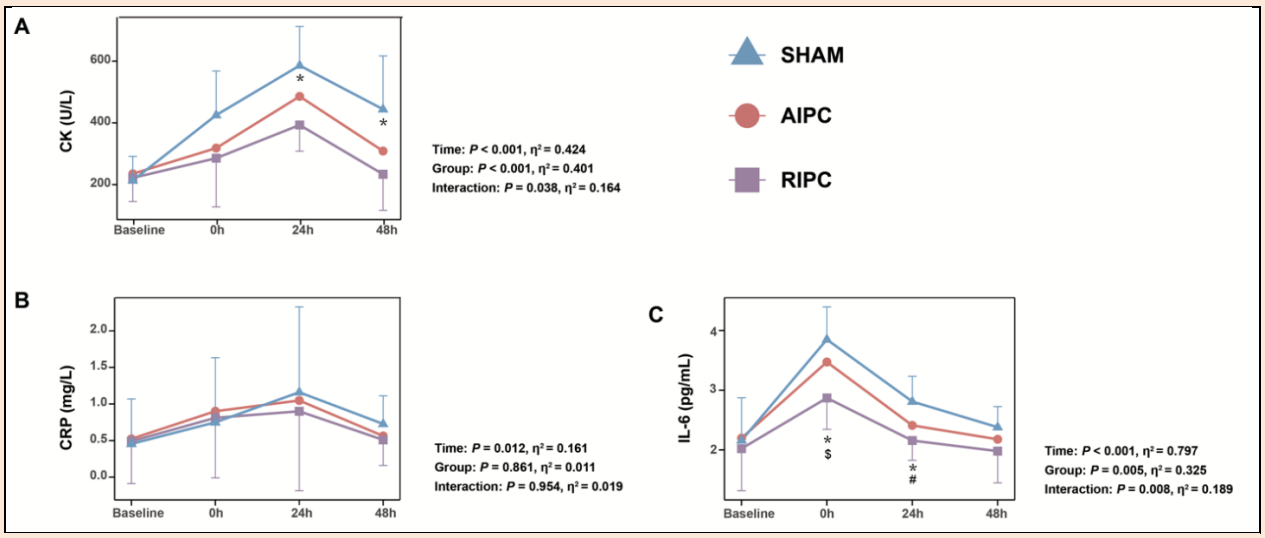

Figure 3. Changes in CK, CRP, and IL-6. * Indicates a significant difference between RIPC and SHAM. # indicates a significant difference between AIPC and SHAM. $ indicates a significant difference between RIPC and AIPC.

Cohen's d = 1.67, 95% CI [0.58, 2.76]; P = 0.001, Cohen's d = 1.32, 95% CI [0.29, 2.36]). MDA levels showed a significant interaction effect (P = 0.002, F = 3.864, η^2 = 0.208). Immediately post-exercise and at 24 hours post-exercise, MDA levels in the AIPC and RIPC groups were significantly lower than those in the SHAM group (AIPC vs. SHAM: P < 0.001, Cohen's d = -2.07, 95% CI [-3.23, -0.90]; P = 0.023, Cohen's d = -1.76, 95% CI [-2.87, -0.66]; RIPC vs. SHAM: P = 0.001, Cohen's d = -1.83, 95% CI [-2.94, -0.71]; P = 0.005, Cohen's d = -1.25, 95% CI [-2.27, -0.22]). Furthermore, immediately post-exercise, MDA levels in the RIPC group were significantly lower than those in the AIPC group (P = 0.014, Cohen's d = -1.43, 95% CI [-2.14, -0.31]). GSH levels also showed a significant interaction effect (P = 0.038, F = 2.594, η^2 = 0.161). Immediately post-exercise, GSH levels in the AIPC and RIPC groups were significantly higher than those in the SHAM group (AIPC vs. SHAM: P = 0.035, Cohen's d = 1.31, 95% CI [0.27, 2.34]; RIPC vs. SHAM: P = 0.001, Cohen's d = 1.75, 95% CI [0.64, 2.85]).

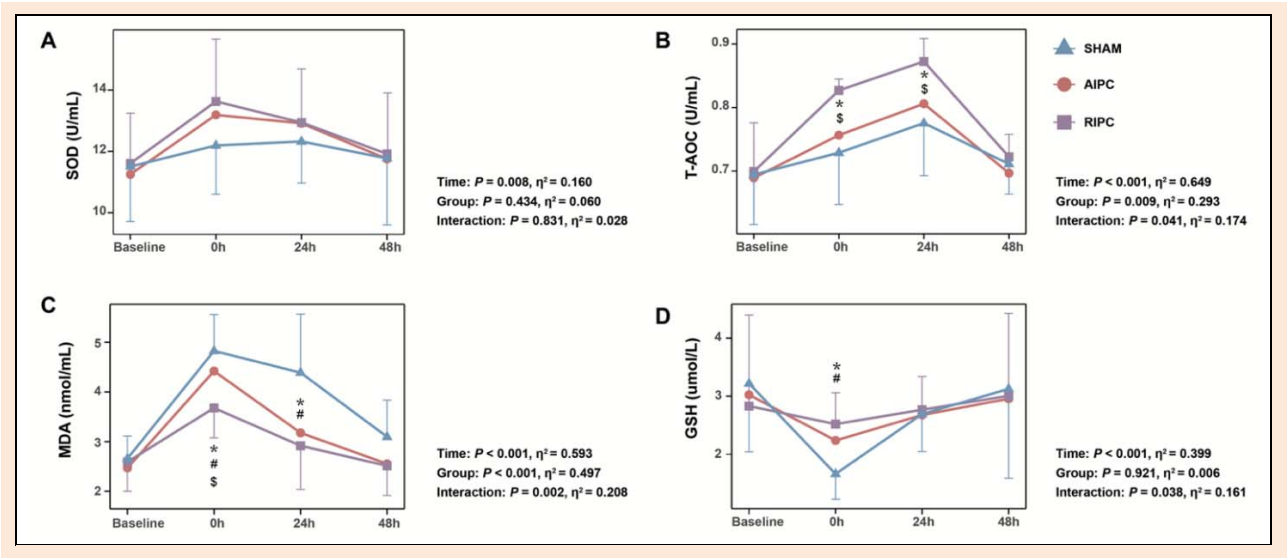

Figure 4. Changes in SOD, T-AOC, MDA, and GSH. * Indicates a significant difference between RIPC and SHAM. # indicates a significant difference between AIPC and SHAM. $ indicates a significant difference between RIPC and AIPC.

Discussion

This study systematically evaluated the effects of AIPC and seven consecutive days of RIPC on both internal and external load recovery in athletes following high-intensity swim training, covering limb circumference, exercise performance, muscle damage, inflammatory response, and oxidative stress markers. Results indicated that both AIPC and RIPC effectively supported recovery of internal and external loads after high-intensity swim training, with RIPC demonstrating superior benefits. These results confirmed our initial hypothesis. Specifically, both AIPC and RIPC significantly reduced inflammatory responses and oxidative stress levels, enhanced antioxidative capacity, and promoted performance recovery, with RIPC showing a notably greater ability to reduce inflammation, oxidative stress, and skeletal muscle damage compared to AIPC.

The seven-session 200-meter freestyle training protocol used in this study was adapted from Jean-St-Michel et al.'s submaximal swim training method (Jean-St-Michel et al., 2011), designed to induce fatigue in athletes through repeated high-intensity exercises. The choice of 200-meter freestyle—a moderate-distance event—was strategic, as it involves both aerobic and anaerobic metabolism, allowing for rapid accumulation of substantial physiological load in a short time frame. All participants completed the training protocol as required. Results confirmed that this protocol effectively induced exercise fatigue, as indicated by significantly elevated CK levels post-training (P < 0.001). Furthermore, the IPC protocols used in this study were standardized according to previous research (Daab et al., 2021; Patterson et al., 2021), improving the reproducibility and applicability of results while verifying the effectiveness of standardized IPC protocols under specific experimental conditions. Color Doppler ultrasound monitoring revealed that 220 mmHg occlusion pressure successfully achieved complete occlusion of the lower limb arteries without causing significant discomfort for participants.

Regarding external load, the RIPC group outperformed the AIPC group on several metrics. The RIPC group demonstrated significantly higher quadriceps mean power and total upper limb work at all post-training time points compared to the SHAM group. Notably, the large effect size for total upper limb work indicates that this enhancement is not only statistically significant but also practically meaningful, suggesting substantial benefits for muscle recovery and functional performance in athletic and rehabilitation settings. In contrast, the AIPC group only showed significant differences from the SHAM group at 48 hours post-training. Previous studies have shown that both AIPC and RIPC can promote the recovery of muscle strength following eccentric lower limb exercises, with RIPC being more effective than AIPC (Patterson et al., 2021). This study further validates this conclusion by examining both internal and external loads following swimming, thus supporting the application of IPC across

different sports. It is noteworthy that, although the IPC intervention site in this study was the bilateral thighs, a significant recovery in upper limb total power was observed, suggesting that IPC may have a remote effect. The transient ischemia–reperfusion induced by IPC can promote the release of vasoactive substances such as nitric oxide and adenosine, thereby enhancing microcirculation in remote muscle tissues (Marocolo et al., 2025). In addition, IPC may augment functional sympatholysis, a process in which active muscles exhibit a reduced vasoconstrictive response to sympathetic stimulation during exercise, facilitating increased local blood flow and oxygen delivery (Teixeira et al., 2023). These adaptations may contribute to improved recovery and performance in non-occluded muscle groups. Supporting this, previous studies have shown that IPC applied to the lower limbs can enhance endurance in the upper limbs (Barbosa et al., 2014). IPC may improve hemodynamics (Jones et al., 2014; Jones et al., 2015; Kimura et al., 2007; Moro et al., 2011; Teixeira et al., 2023) and enhance muscle oxygen supply (Kido et al., 2015; Paradis-Deschênes et al., 2017; 2020; Wiggins et al., 2019), which could partly explain its benefits in muscle strength recovery following high-intensity swim training. The enhanced effects of RIPC, compared to AIPC, may be attributed to IPC's temporal effects, which manifest in two phases characterized by a "biphasic" response: the first phase occurs immediately after IPC and lasts approximately 4 hours, while the second phase begins 24 hours post-IPC and can last up to 72 hours (Lisbôa et al., 2017; Loukogeorgakis et al., 2005). Thus, the use of RIPC may create a cumulative effect, effectively supporting muscle repair. Similarly, whole-body cryotherapy (WBC) has been shown to exert cumulative effects on post-exercise recovery (Pournot et al., 2011). However, while WBC reduces post-exercise swelling and inflammation by inducing vasoconstriction through temperature reduction (Costello et al., 2015), IPC's mechanism is believed to be related to enhanced blood flow during exercise (Teixeira et al., 2023). Additionally, IPC is simple to apply, cost-effective, and highly practical. Implementing RIPC during the training period before major competitions could help accelerate muscle recovery, reduce injury risk, and improve competitive readiness. Future studies may consider combining IPC with other recovery modalities such as WBC or CWI, to explore potential synergistic effects on post-exercise recovery.

This study also analyzed the effects of AIPC and RIPC on internal load recovery, including muscle damage (CK), antioxidative markers (T-AOC, SOD, GSH), oxidative stress (MDA), and inflammatory response (CRP, IL-6). The results showed that both AIPC and RIPC significantly facilitated internal load recovery after training by reducing inflammation and oxidative stress levels, while enhancing antioxidative capacity. This finding is consistent with previous research conducted in our laboratory (Zihan et al., 2024), further emphasizing the advantages of IPC in reducing oxidative stress and inflammation following swimming exercise. Moreover, this finding is consistent with two studies by Mieszkowski et al. involving marathon runners, in which a 10-day RIPC intervention effectively attenuated marathon-induced inflammation and oxidative stress(Mieszkowski et al., 2020; Mieszkowski et al., 2021). These results further support the broad applicability of IPC in mitigating internal load-related stress across different types of exercise. Interestingly, RIPC was significantly more effective than AIPC, particularly at 24- and 48-hours post-training, with CK levels in the RIPC group remaining significantly lower than those in the SHAM group, while no significant difference was observed between the AIPC and SHAM groups. Elevated CK levels may indicate more severe muscle damage, and the recovery period may be prolonged. The results of this study suggest that RIPC is more effective in promoting skeletal muscle recovery and reducing muscle damage following high-intensity swim training. As noted, RIPC for seven consecutive days can have an additive effect, thereby effectively reducing muscle damage after swimming training, shortening recovery time, and improving performance in subsequent training sessions or competitions. However, our findings contrast with those of Patterson et al. (Patterson et al., 2021), who reported that three days of RIPC did not significantly promote CK recovery following eccentric resistance exercise. Several methodological distinctions may account for this discrepancy. First, Patterson's study involved resistance-based eccentric loading, whereas our protocol utilized high-intensity, whole-body endurance exercise—specifically swimming—which elicits different mechanical, metabolic, and circulatory demands. These sport-specific physiological characteristics may modulate the efficacy of IPC. Second, our RIPC intervention was implemented over a longer period (seven consecutive days), potentially allowing both the immediate and delayed phases of IPC-mediated protection to exert cumulative benefits. These differences may explain the more pronounced improvement in CK recovery observed in our study. MDA is an important marker of oxidative stress, and following high-intensity training, oxidative stress levels typically increase, leading to enhanced cell damage and fatigue. The levels of T-AOC, SOD, and GSH reflect the status of antioxidant defense system. IPC may alleviate post-exercise oxidative stress and inflammation by increasing the activity of endogenous antioxidant enzymes, promoting antioxidant synthesis, and regulating cytokine release (Mieszkowski et al., 2020; Mieszkowski et al., 2021). This mechanism is particularly important for high-intensity sports like swimming, where prolonged training can lead to significant oxidative stress accumulation (Powers and Jackson, 2008), thereby increasing the risk of muscle fatigue.

However, immediately post-exercise and at 24 hours post-exercise, limb circumferences in the SHAM, AIPC, and RIPC groups significantly increased without significant differences between groups. While previous literature has suggested that IPC can significantly promote recovery of limb circumference after eccentric exercise (Patterson et al., 2021), this effect was not observed following swim training in this study. This discrepancy may be due to the relatively mild skeletal muscle damage associated with swimming, which involves reduced load-bearing in water compared to eccentric exercises, thus posing a lower risk of muscle micro-damage.

Consequently, IPC's impact on limb circumference recovery post-swimming may be less pronounced. Additionally, the well-trained participants in this study might have influenced these findings, as their prolonged training experience and consistent conditioning enable them to better adapt and recover from exercise-induced fatigue, facilitating rapid limb circumference recovery.

Several methodological considerations warrant discussion. First, only male participants were tested, as research by Teixeira et al. (Teixeira et al., 2023) and Paradis-Deschenes et al. (2017) suggested that IPC effects might vary by gender. Future research should explore potential sex differences in IPC responses. Secondly, the timing of blood sampling in this study was relatively limited, with wide intervals and measurements only extending to 48 hours post-intervention. This design may have missed the peak responses of certain cytokines following high-intensity exercise and potentially overlooked the delayed recovery effects of IPC beyond 48 hours. Previous research has suggested that the benefits of IPC may continue up to 72 hours after training (Patterson et al., 2021). Future studies should consider including additional blood sampling time points and extending the observation period to more comprehensively evaluate the time-course effects of IPC on exercise recovery. Third, sleep quality was not assessed, and baseline hydration status (e.g., urine specific gravity) was not controlled; although mean daily caloric intake was recorded, potential confounding effects of diet, sleep, and hydration remain unaddressed. Besides, athlete fitness levels and individual differences may also impact results; thus, future studies could investigate IPC responses across athletes of varying performance levels. To further support the application of this protocol in elite training environments, its efficacy should be validated not only through short-term interventions, as in this study, but also throughout an entire competitive season. Such long-term investigations would help clarify its impact on recovery, performance optimization, and injury prevention in real-world settings. Lastly, this study used a SHAM group instead of a blank control group. Although low-pressure SHAM is commonly used, it may still produce minor physiological effects, such as sensory input or altered blood flow. Without a blank control, it remains unclear whether the observed benefits are entirely attributable to IPC. Furthermore, we note that some studies have suggested that, compared to blank control group, IPC may have an adverse effect on anaerobic performance (Paixão et al., 2014). Based on this, future research could consider including a blank control group for further validate our findings.

Conclusion

In conclusion, both acute and repeated ischemic preconditioning can effectively promote external and internal load recovery after high-intensity swimming training compared to SHAM, with repeated applications of IPC being more effective than its acute application. Based on these findings, incorporating daily IPC sessions over a 7-day period in the lead-up to competition may be a practical strategy to support optimal recovery and performance in male amateur swimmers.

Acknowledgements

The authors gratefully acknowledge the financial support by the Fundamental Research Funds for the Central Universities under grant number 2024GCZX004 and 2025KYPT03, and the participants for their time during the study. The experiments comply with the current laws of the country in which they were performed. The authors have no conflict of interest to declare. The datasets generated during and/or analyzed during the current study are not publicly available but are available from the corresponding author who was an organizer of the study.

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Key points

- Both acute and repeated ischemic preconditioning (IPC) effectively promote recovery of external and internal loads following high-intensity swimming training compared to SHAM.
- Repeated IPC applications are more effective than acute IPC in promoting recovery.
- IPC can be a valuable tool for athletes to enhance recovery from intense training sessions, especially when applied repeatedly.

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