

Enhancing physical performance with ischemic preconditioning: a systematic review and meta-analysis of moderators and performance outcomes

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ABSTRACT: This study examined the effects of ischemic preconditioning (IPC) on physical performance, considering the influence of timing, warm-up (WU), participant characteristics, and IPC protocols structure. A total of 90 trials (1,439 participants) were retrieved from three databases and assessed using PICOS criteria. Multilevel meta-analyses with cluster-robust variance adjustments were conducted to calculate pooled effect sizes (Hedge's g). Risk of bias and certainty of evidence were assessed using the RoB 2 tool and GRADE framework. IPC produced a *trivial* but significant improvement in physical performance ($g = 0.13$, $P < 0.01$), which persisted after excluding SHAM effects ($g = 0.10$; $P < 0.01$). Significant improvements were observed for maximum repetitions, time to failure, and power output, but not for jump ability, strength, or oxygen uptake. Comparable benefits were found for anaerobic ($g = 0.15$) and aerobic ($g = 0.10$) exercise, with greater effects in males and less-trained participants. Performance was further enhanced when IPC was followed by WU ($g = 0.16$), with the optimal IPC-to-WU interval being ~42 minutes. Without WU, the effective IPC window narrowed to 6–7 minutes. In practice, IPC can enhance physical performance, independently of sham effects, moderated by sex, training level, and WU. For competition or testing, the most effective strategy appears to be 3 or 4 × 5-min IPC protocol, followed by a 42-min interval, standardized warm-up, and endurance testing. For mechanistic studies, WU should be excluded, and testing conducted 6–7 minutes post-IPC. Future research should target women, middle-aged individuals, and elite athletes.

CITATION: Zhang Y, Xu K, Kong H et al. Enhancing physical performance with ischemic preconditioning: a systematic review and meta-analysis of moderators and performance outcomes. *Biol Sport*. 2026;43:511–554.

Received: 2025-07-09; Reviewed: 2025-08-17; Re-submitted: 2025-08-30; Accepted: 2025-10-06; Published: 2025-10-31.

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Key words:

Blood flow restriction
Exercise performance
Ergogenic aids
Warm-up protocols
Time window
Training level
Placebo

INTRODUCTION

Researchers have long sought optimal interventions to enhance physical performance [1–4]. Ischemic preconditioning (IPC) has emerged as a promising intervention, showing significant physiological effects, such as reducing ischemia-induced ultrastructural damage and delaying irreversible myocardial injury [5, 6]. Additionally, IPC has been shown to decrease energy metabolism rates [6], enhance tolerance to subsequent ischemia [7], and preserve adenosine

triphosphate (ATP) levels through intermittent reperfusion [8]. Collectively, these mechanisms support the potential of IPC as a viable non-pharmacological intervention for enhancing athletic performance.

Despite decades of research, the efficacy of IPC in enhancing physical performance remains controversial [9]. Some studies report improvements in anaerobic performance, such as short-duration swimming [10, 11], the maximal number of repetitions (RM) in high-load

resistance exercises [12, 13], and performance in exhaustion tests [14, 15]. IPC has also been shown to enhance aerobic performance in tasks such as 5-km runs [16, 17], cycling time trials [18], incremental tests [18–20], and supramaximal intensity tests [21], while also increasing maximal oxygen uptake ($\dot{V}O_{2\max}$) [20, 21]. However, other research reports no significant performance enhancement following IPC in anaerobic-type efforts such as sprinting [22, 23], time trials [24, 25], jump ability [26], maximal voluntary contraction (MVC) force [27, 28], or one-repetition maximum (1RM) [29]. Likewise, IPC has not consistently improved aerobic-like efforts including time trials [30–34], time to exhaustion [35, 36], or $\dot{V}O_{2\max}$ [30, 37, 38].

Research suggest that IPC may exert a greater influence on aerobic than anaerobic physical performance. In their systematic review, Caru et al. [2] concluded that IPC enhances aerobic performance, primarily through improved oxygen utilization and reduced blood lactate production. A recent meta-analysis also demonstrated that IPC significantly reduces task completion time in activities predominantly reliant on aerobic metabolism and tends to extend time to exhaustion [39]. Although no significant improvement in $\dot{V}O_{2\max}$ was observed, this may be attributed to the already high training levels of participants, whose $\dot{V}O_{2\max}$ values were likely approaching their genetic ceiling [39]. Highly trained athletes may exhibit a diminished response to IPC, while individuals with lower training levels may derive greater benefits. However, these assumptions require confirmation through larger, well-controlled studies.

The time interval between IPC application and subsequent exercise testing is crucial to its efficacy [2]. That said, reported time intervals in the literature vary widely – from immediate to several hours – with no clear consensus. This inconsistency may stem from inconsistent reporting and a failure to account for the additive effects of WU included within the IPC-to-test timeline. For example, Kaur et al. [38] reported a 15-min interval between IPC and testing, but this actually included a 3-min WU and 2 min of measurement, extending the real interval to 20 min. Lisbôa et al. [40] found no performance improvement in a 50-m sprint swim 1-h post-IPC, yet significant improvements emerged at 2 and 8-h (i.e., intervals that also included a 20-min WU). Similarly, Richard et al. [25] reported a 1-h interval from IPC to testing, which also included a 20–40-min WU. These inconsistencies highlight the need for a systematic evaluation of IPC timing, as no standardized protocol currently exists. Establishing the optimal IPC-to-exercise interval is essential to maximize potential performance-enhancing effects and reduce variability across studies.

Previous meta-analyses have not fully accounted for key moderating factors, such as sex, age, standardized IPC and exercise protocols, and the additive effects of WU [39, 41, 42]. Controlling for WU is critical, as it is a well-established performance enhancer. For example, Souza et al. [41] reported IPC improved performance in exhaustion tests (standardized mean difference [SMD] = 0.51) and RM (SMD = 0.97) compared to CON, but not *versus* sham. This suggests that the observed IPC benefits may partly overlap with the

effects of WU, and inadequate control could underestimate of IPC's true effects beyond sham. Although Chen et al. [39] demonstrated that IPC could improve physical performance, such as enhancing exhaustive test results and reducing task completion time, they did not account for factors such as sham effect or the varying time intervals between IPC and testing, which ranged from immediate to 24 h in the included studies [39, 41]. This indicates that even recent meta-analyses have overlooked the importance to standardize interval times, despite previous research highlighting their variability [2]. Therefore, standardized protocols for both exercise and IPC interventions, particularly regarding WU and timing intervals, are needed to accurately isolate the true effects of IPC [41, 42].

The limitations of existing literature extend beyond IPC interval time definition to include methodological heterogeneity and demographic variables. For example, Souza et al. [41]'s recent meta-analysis extracted only one data point per study to avoid duplicate calculations, which likely underestimated the true effect size (ES), as multi-level meta-analyses can better account for multiple datasets within a single study [43–45]. Additionally, factors such as the inclusion of a SHAM control group, the incorporation of a WU, and ischemia-reperfusion parameters (e.g., duration) can significantly influence IPC outcomes. For instance, the sham effect may overestimate the true efficacy of IPC [41]. Demographic factors such as sex and age may also play a role. For example, Teixeira et al. [46] found sex differences in functional sympathetic responses during grip strength exercises following IPC. Specifically, IPC significantly enhanced functional sympatholysis in males (Δ –3% $\pm$ 9% vs. baseline Δ –8% $\pm$ 7%, P = 0.02) but not in females (Δ –5% $\pm$ 10% vs. baseline Δ –8% $\pm$ 9%, P = 0.13). Similarly, Pereira et al. [15] showed improved time to exhaustion after IPC in males only. Age-related physiological changes, such as reduced vascular elasticity and metabolic capacity, may also affect the efficacy of IPC in older populations. Despite extensive research, controversies persist regarding the optimal IPC protocols, particularly the timing of intervention, its effects on different exercise types (aerobic vs. anaerobic), and how athletes' training levels influence outcomes.

This study aims to evaluate the effects of IPC on physical performance and optimize its application protocols through meta-analysis and systematic review. The specific objectives include: (1) assessing the physical performance effects of IPC on anaerobic and aerobic performance; and (2) exploring potential moderators including participant characteristics (training level, sex, age) and study design factors (time intervals, sham effects, ischemia-reperfusion parameters, WU protocols, and exercise types) on IPC efficacy through subgroup and regression analyses.

MATERIALS AND METHODS

Registration of Systematic Review Protocol

The systematic review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines (Supplementary Material) [47]. The study was retrospectively

registered in PROSPERO (CRD42024614265) after the initial data analysis and chart preparation, but before the secondary search and re-analysis.

Search Strategy

Before the formal search, one author (Y.L.Z) conducted an abbreviated search. A systematic literature search was then performed by two independent reviewers (K.X and M.Y.Y) in PubMed (MEDLINE), Web of Science, and EMBASE, ending on 4 September 2024. The search terms included a combination of database specific MeSH terms and keywords: “remote ischemic preconditioning” OR “remote ischaemic preconditioning” OR “remote preconditioning” OR “remote

conditioning” OR “remote ischemic conditioning” OR “remote ischaemic conditioning” OR “transient limb ischemia” OR “muscle ischemia” OR “ischemic preconditioning” AND “performance” OR “sport*” OR “exercise” OR “strength training” OR “running” OR “swimming” OR “cycling” OR “athletes” OR “athletic performance”. When possible, human filters were added in each database (Detailed search terms for the different databases are provided in Supplementary Material). Additionally, reference lists of all identified studies were manually scanned for additional studies.

Study Selection and Eligibility Criteria

One author (Y.L.Z) performed the literature identification and screening. During the eligibility phase, two authors (K.X and M.Y.Y) reviewed the full texts, applying the exclusion and inclusion criteria. In cases of uncertainty, a third author (Y.L.Z) made the final decision. All processes were conducted using Zotero. The eligibility criteria, based on the “PICOS” framework (P, participants; I, intervention; C, control; O, outcome; S, study), are provided in Table 1.

TABLE 1. Inclusion and Exclusion criteria.

Inclusion criteria
P: Include healthy subjects of all ages (from adolescents to older adults) and covering a wide range of physical activity levels, from sedentary individuals to world-class athletes.
I: Intervention involves IPC combined with exercise, applied solely before exercise, not during or post-exercise/testing. Crossover studies must include CON, SHAM, and IPC groups. Groups without IPC were considered as CON, those with very low pressure (e.g., 20 mmHg) were considered as SHAM, and IPC was defined as the application of regular occlusion pressure, such as 220 mmHg.
C: Control groups for IPC must be SHAM (using lower pressure values) or CON (no ischemic conditions).
O: Include outcomes related to physical performance: balance, jump, strength, MAOD (maximal accumulated oxygen deficit), power output, repetitions, time trial performance, time-to-exhaustion tests, and $\dot{V}O_2$.
S: Include randomized controlled trials and randomized crossover studies.
Exclusion criteria
A. Exclude studies involving subjects with any medical conditions.
B. Exclude studies applying IPC during or after exercise/testing.
C. Studies combining IPC with other interventions (e.g., caffeine, hypoxia) are not excluded if they include IPC vs. CON/SHAM comparisons.
D. Exclude non-English publications.
E. Exclude non-human studies.
F. Exclude studies lacking physical performance outcomes.
G. Exclude reviews, meta-analyses, and conference abstracts.
H. Exclude non-IPC interventions (e.g., blood flow restriction) and long-term IPC interventions.
I. Exclude duplicate publications of the same experiment; retain only one version.

IPC, Ischemic preconditioning; SHAM/CON, SHAM/Control Group;

Risk of Bias Assessment

The Cochrane Risk of Bias 2 (ROB2 IRPG beta and ROB2 crossover beta) tool was used to assess the risk of bias in randomized controlled trials (RCTs) and randomized crossover trial (RC) studies meeting the inclusion criteria [48]. The tool evaluates five domains: (D1) randomization process, (DS) period/carryover effects, (D2) deviation from intended intervention (assignment effects and adherence), (D3) missing outcome data, (D4) outcome measurement, and (D5) selection of the reported result. Each domain was rated as “yes,” “probably yes,” “probably no”, or “no”. Bias risk was classified as “high”, “some concerns”, or “low” according to Cochrane’s guidelines [49]. A study was rated “high risk” if at least one domain was high risk, “some concerns” if at least one domain raised concern but none were high risk, and “low” if all domains were rated low [49]. Two reviewers independently assessed the domains and physical performance bias qualification for each study, with discrepancies resolved by a third reviewer.

Data extraction and collation

We meticulously extracted study characteristics including participants’ sex, age, exercise experience, the number and duration of IPC cycles, cuff pressure, limb location, WU content and intensity, IPC timing relative to WU and testing, interval times between different IPC timings, exercise types, and pre- and post-test outcome data for IPC, SHAM, and CON groups. We strictly defined interval times, specifying whether they referred to the period from IPC to testing or from IPC to WU. This distinction was necessary as some studies included WU within the interval, while others did not.

Studies were categorized as anaerobic and aerobic based on exercise duration (75 s) [50, 51]. For each outcome, three reviewers carefully reviewed the exercise protocols to determine the total duration. Exercises lasting more than 75 seconds were classified as

aerobic, while those lasting 75 seconds or less were classified as anaerobic. Studies including both types were categorized separately. Classifications were conducted by H.K. and K.X., with disagreements resolved by Z.Y.L. The exercise experience level of participants was classified into six categories (0–5) according to McKay et al. [52]’s criteria: sedentary, recreationally active, developing or trained, highly trained or national level, elite or international level, and world-class athletes. WU content was classified as maximal if it met the “RAMP” criteria [53]; otherwise, it was considered submaximal. These classifications were derived from the original descriptions in the included studies. If participant experience levels were not detailed, they were assigned to the lowest level (i.e., “0.”).

The age of participants was analyzed based on the mean values provided in the original studies. When an age range (e.g., 18–35 years) was given, the median value was used. If separate ages for IPC, SHAM, or CON groups were provided, the average age was calculated by summing all ages and dividing by the number of groups. In studies comparing local and remote IPC or other parameter-related comparisons, data were combined (e.g., remote IPC vs. SHAM and local IPC vs. SHAM were merged into IPC vs. SHAM). For studies with incomplete data, we contacted the authors via email to request the full dataset, especially when only post-hoc comparisons were provided without specific pre- and post-test data. For studies with data presented graphically, we used a data extraction tool (WebPlot-Digitizer – Copyright 2010-2024 Ankit Rohatgi) to extract the data. When comparing the number of IPC interventions (e.g., one intervention 48 h before testing, one 24 h before testing, and one 15 min before testing), only the data from the 15 min pre-test intervention (one intervention) were extracted and compared with CON or SHAM data [54].

When extracting time trial data, we encountered studies that provided total distance and speed. In these cases, we calculated the time using the formula: time = distance / speed. Additionally, for studies presenting data as IPC responders and non-responders, or providing individual participant data instead of group data, we extracted the data for each participant and recalculated the mean and standard deviation [55].

Statistical Analysis

Data Synthesis and Effect Measures

In the included studies, two comparison formats were identified:

- 1) Between-group post-test comparison: in this format, IPC, CON, and SHAM groups lack pre-test data, and only post-test results are directly compared (IPC_{post} vs. CON_{post} , IPC_{post} vs. $SHAM_{post}$);
- 2) Pre-post change value comparison: this format involves groups (IPC, CON, and SHAM) with both pre- and post-test data. The change values for each group are calculated, and differences in change magnitudes between groups are then compared.

To establish a unified analytical framework, for the first type of comparison (groups lacking pre-test data), we set the pre-test values

to baseline (Mean = 0, SD = 0). We then compared the differences between groups using change values. Additionally, as part of the sensitivity analysis, a comparison model using only post-test data was established to verify the robustness of the study conclusions. The following formulas were used to calculate change values and ES:

$$M_{\text{change}} = M_{\text{post}} - M_{\text{pre}}$$

$$SD_{\text{change}} = SD_{\text{pre}}^2 + SD_{\text{post}}^2 - (2 \times r \times SD_{\text{pre}} \times SD_{\text{post}})$$

$$ES =$$

$$\sqrt{\frac{(M_{\text{post}} - M_{\text{pre}})}{SD_{\text{pooled}}} \times \left(1 - \frac{3}{4(n_1 + n_2 - 2) - 1}\right)}$$

where M_{post} and M_{pre} are the means of the pre- and post-test performances of the IPC or CON or SHAM; n_1 and n_2 are the sample sizes of the pre- and post-test performances of the IPC or CON or SHAM; and SD_{pooled} is the pooled standard deviation of the measurements [56]. The pre-post correlation coefficient r was set to 0.6, followed by a sensitivity analysis across the range of 0.5 to 0.9. The ES was calculated as Hedge’s g , adjusted for small sample bias.

When standard errors (SE) were reported, SD was calculated using:

$$SD = SE \times \sqrt{N}$$

ES values were classified as *trivial* (0.2), *small* (0.2–0.5), *medium* (0.5–0.8), and *large* (> 0.8) [57].

Heterogeneity was evaluated using I^2 , τ^2 , and Q tests, with I^2 of 25%, 50%, and 75% indicating *low*, *moderate*, and *high* heterogeneity, respectively. The Q test was considered significant at $p < 0.1$. These indicators represent both relative and absolute values of residual heterogeneity, reflecting the amount of unaccounted variability attributed to residual heterogeneity. Prediction intervals (PI) were calculated to account for potential variability in similar future studies.

Multi-Level Meta analysis

Given the characteristics of multiple groups and ES in the included IPC studies, a multilevel mixed-effects model was employed for analysis [43–45, 58]. Specifically, the model incorporated study, comparison type (IPC vs. CON, IPC vs. SHAM), and within-group ES as explicitly nested random intercepts (i.e., within-group ES nested within comparisons, and comparisons nested within studies). The goodness-of-fit of this model was compared to traditional two-level and three-level models, with the final model selected based on the Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) criteria [59]. Effects were weighted by inverse sampling

variance to account for within-level, comparison-study, and between-study variance [60].

We employed cluster-robust variance estimation [44] methods with small-sample adjustments [61] to account for within-study correlations between ES. Assuming a within-study correlation of 0.6, sensitivity analyses with correlations of 0.4 and 0.8 showed no differences in the meta-analysis outcomes. Model parameters were estimated using the Restricted Maximum Likelihood method. Individual coefficients and their corresponding confidence intervals (CI) were tested using a t-distribution [59]. Three-level meta-analyses were conducted using the *metafor* package in R (version 4.3.0; R Core Team, Vienna, Austria) [62], while cluster-robust variance estimation and small-sample adjustments were implemented using the *clubSandwich* package [63, 63].

Subgroup and Meta-regression Analysis

Subgroup analyses were conducted on dichotomous moderating variables including sex, comparison type, participants' training experience, IPC sets, presence of WU, and measurement outcomes to explore their influence on IPC effects. Regression analyses were conducted to determine the optimal IPC timing to enhance physical performance. All models were compared using linear and various

non-linear meta-regressions, including simple linear, cubic polynomial (with 2 and 3 knots), restricted cubic spline (with 3 and 4 knots), and natural cubic spline. Furthermore, a range of models were fitted and compared with (1) random intercepts only, (2) a random slope for estimated interval at the study level, and (3) random slopes for estimated interval at both the study and comparison levels to account for potential heterogeneity [64].

In addition to the single-factor regression analysis, multiple linear regressions were conducted with three fixed effects *a priori*: 1) timing, 2) IPC sets, and 3) experience level. A separate regression analysis was also performed to evaluate the influence of WU presence on IPC effects. Model fit was assessed using Akaike Information Criterion and Bayesian Information Criterion. Moreover, we considered real-world applications, as the effects of IPC on athletic performance do not always increase or decrease proportionally with longer or shorter time intervals, making linear regression models unrealistic for evaluating IPC timing [65]. Therefore, we also reported models that better reflect these conditions, even if their goodness of fit was less optimal. The "optim" algorithm was applied to resolve model convergence issues with the control setting *control = list(optimizer = "optim")*. All regression models were performed using the *metafor* package and visualized with *ggplot2* package [66, 67].

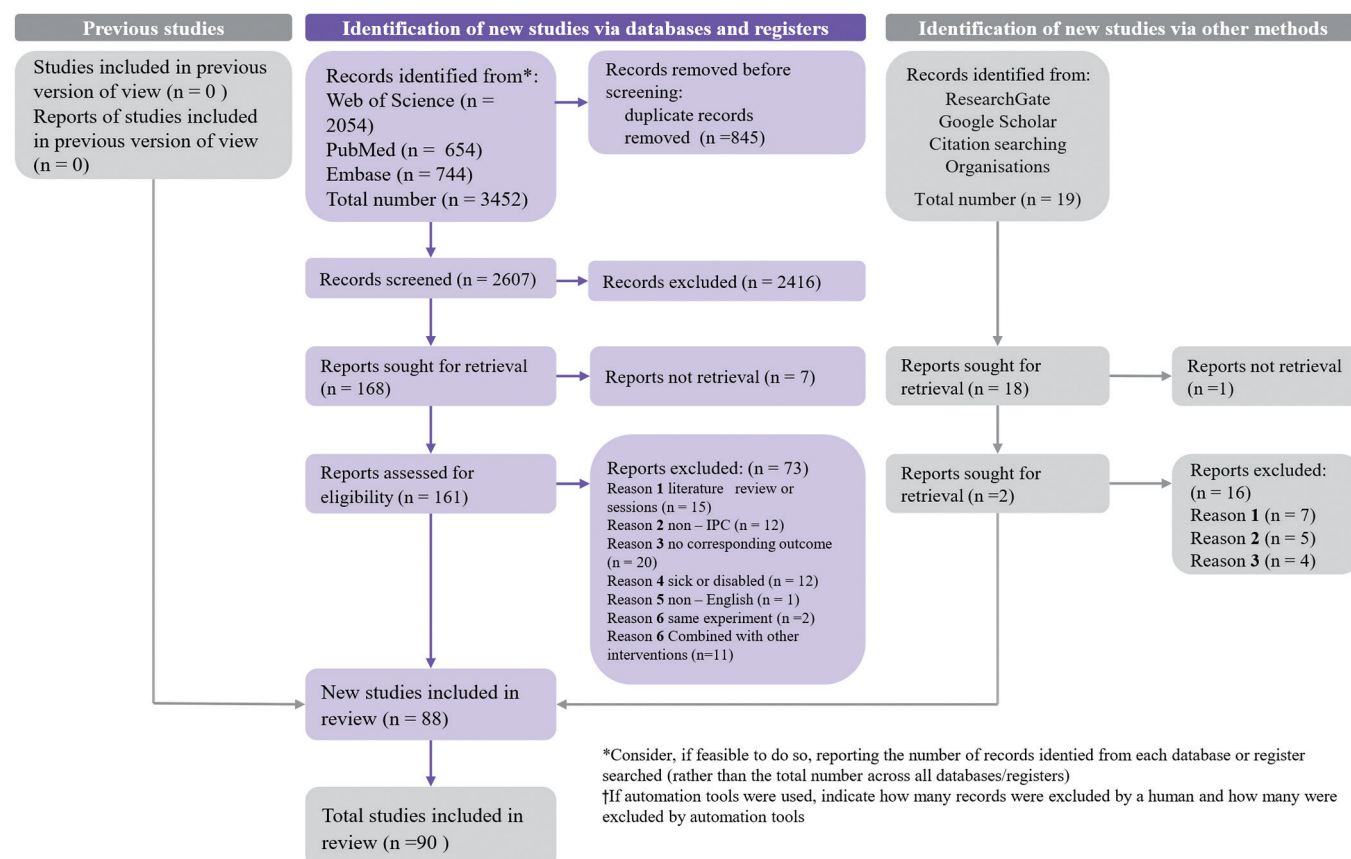


FIG. 1. PRISMA flow diagram for included and excluded study.

Publication Bias and Sensitivity Analysis

Publication bias was assessed using funnel plots [68] combined with Egger's test [69], with $p > 0.05$ indicating no bias.

Leverage, outliers, and influence were assessed for all meta-analysis models by calculating hat values, Cook's distances, and studentized residuals, respectively [70–72]. Outliers were flagged if hat values and Cook's distances exceeded three times the mean, and if studentized residuals were greater than 3. After removing outliers, calculations were re-run. If results remained unchanged, the original model was retained; otherwise, the model excluding outliers was considered [73].

Evidence Certainty Assessment

The quality of scientific evidence was evaluated according to the GRADE Handbook [74]. Certainty was rated as *high*, *moderate*, *low*, or *very low* using the GRADEpro GDT software. The evaluation considered risk of bias, inconsistency of results, indirectness of evidence, imprecision of results, and publication bias. Evidence started at high certainty but was downgraded for: (1) risk of bias: one level for bias, two for serious bias; (2) indirectness: significant heterogeneity without explanation; (3) imprecision: if PICOS criteria were unmet;

(4) inconsistency: small sample size or wide confidence intervals; (5) publication bias: downgrade if present [74, 75, 76]. Evidence was upgraded for: (1) large effect sizes; (2) dose-response relationship; (3) plausible residual confounding likely reducing the observed effect [77].

RESULTS

Search Results

A total of 3,452 documents were initially retrieved using the developed lead terms. After eliminating duplicates, 2,608 papers were left. Following the screening of titles and abstracts and applying the inclusion and exclusion criteria (Table 1), 88 papers were selected. Two additional papers were included from other sources such as "ResearchGate", "Google Scholar", and similar platforms. Therefore, the final number of articles that met the inclusion criteria was 90 (Fig. 1).

Study Characteristics

Supplementary Material provides a detailed list of the study characteristics for the 90 included articles [10–26, 28, 29, 31, 32, 34–38, 40, 55, 78–139], encompassing demographic factors and

TABLE 2. Certainty Assessment

	Risk of bias	Inconsistency	Indirectness	Imprecision	Publication bias	Certainty	Certainty-Upgraded	Reason for Upgraded
Effect of IPC on physical performance (anaerobic and aerobic)	↓	I^2 -2 = 0%; I^2 -3 = 9.13%; I^2 -4 = 5.74%	↔	↔ Clear direction of effect size	↔ $P = 0.38$	↔ moderate	high	Dose-response gradient (WU, interval time and sham)
Effect of IPC on anaerobic	↓	I^2 -2 = 0%; I^2 -3 = 13.64%; I^2 -4 = 0%	↔	↔ Clear direction of effect size	↔ $P = 0.33$	↔ moderate	high	Dose-response gradient (each outcome)
Effect of IPC on aerobic	↓	I^2 -2 = 0%; I^2 -3 = 16.53%	↔	↔ Clear direction of effect size	↔ $P = 0.63$	↔ moderate	high	Dose-response gradient (each outcome)
Effect of $\dot{V}O_2$ on IPC	↓	all $I^2 < 20\%$	↔	↔ NO clear direction of effect size	↓ all $P > 0.05$	↔ low	low	None
Effect of time to failure on IPC	↓	$I^2 = 49.89\%$ and 0 %	↓	↔ Clear direction of effect size	↔ all $P > 0.05$	↔ low	moderate	Dose-response gradient (sham)
Effect of time to complete on IPC	↓	$I^2 = 30.91\%$ and 0 %	↓	↔ NO clear direction of effect size	↓ all $P > 0.05$	↔ very low	very low	None
Effect of strength on IPC	↓	all $I^2 < 20\%$	↔	↔ NO clear direction of effect size	↓ all $P > 0.05$	↔ low	low	None
Effect of MR on IPC	↓	I^2 -2 = 0.04%; I^2 -3 = 25.91%	↓	↔ Clear direction of effect size	↔ all $P > 0.05$	↔ low	moderate	Dose-response gradient (sham)
Effect of power output on IPC	↓	all $I^2 < 20\%$	↔	↔ Clear direction of effect size	↔ all $P > 0.05$	↔ moderate	moderate	None

↓: demoted one level; ↔: do not demoted level; I^2 -2/3/4: Heterogeneity of models at different levels;

IPC-related parameters. All 90 articles were acute randomized cross-over (85 studies) or randomized controlled trials (between-participants design; 5 studies), involving a total of 1,439 participants, of whom 1,033 were males and 210 were females, with 196 had unspecified sex. Based on exercise duration of 75 s, 46 articles examined anaerobic exercise [10–15, 22, 23, 25, 26, 28, 29, 40, 80–112], while 41 articles focused on aerobic exercise [16–21, 31, 32, 34–38, 55, 113–139]. Three articles reported outcomes for both anaerobic and aerobic exercise [24, 78, 79]. Additionally, 20 articles did not include a WU protocol.

Risk of Bias

The physical performance risk of bias for all selected studies was assessed as “some concerns.” According to the RoB 2.0 tool, the primary reasons were: (1) failure to report baseline characteristics of participants; and (2) incomplete participation, leading to partial missing outcome data (Supplementary Material).

Risk of Publication Bias and Certainty Assessment

The funnel plot showed a symmetrical distribution, and the Egger test results were non-significant, indicating no publication bias.

For physical performance, anaerobic performance, and aerobic performance, no downgrading was applied given the absence of publication bias, high heterogeneity, and consistency with the PICOS framework. However, the quality of evidence was downgraded from high to moderate due to a “some concerns” risk of bias. Conversely, evidence for physical performance was upgraded back to *high*, ES demonstrated a dose–response relationship influenced by warm-up, interval timing, sham, and outcome measurements.

Across different outcome measures, $\dot{V}O_{2\max}$, time to failure, time to complete, strength, RM, and power output were rated as *low*, *moderate*, *very low*, *low*, *moderate*, and *moderate*, respectively (Supplementary Material and Table 2).

In addition, for MAOD, jump, and balance outcomes, the sample sizes were less than 10, which was insufficient for Egger's test and certainty assessment.

Main Effects

Based on goodness-of-fit comparisons, a four-level model was used to analyze the effects of IPC on physical performance and anaerobic performance, while a three-level model was used for aerobic performance. The results remained consistent across different pre-post

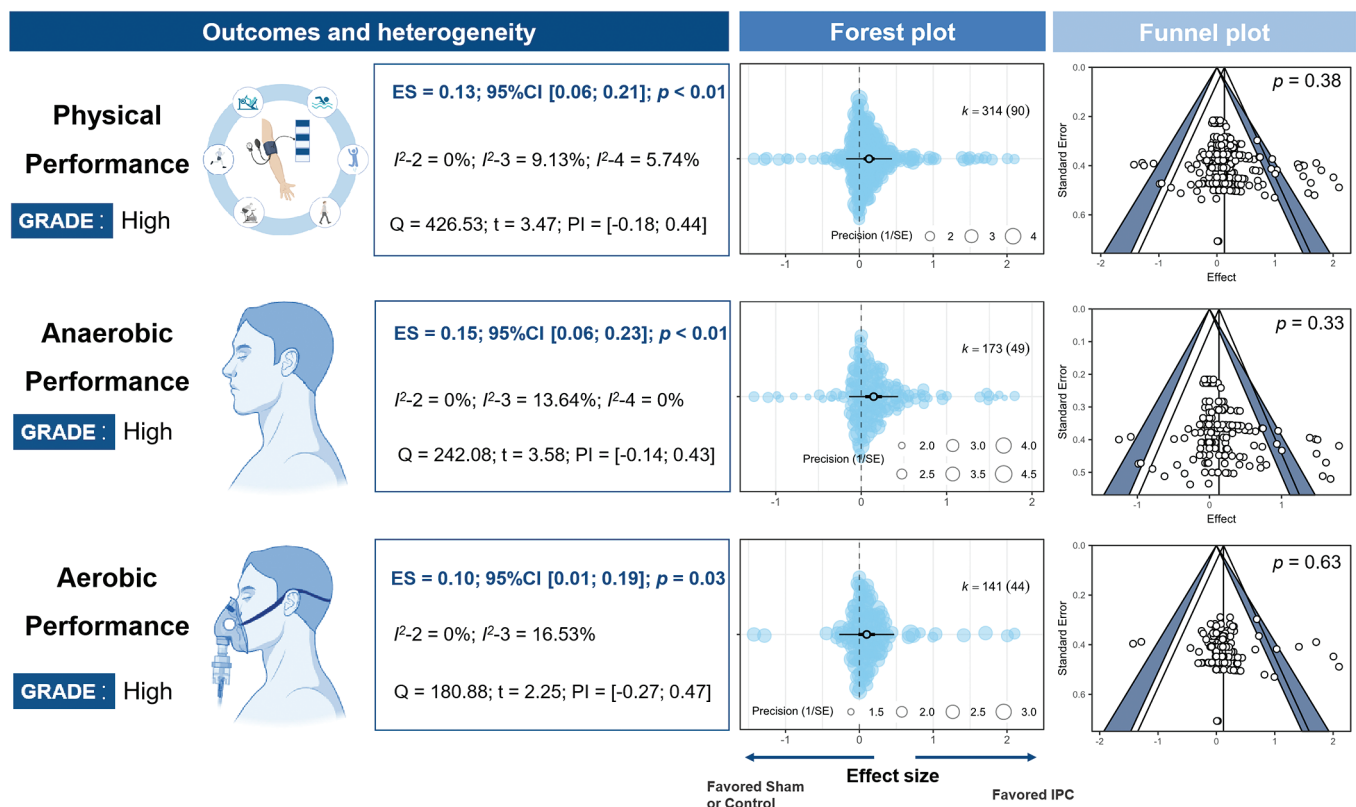
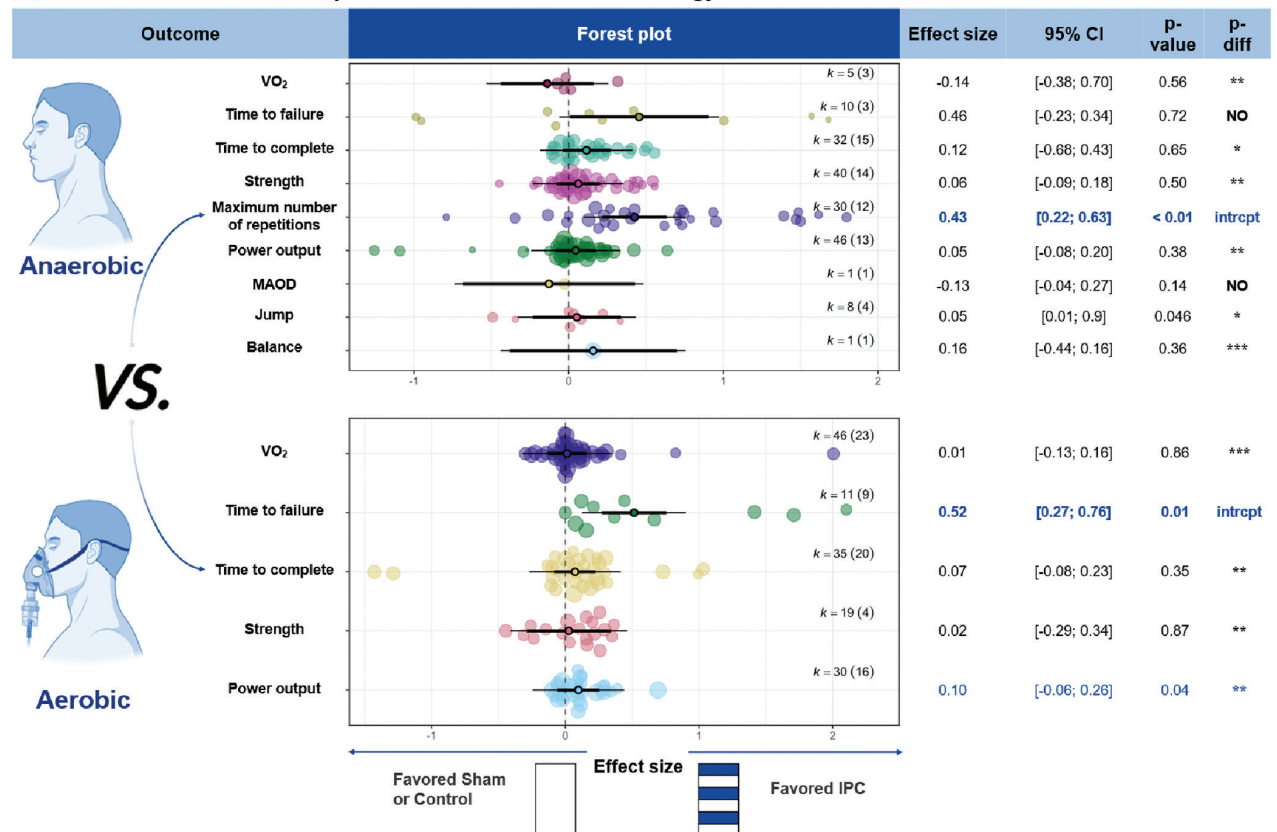


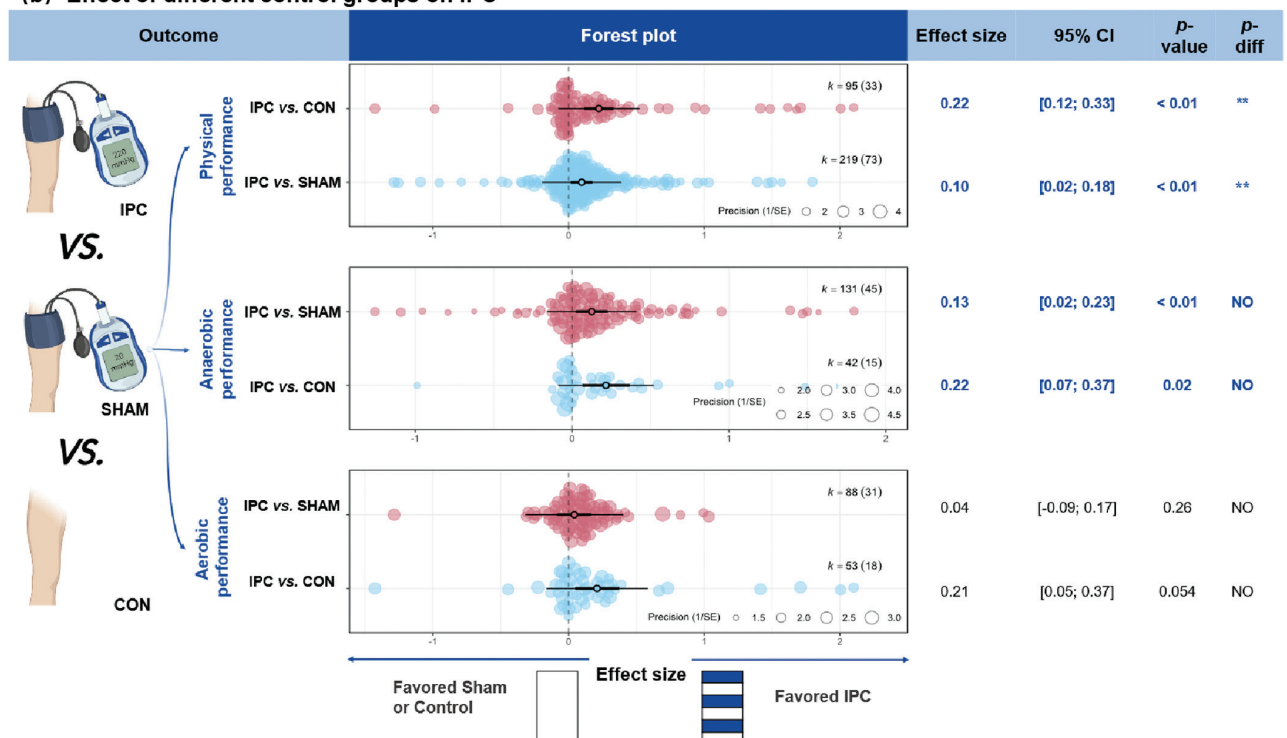
FIG. 2. Effects and funnel plot of IPC on performance.

Note: ES, effect size; I^2 -2/3/4, Heterogeneity of models at different levels; K , the total number of effects and studies included in the pooled effect size; P , statistically significant P values for results; Q , Cochran's Q statistic; SE, standard error; 95% CI, 95% confidence interval; SHAM/CON/IPC, SHAM /Control/IPC Group; PI, prediction interval.

(a) Effect of IPC on exercise performance under different energy metabolisms



(b) Effect of different control groups on IPC

**FIG. 3.** Effects of IPC on performance under different energy metabolisms and different IPC's control groups.

Note: ES, effect size; K, the total number of effects and studies included in the pooled effect size; P-value, statistically significant P values for results; 95%CI, 95% confidence interval; P, Power Output; RM, Maximum repetitions; P-diff, Statistical results of differences between groups; SHAM/CON/IPC, SHAM /Control/IPC Group; MAOD, Maximum acumulative oxygen deficit; VO₂, oxygen uptake; intrcpt, Comparison with other groups as an intercept; *, Statistically significant and P-diff < 0.05 compared to the intercept; **, Statistically significant and P-diff < 0.01 compared to the intercept; ***, Statistically significant and P-diff < 0.001 compared to the intercept; NO, Statistically insignificant differences between group comparisons and P > 0.05.

correlation (r) values, comparison methods, and after excluding outliers (Supplementary Material). The improvement in physical performance due to IPC was *trivial* ($ES = 0.13$, 95% CI [0.07; 0.19], $P < 0.001$, $Q = 427$, I^2 -Level 2 = 0%, I^2 -Level 3 = 9.13%, I^2 -Level 4 = 5.74%, $PI = -0.18$; 0.44). Specifically, the effects on anaerobic performance were *trivial* ($ES = 0.15$, 95% CI [0.05; 0.24], $P < 0.001$, $Q = 180$), as were the effects on aerobic performance ($ES = 0.1$, 95% CI [0.01; 0.19], $P = 0.03$, $Q = 242$) (Fig. 2). Egger's tests showed no significant differences ($P > 0.05$). All statistical power values were below 10% (Supplementary Material).

Subgroup analysis

Anaerobic and aerobic performance

The ES of IPC on anaerobic ($ES = 0.15$) and aerobic performance ($ES = 0.10$) were comparable, with no significant differences between them ($P = 0.87$, Fig. 2). For anaerobic performance, IPC significantly increased the RM ($ES = 0.43$, 95% CI [0.12; 0.74], $P = 0.01$). This effect was significantly greater ($P < 0.05$) than improvements in jump performance ($ES = 0.05$, $P > 0.05$), anaerobic

power output ($ES = 0.05$, $P > 0.05$), strength ($ES = 0.06$, $P > 0.05$), time trial completion time ($ES = 0.11$, $P > 0.05$), and $\dot{V}O_2$ ($ES = -0.14$, $P > 0.05$). For aerobic performance, IPC significantly prolonged time to exhaustion ($ES = 0.51$, 95% CI [0.16; 0.87], $P = 0.01$), with a smaller but significant improvement in aerobic power output ($ES = 0.10$, 95% CI [0.00; 0.19], $P = 0.04$). The improvement in exhaustion tests was significantly greater than for other aerobic performance metrics ($P < 0.05$).

Comparison

IPC demonstrated a *small* but significant improvement in physical performance compared to CON (ES of IPC vs. CON = 0.22, 95% CI [0.09; 0.35], $P < 0.01$) and a *trivial*, non-significant improvement compared to SHAM ($ES = 0.10$, 95% CI [0.03; 0.16], $P = 0.09$) (Fig. 3 b). The ES for IPC vs. CON was significantly greater than for IPC vs. SHAM. ($P = 0.02$). For anaerobic performance, IPC provided a *trivial* but significant benefit compared to both CON (ES of IPC vs. CON = 0.18, 95% CI [0.07; 0.30], $P < 0.01$) and SHAM ($ES = 0.13$, 95% CI [0.04; 0.22], $P < 0.01$). For aerobic performance, IPC showed a *small* improvement compared to CON

TABLE 3. Results of sham effects across different outcome measures.

	RM	term	K	n	ES	95%CI	P-value	P-diff
anaerobic	RM	IPC vs. CON	2	4	1.26	[0.69; 1.83]	< 0.01	< 0.01
		IPC vs. SHAM	11	26	0.39	[0.09; 0.69]	0.01	
	strength	IPC vs. CON	4	12	0.16	[-0.10; 0.42]	0.22	0.39
		IPC vs. SHAM	13	28	0.06	[-0.14; 0.26]	0.56	
	Power output	IPC vs. CON	6	14	-0.01	[-0.21; 0.18]	0.89	0.69
		IPC vs. SHAM	11	32	0.02	[-0.15; 0.18]	0.82	
	Time to complete	IPC vs. CON	4	7	0.05	[-0.19; 0.30]	0.39	0.38
		IPC vs. SHAM	14	25	0.15	[-0.03; 0.33]	0.01	
	Time to failure	IPC vs. CON	2	5	0.38	[-0.82; 1.57]	0.48	0.86
		IPC vs. SHAM	2	5	0.26	[-0.93; 1.46]	0.28	
aerobic	$\dot{V}O_2$	IPC vs. CON	10	21	0.18	[-0.03; 0.39]	0.09	0.18
		IPC vs. SHAM	17	25	0.02	[-0.16; 0.20]	0.83	
	strength	IPC vs. CON	1	2	-0.11	[-0.88; 0.67]	0.78	0.66
		IPC vs. SHAM	3	17	0.08	[-0.35; 0.52]	0.69	
	Power output	IPC vs. CON	7	11	0.00	[-0.26; 0.26]	1.00	0.27
		IPC vs. SHAM	11	19	0.15	[-0.05; 0.35]	0.15	
	Time to complete	IPC vs. CON	9	14	0.11	[-0.18; 0.40]	0.44	0.90
		IPC vs. SHAM	14	21	0.09	[-0.15; 0.33]	0.45	
	Time to failure	IPC vs. CON	5	5	1.17	[0.59; 1.76]	< 0.01	0.02
		IPC vs. SHAM	5	6	0.13	[-0.43; 0.70]	0.61	

ES, effect size; K, number of studies; n, Total number of effects included; 95%CI, 95% confidence interval; P-value, statistically significant P values for results; P-diff, Statistical results of differences between groups; SHAM/CON/IPC, SHAM /Control/IPC Group; vs.: versus;

(ES = 0.22, 95% CI [0.04; 0.40], $P = 0.02$), and a *trivial* improvement compared to SHAM (ES = 0.13, 95% CI [-0.09; 0.17], $P = 0.01$).

Regarding exercise outcome measures, sham effects were generally non-significant ($P > 0.05$). Significant sham effects were found for RM ($P < 0.01$) and time-to-failure tests within aerobic performance ($P = 0.02$; Table 3). Sham effect analyses could not be conducted for other outcomes due to very small sample sizes and the presence of only a single comparison group; for example, jump performance was assessed only in IPC vs. SHAM comparisons.

Sex

IPC demonstrated a *small* improvement in physical performance for males (Fig. 4 (a), ES = 0.20, 95% CI [0.12; 0.28], $P < 0.001$), while the effects for females, mixed-sex groups, and groups with unreported sex were not significant ($P > 0.05$). For anaerobic performance, IPC showed a *small* improvement for males (ES = 0.22, 95% CI [0.10; 0.35], $P < 0.001$) and a *trivial* improvement in mixed-sex participants (ES = 0.09, 95% CI [0.01; 0.17], $P = 0.04$). There were no significant differences between sex groups ($P > 0.05$). For aerobic performance, IPC showed a *trivial* improvement in males (ES = 0.15, 95% CI [0.01; 0.29], $P = 0.04$), while the effects for females, mixed-sex groups, and groups with unreported sex were not significant.

Training Experience Level

IPC showed a *trivial* improvement in physical performance across participant training levels: *sedentary* (Fig. 4 (b), ES = 0.14, 95% CI [0.02; 0.26], $P = 0.02$), *recreationally active* (ES = 0.15, 95% CI [0.02; 0.27], $P = 0.02$), and *developing or trained* participants (ES = 0.18, 95% CI [0.04; 0.33], $P = 0.01$). For anaerobic performance, a *trivial* improvement was observed in *recreationally active* participants (ES = 0.16, 95% CI [0.02; 0.29], $P = 0.03$). For aerobic performance, *trivial* improvements were seen in *sedentary* (ES = 0.11, 95% CI [-0.02; 0.24], $P = 0.07$), *developing or trained* (ES = 0.13, 95% CI [0.0389; 0.2255], $P = 0.01$), and *world-class* athletes (ES = 0.16, 95% CI [0.14; 0.17], $P < 0.01$).

Ischemia and reperfusion time

Ischemia-reperfusion protocols of 4 × 5-min (ES = 0.10, 95% CI [0.02; 0.19], $P = 0.02$) and 3 × 5-min (ES = 0.14, 95% CI [0.03; 0.25], $P < 0.01$) were found to enhance physical performance (Fig. 5 (a)). For anaerobic efforts, both the 1 × 5-min (ES = 1.62, 95% CI [0.65; 2.58], $P < 0.01$) and 3 × 5-min (ES = 0.13, 95% CI [0.04; 0.21], $P < 0.01$) protocols significantly improved performance. Significant differences were observed between the 1 × 5 min protocol and the 3 × 5-min, 4 × 5-min, and 5 × 5-min protocols ($P < 0.01$). For aerobic performance, ischemia-reperfusion durations of 1 × 5-min (ES = 0.27, 95% CI [-0.24; 0.78], $P = 0.09$) and 4 × 5-min (ES = 0.08, 95% CI [-0.01; 0.16], $P = 0.09$) tended to improve aerobic performance.

WU and IPC

IPC combined with WU significantly enhanced physical performance (Fig. 5 (b), ES = 0.14, 95% CI [0.07; 0.22], $P < 0.01$), whereas no significant effect was observed without WU (ES = 0.10, 95% CI [-0.08; 0.27], $P = 0.25$). For anaerobic performance, IPC combined with WU showed a significant improvement (ES = 0.16, 95% CI [0.06; 0.26], $P < 0.01$), while no significant effect was observed without WU (ES = 0.08, 95% CI [-0.06; 0.22], $P = 0.19$). For aerobic performance, neither the presence ($P = 0.052$) nor absence ($P = 0.54$) of WU showed significant improvements.

Meta-regression analysis

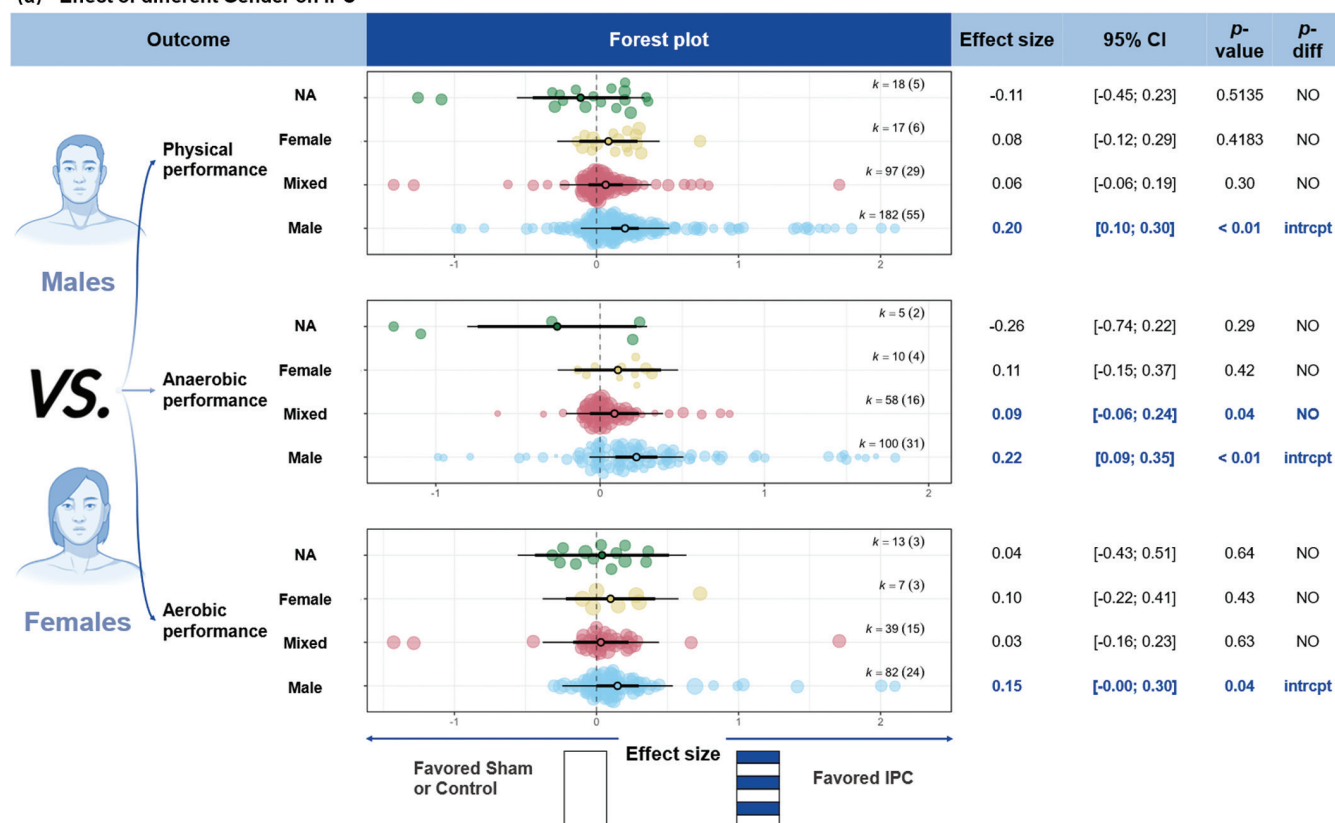
Among all fitted models, the linear meta-regression for the single-factor interval demonstrated the best fit. However, non-linear regression models better explained the timing of IPC's effects on performance, capturing the non-monotonic relationship over time. The interval from IPC to testing ranged from 5 to 570 min, with the optimal improvement at approximately 37 min (Fig. 6 B). With WU, the interval from IPC to performance testing ranged from 13 to 102 min, with the optimal effect at 42 min (Fig. 6 E). Without WU, the IPC-to-testing interval ranged from 6 to 7 min, with the optimal interval at 14 min, although this time point was not statistically significant (Fig. 6 H, $P > 0.05$). Age did not significantly predict or moderate the performance-enhancing effects of IPC. Detailed analysis results can be found in Supplementary Material.

DISCUSSION

This systematic review and meta-analysis assessed the effects of IPC on physical performance, identified the optimal timing, and explored the influence of moderating factors including sex, training level, ischemia-reperfusion duration, and the presence of WU. The main findings indicated IPC had a *trivial* effect on overall physical performance, with variations based on exercise type and testing conditions. For anaerobic performance, IPC significantly improved RM with a *small* ES, while no significant improvements were observed for jump performance, anaerobic power output, strength, time-trial completion time, or $\dot{V}O_2$. Regarding aerobic performance, IPC significantly prolonged time to exhaustion with a *medium* ES, outperforming other aerobic outcomes. Additionally, IPC produced *small* to *trivial* improvements in physical performance compared to both CON and SHAM groups, with a more pronounced effect relative to SHAM, indicating a placebo component. However, performance benefits persisted after accounting for placebo effects, supporting the efficacy of IPC.

IPC demonstrated larger improvements in physical performance for males, particularly in anaerobic exercises, while non-significant effects were noted for females, mixed-sex groups, or groups with unreported sex. *Sedentary*, *recreationally active* and *developing or trained* participants experienced only *trivial* improvements. Furthermore, IPC effectiveness was influenced by protocol duration, with 4 × 5-min and 3 × 5-min protocols showing the greatest

(a) Effect of different Gender on IPC



(b) Effect of different experience level on IPC

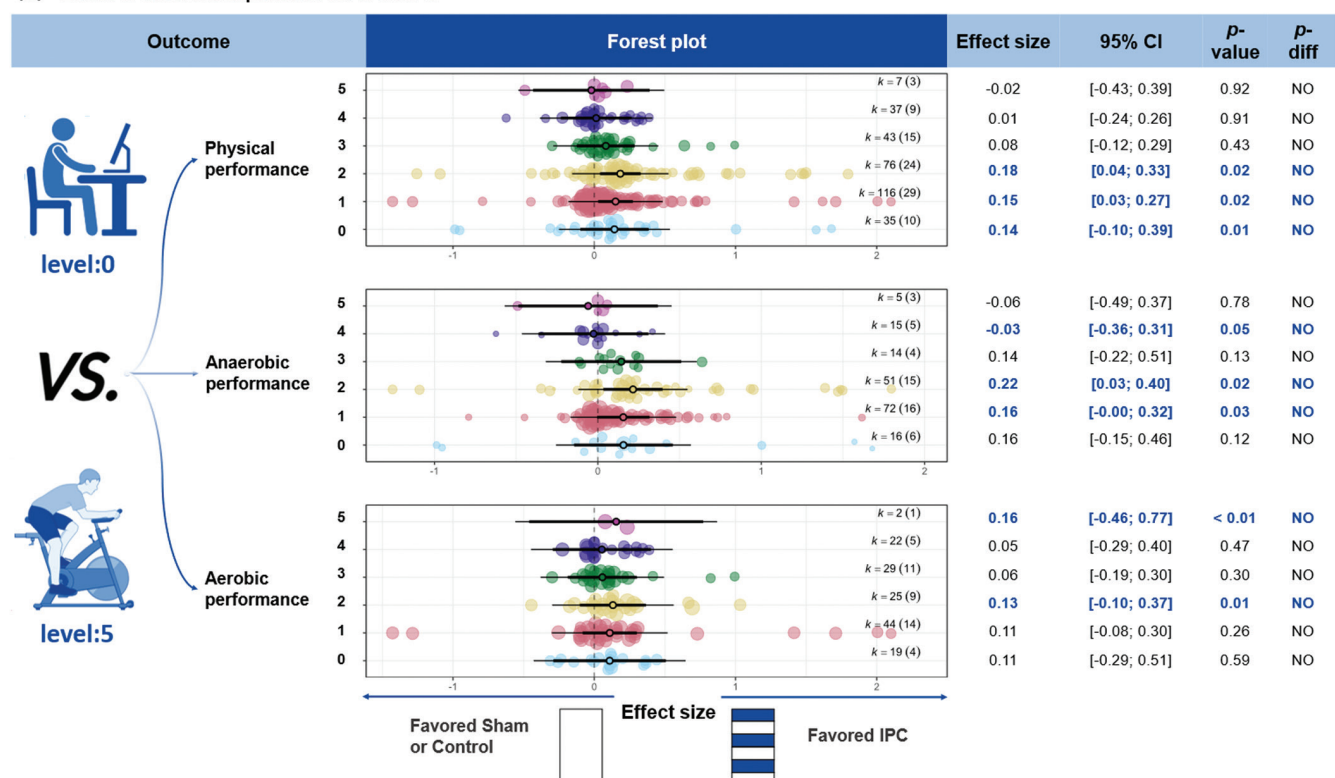
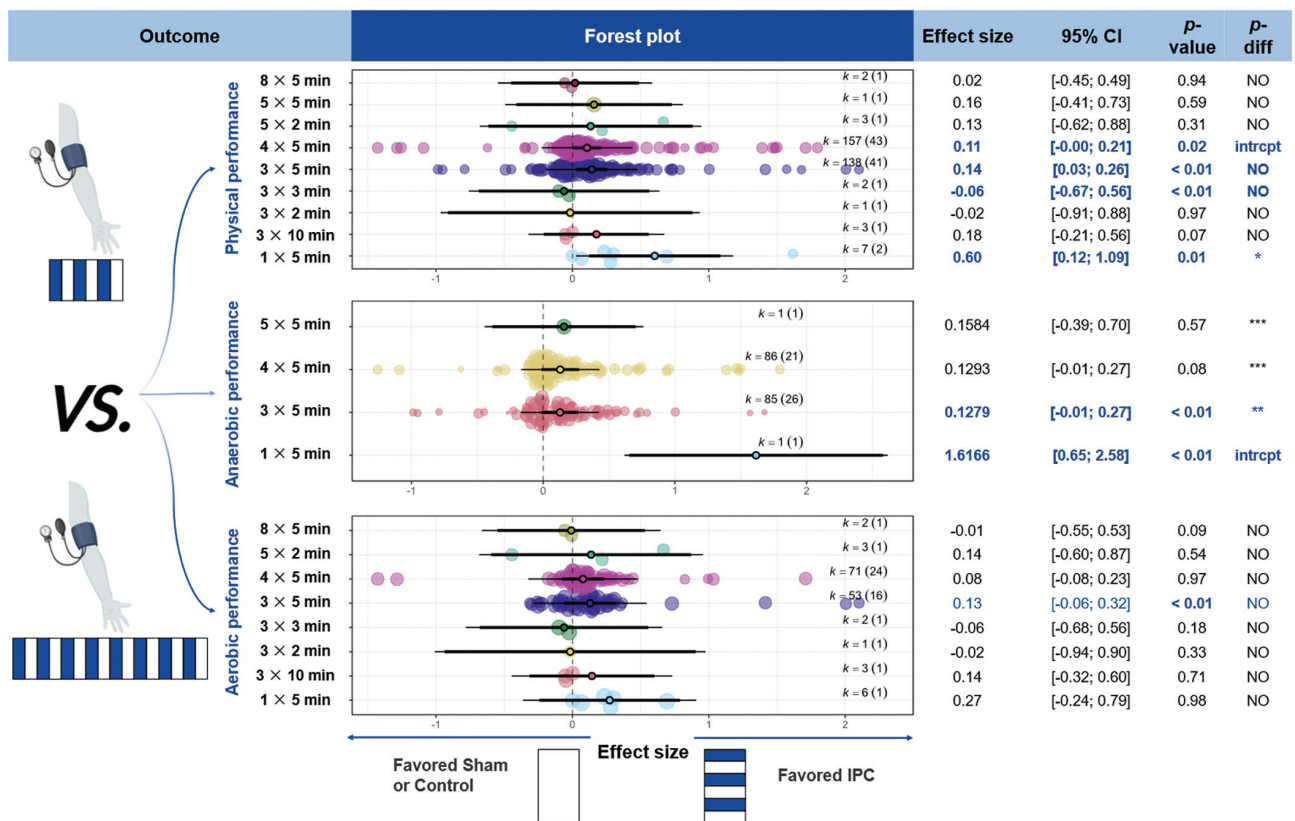


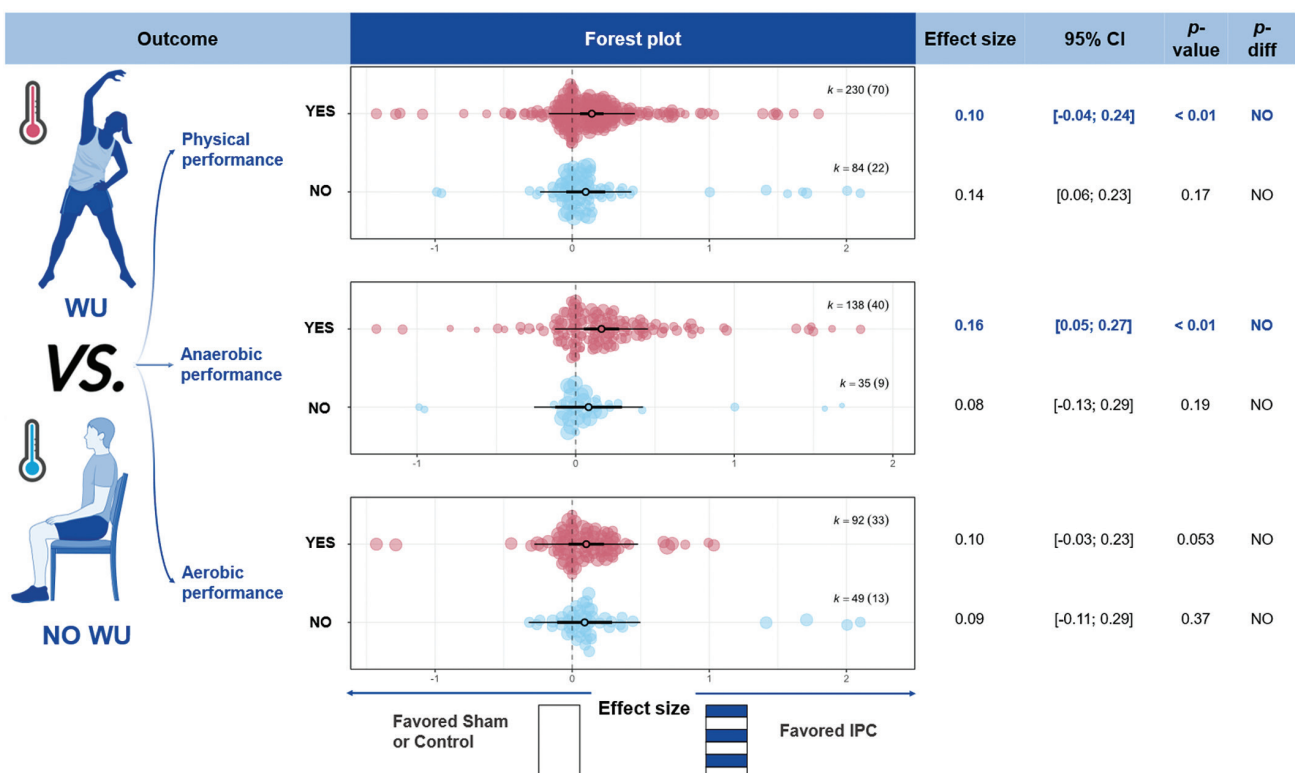
FIG. 4. Effect of different Gender and experience level on IPC.

Note: ES, effect size; K, the total number of effects and studies included in the pooled effect size; P-value, statistically significant P values for results; 95%CI, 95% confidence interval; P-diff, Statistical results of differences between groups; SHAM/CON/IPC, SHAM /Control/IPC Group; NA, Sex not reported in detail; intrcpt, Comparison with other groups as an intercept; NO, Statistically insignificant differences between group comparisons and $P > 0.05$; 0, sedentary; 1, recreationally active; 2, developing or trained; 3, highly trained or national level; 4, elite or international level; 5, world-class athletes; NO, Statistically insignificant differences between group comparisons and $P > 0.05$.

(a) Effect of different programme on IPC



(b) Effect of warm-up on IPC

**FIG. 5.** Effect of warm-up and IPC programme on performance.

Note: ES, effect size; K, the total number of effects and studies included in the pooled effect size; P-value, statistically significant P values for results; 95%CI, 95% confidence interval; P-diff, Statistical results of differences between groups; SHAM/Control/IPC, SHAM /Control/IPC Group; min, minute; intrcpt, Comparison with other groups as an intercept; *, Statistically significant and P-diff < 0.05 compared to the intercept; **, Statistically significant and P-diff < 0.01 compared to the intercept; ***, Statistically significant and P-diff < 0.001 compared to the intercept; NO, Statistically insignificant differences between group comparisons and P > 0.05.

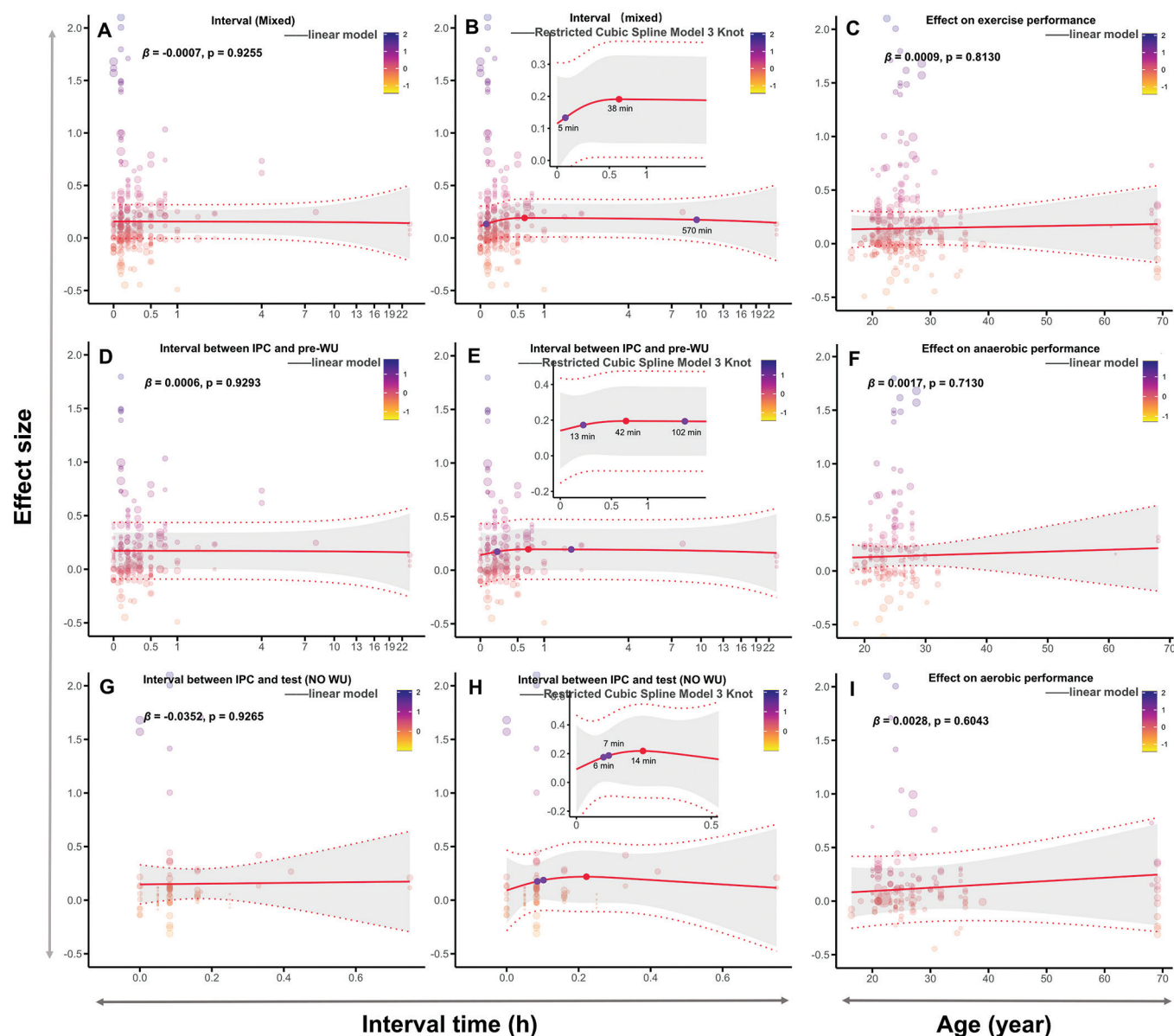


FIG. 6. Meta-Regression analysis: effect of interval and age on IPC.

Note: Mixed, both with and without warm-up; WU, warm-up; pre-WU, before the warm-up; h, hour; min, minute; β , regression coefficient; P , statistically significant P values for results; A and B, linear and nonlinear regression analyses of the effect of the interval between IPC and testing on physical performance, without considering the WU protocol; D and E, linear and nonlinear regression analysis of the effect of the interval between IPC and WU on physical performance; G and H, linear and nonlinear regression analysis of the effect of the interval between IPC and testing on physical performance in the absence of WU; C, F and I, linear regression analyses of age and IPC on overall performance, anaerobic performance, and aerobic performance, respectively.

enhancements in physical performance. Anaerobic performance significantly improved with 1 × 5-min and 3 × 5-min protocols.

When combined with a WU, IPC showed larger improvements in physical performance, particularly in anaerobic performance. However, IPC alone, without WU, had no significant effects. The optimal timing for IPC was approximately 37 min before exercise testing (regardless of WU), with the most notable effects observed at 42 min when paired with WU, and an effective range of 6-7-min without WU. Age did not significantly influence the effects of IPC.

Effects of IPC on Physical performance and WU Protocols

This study demonstrates that IPC can boost physical performance ($ES = 0.13$), with *trivial* but significant effects on both anaerobic ($ES = 0.14$) and aerobic performance ($ES = 0.10$). However, there was no significant difference in the magnitude of improvement between anaerobic and aerobic performance. These findings align with those of Salvador et al. [140] and Marocolo et al. [141], who also reported positive effects of IPC on both types of performance. Additionally, IPC was particularly effective in improving exercise endurance, with

significant increases in time to exhaustion ($ES = 0.52$) and the RM ($ES = 0.43$), both showing larger ES compared to other performance metrics (Fig. 3). These results are consistent with a recent meta-analysis [39], which found significant enhancements in anaerobic endurance (mean difference, $MD = 0.68$) and time to exhaustion in aerobic exercise ($MD = 22.68$).

From a mechanistic standpoint, IPC may enhance endurance capacity by increasing nitric oxide (NO) and adenosine concentrations, activating K-ATP channels, and improving mitochondrial function [142, 143]. It may also enhance endurance performance by improving hypoxia tolerance [139] and modulating perceived exertion [20]. Nonetheless, Sabino-Carvalho et al. [132] found that IPC-induced endurance improvements may largely reflect placebo effects, as gains did not significantly exceed those in the sham group. This finding aligns closely with our study. In aerobic endurance tasks (time-to-failure tests), IPC improved performance compared with CON, but no significant benefit remained after accounting for sham effects (Table 3). Given the *trivial* ES, placebo likely plays a key role in IPC's influence on endurance performance. Neural regulation independent of metabolic changes – such as reduced inhibition of central motor drive via suppression of type III/IV muscle afferent feedback – may also play a role in determining endurance limits [144, 145]. Supporting this, IPC has been shown to improve neuromuscular recovery, such as reducing force decline during repeated isometric contractions [146]. Further evidence suggests IPC may reduce presynaptic inhibition, increase motor neuron excitability, and modulate sympathetic nervous system activity [46, 87]. For example, IPC can enhance resistance performance by increasing neural excitability, thereby inducing a higher level of arousal [147]. Therefore, IPC likely enhances endurance through a multifactorial synergy involving metabolic pathways (NO activation, mitochondrial efficiency, hypoxia tolerance), neural mechanisms (reduced central motor inhibition, sympathetic modulation), and potential placebo effects. This underscores the complex, multidimensional nature of IPC's mechanisms and highlights the need for further research to disentangle the contributions of each component.

From a study design perspective, we propose that IPC may have an additive effect when combined with a WU. For example, one study found no improvement in 50-meter sprint swimming performance 1 h after IPC, but significant benefits at the 2-h and 8-h marks [40]. However, this study added a 20-min WU within the 1-h, 2-h, and 8-h intervals after IPC, meaning the interval was actually measured from IPC to the start of WU, not from IPC to the testing itself [40]. Similar issues were observed in studies by Valenzuela et al. [29] and Richard et al. [25]. Additionally, some studies applied IPC between WU and testing phases [106, 111, 137]. The inconsistent definitions of IPC-to-testing intervals, along with heterogeneity in intervention timing (e.g., pre- or post-warm-up), may obscure IPC's independent effect on athletic performance, compromising the reliability of estimates on its true impact in current meta-analyses and exper-

imental research.

Among the studies included in our analysis, 20 did not include WU protocols, while 70 did. Subgroup analyses revealed that adding WU after IPC significantly improved physical performance ($ES = 0.14$, $P < 0.01$), while no significant effect was observed without WU ($P = 0.13$) (Fig. 5 (b)). Numerous studies have demonstrated that WU enhances short-, medium-, and long-term physical performance [148–153], with varying effects depending on the specific WU strategy [148, 152]. However, no studies have directly investigated whether IPC and WU have additive effects, though some have indirectly addressed this. For example, Vangsoe et al. [112] compared IPC, post-activation potentiation, and self-selected WU strategies on 1-km time trial performance and found no significant differences among the three. Additionally, Guilherme da Silva Telles et al. [93] compared the effects of IPC, SHAM IPC, specific WU, aerobic exercise, and active stretching on resistance training outcomes, and found that IPC combined with resistance training significantly increased RM and total training volume.

In summary, the crucial role of IPC in enhancing physical performance may have been overlooked, contributing to the variability in its effects. Future guidelines for research end-users should propose to standardize IPC protocols – including well-defined WU procedures and precise interval timing – to minimize heterogeneity. Additionally, rigorous experimental designs are needed to isolate IPC's true physiological effects from sham influences, particularly under controlled conditions (e.g., standardized WU and intervals).

IPC Interval Timing Based on WU Control

This meta-analysis found that, compared to traditional cardioprotective protocols in animals (early and late phases, typically 2–3 or 12–24 h) [142, 154–156], the effective IPC protocol to boost performance in humans is significantly shorter. Specifically, the optimal interval for IPC to enhance physical performance (regardless of WU) was approximately 38 min (range: 5 to 570 min). With WU, the optimal interval from IPC to the start of WU extended to 42 min (range: 13 to 102 min). Without WU, the effective interval time was reduced to 6–7 min. These findings align with Incognito et al. [2]'s systematic review, which suggested that variability in IPC effects on physical performance is primarily due to differences in interval times.

Although our results differ from the traditional early (2–3-h) and late (12–24-h) IPC-induced endothelial protection windows [142, 154–156], this discrepancy may stem from the fact that classical studies focused on animal models and did not consider exercise interventions. However, our findings partly align with Lindner et al. [26], who compared the effects of IPC with 0-min or 20-min intervals before WU on strength and sprint performance. They found no significant differences but recommended a 25–45-min interval from IPC to WU for optimal performance. Additionally, Seeley et al. [157] demonstrated that a 45-min interval from IPC to WU improved muscle oxygen saturation in the recovery phase after sprint exercise, outperforming a 5-min interval. These conclusions align

closely with our finding of a 42 min optimal interval, further supporting the notion that combining IPC with WU extends its physiological benefits.

Mechanistically, IPC may enhance endothelial nitric oxide synthase (eNOS) activity, promoting NO release and thereby improving vasodilation and oxygen delivery [158]. Exercise itself also activates eNOS through shear stress, increasing NO synthesis and consumption [159]. The release of NO typically peaks within minutes and gradually returns to baseline levels [160]. Without a WU, the physiological benefits of NO may not last long, which may explain the short effective interval for IPC (6–7 min). In contrast, when WU is included, the optimal interval extends to 42 min (range: 6 to 102 min). This may occur because IPC activates eNOS to release NO, while WU induces a secondary NO release (via adenosine receptor signaling) combined with the increase in body temperature. This synergistic effect enhances hemodynamic responses [161] and allows the benefits of IPC to extend into the testing phase.

From a practical perspective, experimental designs without WU (6–7-min interval) may be better suited for mechanistic studies of IPC, as they offer better control over variables. However, in real-world applications such as competitive settings, it is recommended to perform IPC before a WU (42-min interval) to avoid potential injury risks associated with high-intensity exercise. Additionally, low-intensity exercise can induce physiological benefits associated from IPC. For example, Telles et al. [110] found that both low and high-pressure IPC similarly enhance 1 RM testing through more favorable psychophysiological responses, such as neural stimulation of type III and IV afferent fibers. Additionally, IPC combined with varying-intensity exercise (e.g., 50% MVC grip training [162], 5-km time trials [16], and exhaustion tests at 70% $\dot{V}O_{2\max}$ [122, 123]) can effectively improve physical performance or physiological indicators.

Is the Potent Effect of IPC Derived from SHAM?

This study found that the performance-enhancing effects of IPC are partly influenced by SHAM effects. Specifically, IPC significantly improved physical performance compared to CON (ES = 0.13, $P < 0.01$), and this effect was significantly greater than the effect observed with SHAM ($P = 0.02$). In addition, IPC produced large improvements in the maximum number of repetitions (RM, ES = 1.26) and time to failure (ES = 1.17) compared to CON, which were also significantly greater than those in the SHAM group (Table 3). These findings are supported by subgroup analyses, where the effect size for time to failure (ES = 0.52) was significantly greater than that for other outcomes (Fig. 3a), with RM showing a similar pattern. However, in aerobic performance, the time to failure test did not show significant improvement after adjusting for sham effects. This suggests that the performance-enhancing effects of IPC may be overestimated without proper sham controls. This interpretation aligns with previous meta-analyses showing IPC improves performance versus control, while SHAM

group also outperforms CON [41, 42]. Likewise, de Souza et al. [28] found no additional performance IPC benefits in resistance exercise, likely due to sham effects, and Santos Cerqueira et al. [163] suggested that the muscle-protective effects of IPC following eccentric exercise may improve placebo responses.

The SHAM effect may originate from the potential influence of IPC on sensory nerves. For example, Marocolo et al. [9] found that both real IPC and sham interventions induced tactile sensations from ischemic pressure, stimulating subcutaneous low-threshold mechanoreceptors (e.g., Pacinian corpuscles, Meissner corpuscles, Merkel discs, and Ruffini endings) and modulating neural processing. This suggests that IPC might elicit positive expectations in participants, ultimately enhancing overall performance. Supporting this, Souza et al. [164] demonstrated that verbal instructions manipulating expectations in a sham group significantly affected resistance performance, with participants holding positive expectations performing better than those with negative or neutral expectations. Although sham effects contribute to IPC's performance benefits, they may not fully explain its efficacy. Even after controlling for sham effects (IPC vs. SHAM), IPC still improved physical performance (ES = 0.10, $P < 0.01$; Fig. 3b), a pattern also evident in anaerobic outcomes such as RM and time to completion (Table 3). In addition, the studies reviewed revealed significant variability in IPC interval times (0–60 min), with four studies exceeding 60 min [41, 42]. Additionally, these studies did not account for the inclusion of a WU, which is known to enhance physical performance [148–153]. Our meta-analysis showed that adding WU after IPC significantly improved physical performance (ES = 0.14, $P < 0.01$), whereas no significant effect was observed without WU ($P = 0.125$).

Future research should aim to isolate the true physiological mechanisms of IPC by strictly controlling for variables like WU, interval timing, and verbal instructions to determine whether observed benefits are genuinely independent of sham effects.

Ischemia-Reperfusion Duration

This study found that ischemia-reperfusion protocols of 4×5 min (ES = 0.10, $P = 0.02$) and 3×5 -min (ES = 0.14, $P < 0.01$) significantly improved physical performance. These findings align with previous research indicating that 3×5 -min or 4×5 -min IPC protocols are effective to induce the desired physiological stimuli [5–8, 165].

In addition to the 3×5 -min and 4×5 -min IPC protocols, some studies have employed other ischemia-reperfusion cycles, such as 8×5 -min [34], 5×5 -min [108], and 5×2 -min [126], as well as longer [136] or shorter [137] ischemia durations. However, in our analysis of anaerobic performance, a very large ES was observed for the shorter IPC protocol (1×5 -min; ES = 1.62), but this result should be interpreted with caution due to data from only a single study. Interestingly, Gkari et al. [166] reported that a very short IPC duration (1×5 -min) significantly improved performance in track and field high jump athletes as well as vertical jump outcomes.

Therefore, such an ultra-short IPC protocol may be a time-efficient and potentially effective strategy for performance enhancement. In a study by Cocking et al. [34], the ultra-long IPC protocol (8×5 -min) did not improve cycling time trial performance, while the 4×5 -min protocol did. Based on current evidence, we recommend using 3×5 -min or 4×5 -min protocols to optimize physical performance.

Training Experience Level

IPC did not show significant effects on physical performance in participants with higher training levels ($\geq$ *highly trained or national level* participants), according to the performance caliber classification of McKay et al. [52] (*levels 0-5*). However, a significant effect on aerobic performance was observed in participants at world-class athletes. It is important to note that this result may not be fully representative, as only one study included participants at this level.

IPC appears to be more effective for individuals with lower training experience (*sedentary, recreationally active and developing or trained* participants) (Fig. 4 (b)). This may be because individuals with lower training levels have more room for improvement, while those with higher levels may be closer to their genetic potential [39]. For example, one study found no significant difference at well-trained runners in 5-km performance improvement when IPC was applied 24-h before WU *versus* immediately before, suggesting that training experience and exercise type influenced the results [31]. Previous meta-analyses categorized participants as trained or untrained and found differences only in ratings of perceived exertion [41]. However, they did not explore the sources of these differences. We argue that this classification may not be universally applicable, as significant variations in training levels exist within both groups.

In the analyses for anaerobic ($P = 0.12$) and aerobic ($P = 0.07$) efforts, IPC showed no additional performance benefits for sedentary individuals (*sedentary*) (Fig. 4 (b)). While it is easier to identify the upper limits of physiological abilities in athletes, determining the lower limits in sedentary populations remains difficult. Even within sedentary groups, genetic factors may provide some individuals with inherent advantages. For example, in standardized aerobic training, individual variations in $\dot{V}O_{2\max}$ gains are substantial, with approximately 50% of the variation attributed to genetics [167]. Additionally, studies on monozygotic twins have shown that environmental factors can cause notable differences in training levels and body weight, with exercise also inducing epigenetic changes that lead to different health outcomes [168]. This suggests that environmental factors can significantly affect training levels, even among those who are sedentary.

Sex and age

We found that sex does not significantly moderate the performance-enhancing effects of IPC. However, males derived greater performance benefits from IPC, with notable improvements in physical performance physical performance, as well as aerobic and anaerobic performance

(Fig. 4 (a)). In support, a sex-specific study found that IPC enhanced time to task failure only in males [15]. Other research suggests that IPC may influence functional sympathetic modulation, thereby improving grip strength, but this effect was observed exclusively in males [46]. It was proposed that the enhanced endurance [15] and improved grip strength performance [46] in males following IPC may result from greater $\dot{V}O_2$ and strength gains. Nonetheless, the influence of sham effects, WU protocols, and interval timing cannot be ruled out. For instance, despite the better performance outcomes in males, Pereira et al. [15] speculated that individual differences in pain perception might play a crucial role in explaining these results.

Although our regression analysis found that age does not moderate IPC's performance-enhancing effects, most participants in our study were aged 20–30 years, with few participants aged 60–70 years, and none in the 40–60 age range (Fig. 6 C, Fig. 6 F, Fig. 6 I). This uneven distribution of age groups may have influenced the results. Standalone IPC (without exercise) seem ineffective for promoting health in older adults. For example, a study comparing high-intensity interval training, isometric handgrip training, and IPC found no significant reduction in systolic blood pressure reduction with IPC [169]. However, when IPC is combined with exercise, it may still offer benefits for older adults. Research has shown that IPC can acutely improve handgrip strength and functional capacity in active older women [79], enhance balance [108], and reduce systolic blood pressure in older adults without causing additional fatigue [130]. These findings highlight that IPC could serve as a time-efficient health promotion strategy for older adults.

Certainty of Evidence and Risk of Bias

Using the GRADE framework, the certainty of evidence for the overall effects of IPC on physical performance ranged from *moderate* to *high*, particularly for endurance-related outcomes such as time to exhaustion and RM, where dose–response relationships (e.g., warm-up integration, interval timing, and sham controls) supported upgrading. Conversely, the certainty of evidence for $\dot{V}O_2$, strength, and time-to-completion outcomes remained *low* to *very low* due to imprecision and inconsistent ES. These results suggest that while IPC demonstrates small but significant ergogenic benefits overall, the strength of evidence varies considerably across outcome measures.

Risk of bias assessments indicated “some concerns” in most included studies. The primary sources of bias included small sample sizes, insufficient randomization and allocation concealment, and the inherent difficulty of blinding participants and researchers in perceptible IPC interventions. Additional concerns included selective reporting and incomplete descriptions of intervention protocols. The observed sham effects further underscore the challenges of adequately blinding participants in IPC research.

Taken together, although moderate-to-high certainty supports IPC's benefits for endurance-related outcomes, the low certainty for other measures warrants cautious interpretation.

Practical Applications

This study addresses existing controversies surrounding IPC and proposes feasible, standardized protocols to optimize its performance-enhancing effects. Based on our meta-analytic findings, we recommend two standardized IPC protocols suitable for experimental or applied contexts (see Conclusion section).

Evidence indicates that IPC can improve physical performance ($ES = 0.13$), though the effect may be relatively *trivial* and partly influenced by sham. However, sham effects should not be viewed strictly as a limitation, since they may contribute to IPC's ergogenic potential. When IPC provides immediate performance benefits, its application is justified. Notably, IPC produces substantial improvements in endurance-related outcomes, such as time-to-failure in aerobic exercise and the maximal number of repetitions in anaerobic exercise. These findings support the practical value of IPC as an acute performance-enhancing strategy, particularly in resistance and aerobic activities.

Beyond acute performance enhancement, emerging evidence suggests that IPC may also support training recovery and load management. Applying IPC before or after strength training has been shown to facilitate post-exercise recovery and reduce fatigue compared with traditional recovery methods such as static stretching or foam rolling [170]. Moreover, combining IPC with palm cooling during high-intensity resistance training further enhances performance by augmenting arousal responses [147]. These findings suggest that IPC can serve not only as an acute ergogenic aid but also as a complementary tool for recovery optimization and integrated performance strategies in both athletic and rehabilitation contexts.

CONCLUSIONS

IPC can significantly enhance physical performance measures (e.g., RM, time to failure, power output, and jump), supported by *moderate to high* certainty of evidence. However, it appears ineffective for $\dot{V}O_2$, strength, time to completion, MAOD, and balance, where evidence certainty is *low to very low*. Its effects are strongly influenced by sham conditions, warm-up protocols, and the specific IPC protocol applied. Moreover, most studies presented “some concerns” or

“high” risk of bias, highlighting methodological and reporting limitations in the current literature.

The most effective approach appears to be 3–4 × 5-min ischemia with an interval of approximately 42 min, followed by a standardized warm-up and endurance testing (e.g., time to exhaustion). This strategy shows the greatest benefits in males with lower training levels. For mechanistic studies, warm-up should be excluded and the IPC-to-testing interval limited to 6–7 min to better isolate physiological effects. Researchers should also clearly define whether “interval” refers to IPC-to-WU or IPC-to-testing to avoid ambiguity. The potential benefits of IPC for women, middle-aged populations, and elite athletes warrant further investigation.

Conflict of Interest

All authors declare no conflicts of interest related to the research, authorship, or publication of this article.

Availability of data and material

All data, codes and analysis process are available at <https://github.com/Zhangyilin-coder/IPC>.

Contributions

We sincerely thank all authors for any contribution to this study, with the third and fourth authors contributing equally with the second author. Zhang Yilin, Girard. O and Xie Yun jointly proposed and designed the topic of the article. Xie Yun and Girard. O supervised the completion of this research work. Zhang Yilin formulated the literature search strategy, while Zhang Yilin, Xu Kai, and Kong Hao conducted data extraction and analysis. Zhang Yilin, Xu Kai, and Yin Mingyue produced the article's results and figures. Zhang Yilin, Liu Chenghao, and Kong Hao created and revised the tables. Zhang Yilin drafted the initial version of the manuscript. Kilduff. L, Mota. GR, and Xie Yun reviewed the manuscript during its writing and revision, providing critical and constructive feedback to substantially enhance the quality of the research. Xie Yun, Kilduff. L, Mota. GR, and Girard. O conducted the final proofreading of the entire article.

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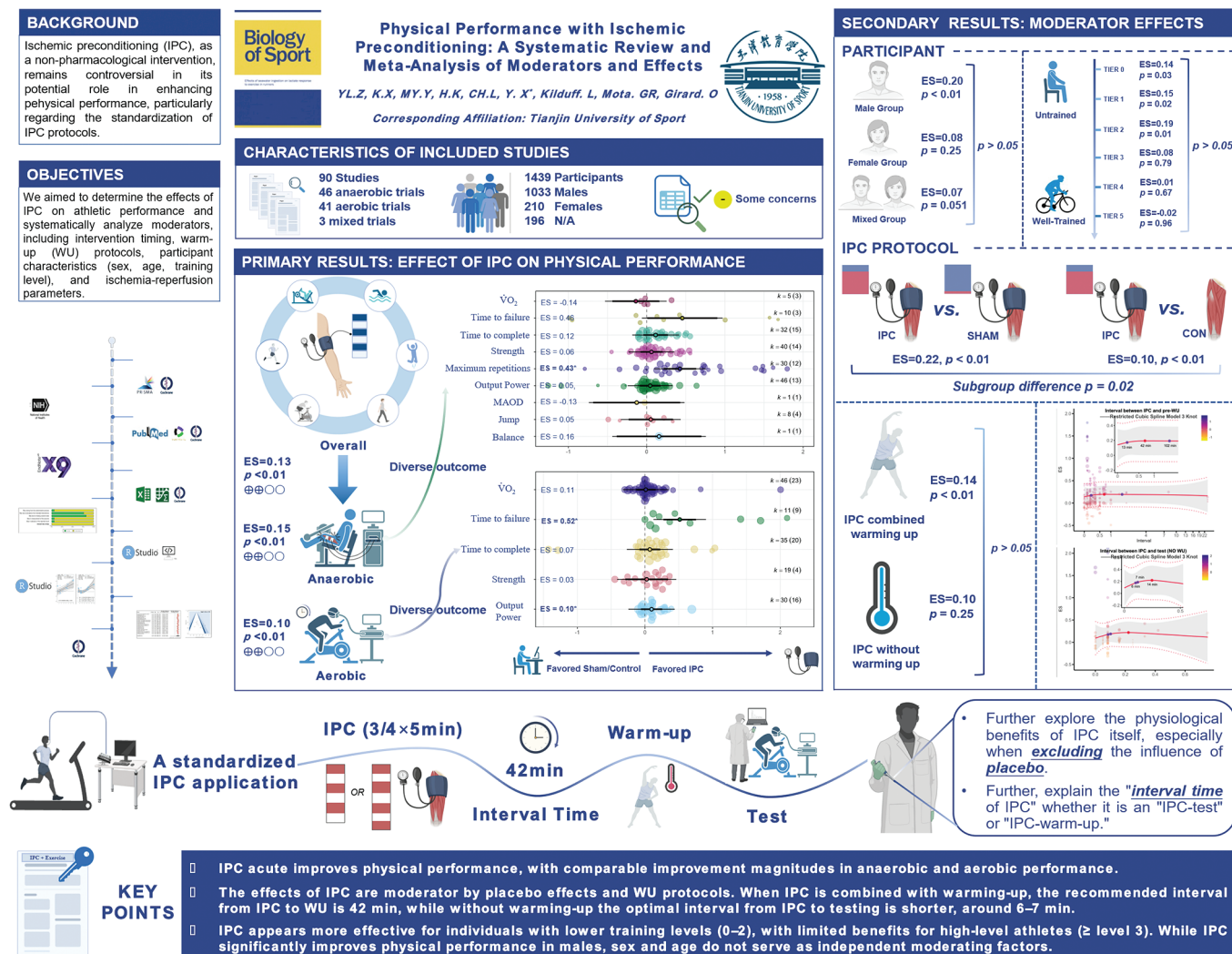
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SUPPLEMENTARY



ELECTRONIC SUPPLEMENTARY MATERIAL CONTENTS

TABLE S1.

Number	Material	Page
1	Electronic Supplementary Material Appendix S1 (PRISMA 2020 checklist)	
2	Electronic Supplementary Material Appendix S2 (Search strategy)	
3	Electronic Supplementary Material Appendix S3 (Physical performance risk of bias assessment)	
4	Electronic Supplementary Material Appendix S4 (Characteristics of the included studies)	
5	Electronic Supplementary Material Appendix S5 (Goodness-of-fit and correlation coefficient comparison results)	
6	Electronic Supplementary Material Appendix S6 (Statistical power analysis)	
7	Electronic Supplementary Material Appendix S7 (Physical performance detailed results of data analysis)	
8	Electronic Supplementary Material Appendix S8 (Funnel plots with Egger's test for exercise outcomes across different energy systems)	

ELECTRONIC SUPPLEMENTARY MATERIAL APPENDIX S1 (PRISMA 2020 CHECKLIST)**TABLE S2.**

Section/topic	#	Checklist item	Reported on page #
Enhancing Physical Performance with Ischemic Preconditioning: A Systematic Review and Meta-Analysis of Moderators and Performance Outcomes			
Title	1	Identify the report as a systematic review, meta-analysis, or both.	1
Structured summary	2	Provide a structured summary including, as applicable: background; objectives; data sources; study eligibility criteria, participants, and interventions; study appraisal and synthesis methods; results; limitations; conclusions and implications of key findings; systematic review registration number.	1
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of what is already known.	3, 4, 5, 6
Objectives	4	Provide an explicit statement of questions being addressed with reference to participants, interventions, comparisons, outcomes, and study design (PICOS).	6
METHODS			
Protocol and registration	5	Indicate if a review protocol exists, if and where it can be accessed (e.g., Web address), and, if available, provide registration information including registration number.	6
Eligibility criteria	6	Specify study characteristics (e.g., PICOS, length of follow-up) and report characteristics (e.g., years considered, language, publication status) used as criteria for eligibility, giving rationale.	6, 7
Information sources	7	Describe all information sources (e.g., databases with dates of coverage, contact with study authors to identify additional studies) in the search and date last searched.	7, 8, 9
Search	8	Present full electronic search strategy for at least one database, including any limits used, such that it could be repeated.	6
Study selection	9	State the process for selecting studies (i.e., screening, eligibility, included in systematic review, and, if applicable, included in the meta-analysis).	6, 7
Data collection process	10	Describe method of data extraction from reports (e.g., piloted forms, independently, in duplicate) and any processes for obtaining and confirming data from investigators.	7, 8, 9
Data items	11	List and define all variables for which data were sought (e.g., PICOS, funding sources) and any assumptions and simplifications made.	7, 8, 9
Risk of bias in individual studies	12	Describe methods used for assessing risk of bias of individual studies (including specification of whether this was done at the study or outcome level), and how this information is to be used in any data synthesis.	7
Summary measures	13	State the principal summary measures (e.g., risk ratio, difference in means).	9, 10
Synthesis of results	14	Describe the methods of handling data and combining results of studies, if done, including measures of consistency (e.g., I^2) for each meta-analysis.	9, 10, 11, 12
Risk of bias across studies	15	Specify any assessment of risk of bias that may affect the cumulative evidence (e.g., publication bias, selective reporting within studies).	7
Additional analyses	16	Describe methods of additional analyses (e.g., sensitivity or subgroup analyses, meta-regression), if done, indicating which were pre-specified.	11, 12
RESULTS			
Study selection	17	Give numbers of studies screened, assessed for eligibility, and included in the review, with reasons for exclusions at each stage, ideally with a flow diagram.	11
Study characteristics	18	For each study, present characteristics for which data were extracted (e.g., study size, PICOS, follow-up period) and provide the citations.	12
Risk of bias within studies	19	Present data on risk of bias of each study and, if available, any outcome level assessment (see item 12).	13
Results of individual studies	20	For all outcomes considered (benefits or harms), present, for each study: (a) simple summary data for each intervention group (b) effect estimates and confidence intervals, ideally with a forest plot.	14
Synthesis of results	21	Present results of each meta-analysis done, including confidence intervals and measures of consistency.	14
Risk of bias across studies	22	Present results of any assessment of risk of bias across studies (see Item 15).	13
Additional analysis	23	Give results of additional analyses, if done (e.g., sensitivity or subgroup analyses, meta-regression [see Item 16]).	14, 15, 16, 17

TABLE S2. Continue.

Section/topic	#	Checklist item	Reported on page #
DISCUSSION			
Summary of evidence	24	Summarize the main findings including the strength of evidence for each main outcome; consider their relevance to key groups (e.g., healthcare providers, users, and policy makers).	17, 18
Limitations	25	Discuss limitations at study and outcome level (e.g., risk of bias), and at review-level (e.g., incomplete retrieval of identified research, reporting bias).	n/a
Conclusions	26	Provide a general interpretation of the results in the context of other evidence, and implications for future research.	28
FUNDING			
Funding	27	Describe sources of funding for the systematic review and other support (e.g., supply of data); role of funders for the systematic review.	n/a

ELECTRONIC SUPPLEMENTARY MATERIAL APPENDIX S2 (SEARCH STRATEGY)

TABLE S3.

Database	retrieval strategy
WOS	(TS = ("remote ischemic preconditioning" OR "remote ischaemic preconditioning" OR "remote preconditioning" OR "remote conditioning" OR "remote ischemic conditioning" OR "remote ischaemic conditioning" OR "transient limb ischemia" OR "muscle ischemia" OR "ischemic preconditioning") AND TS = ("performance" OR sport* OR exercise OR "strength training" OR running OR swimming OR cycling OR athletes OR "athletic performance"))
Pubmed	((("remote ischemic preconditioning" [Title/Abstract] OR "remote ischaemic preconditioning" [Title/Abstract] OR "remote preconditioning" [Title/Abstract] OR "remote conditioning" [Title/Abstract] OR "remote ischemic conditioning" [Title/Abstract] OR "remote ischaemic conditioning" [Title/Abstract] OR "transient limb ischemia" [Title/Abstract] OR "muscle ischemia" [Title/Abstract] OR "ischemic preconditioning" [Title/Abstract]) AND ("performance" [Title/Abstract] OR "sport*" [Title/Abstract] OR "exercise" [Title/Abstract] OR "strength training" [Title/Abstract] OR "running" [Title/Abstract] OR "swimming" [Title/Abstract] OR "cycling" [Title/Abstract] OR "athletes" [Title/Abstract] OR "athletic performance" [Title/Abstract]))
Embase	('remote ischemic preconditioning':ti,ab OR 'remote ischaemic preconditioning':ti,ab OR 'remote preconditioning':ti,ab OR 'remote conditioning':ti,ab OR 'remote ischemic conditioning':ti,ab OR 'remote ischaemic conditioning':ti,ab OR 'transient limb ischemia':ti,ab OR 'muscle ischemia':ti,ab OR 'ischemic preconditioning':ti,ab) AND ('performance':ti,ab OR 'sport*':ti,ab OR 'exercise':ti,ab OR 'strength training':ti,ab OR 'running':ti,ab OR 'swimming':ti,ab OR 'cycling':ti,ab OR 'athletes':ti,ab OR 'athletic performance':ti,ab)

ELECTRONIC SUPPLEMENTARY MATERIAL APPENDIX S3 (CHARACTERISTICS OF THE INCLUDED STUDIES)

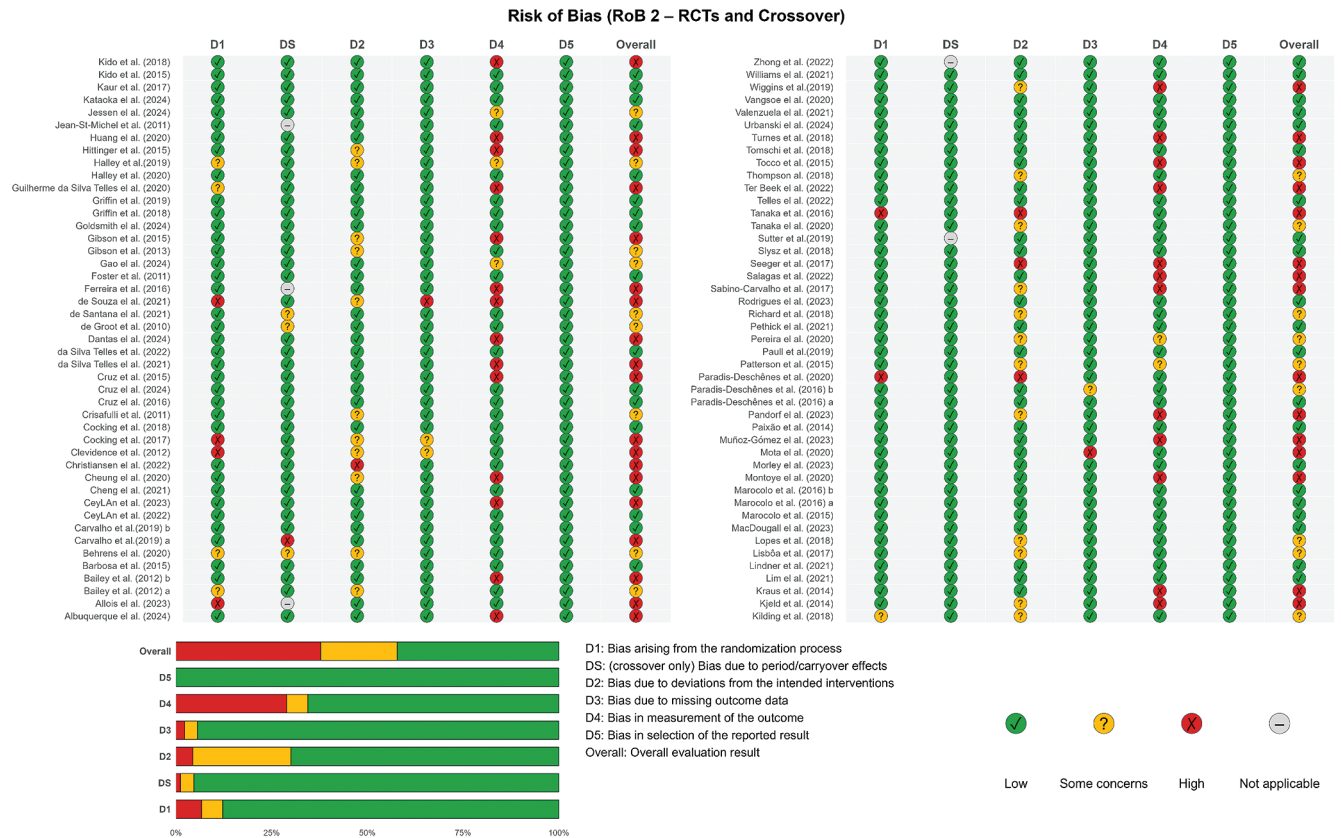


FIG. S2. Physical performance risk of bias assessment

ELECTRONIC SUPPLEMENTARY MATERIAL APPENDIX S4 (CHARACTERISTICS OF THE INCLUDED STUDIES)

TABLE S4. Characteristics of the included studies

Study	Study design	Comparison	Participant population	Age	Experience level	IPC sets	Pressure (mmHg)	IPC limb	Interval (h)	Timing	WU level	Type of exercise	Exercises protocols	performance outcome measure
Albuquerque et al. (2024)	RCOs	IPC vs. SHAM	14 black belt taekwondo athletes (M: 8, FM: 6)	18	4	4 × 5 min	187.5	Thighs (bilateral)	0	pre-WU	submax	Taekwondo	1 min low-intensity taekwondo kicking drills, then 3 CMJ (15 s rest).	Jump; TE
Allois et al. (2023)	RCTs	IPC vs. SHAM	19 healthy participants (M: 15; FM: 4)	27.5	1	3 × 5 min	250	Thighs (bilateral)	0.5	pre-WU	submax	RT	Biceps curl contraction test: 3 s contractions at 80% MVC (3 s rest) until failure.	Strength; RM
Bailey et al. (2012) (a)	RCOs	IPC vs. SHAM	13 healthy males at medium training level	25	2	4 × 5 min	220	Thighs (bilateral)	0.33 and 1	pre-WU	submax	Running	Graded maximal running test: 5 × 3 min followed by 2-min stages until volitional exhaustion; 5 km TT after 45 min rest.	TC; $\dot{V}O_2$
Bailey et al. (2012) (b)	RCOs	IPC vs. SHAM	13 healthy males at medium training level	25	2	4 × 5 min	220	Thighs (bilateral)	0 and 0.75	pre-WU	submax	Running	Graded maximal running test: 5 × 3 min (30 s rest); 5 km TT after 45 min rest.	TC; $\dot{V}O_2$

TABLE S4. Continue.

Study	Study design	Comparison	Participant population	Age	Experience level	IPC sets	Pressure (mmHg)	IPC limb	Interval (h)	Timing	WU level	Type of exercise	Exercises protocols	performance outcome measure
Barbosa et al. (2015)	RCOs	IPC vs. SHAM	22 healthy males	25	1	3 × 5 min	200	Thighs (bilateral)	0.42	pre-test	NO	RT	MVC Test: 60 handgrip reps at 45% MVC until failure.	RM
Behrens et al. (2020)	RCOs	IPC vs. SHAM	16 healthy adult males	26	2	3 × 5 min	254	Thighs (bilateral)	0.33	pre-WU	submax	RT	2 × 5 s at 50%, 70%, and 90% MVC; unilateral isometric knee extension until failure at 20% MVC.	TE; Strength
Carvalho et al. (2019) (a)	RCOs	IPC vs. SHAM	10 resistance-trained males	22	2	4 × 5 min	250	Alternate thighs (bilateral)	0.5	pre-WU	max	RT	1 × 85% 1RM MVC until concentric failure.	RM
Carvalho et al. (2020)	RCOs	IPC vs. SHAM	10 resistance-trained males	22	2	4 × 5 min	250	Alternate thighs (bilateral)	0.5	pre-WU	max	RT	3 × 3 s MVC (2 min rest);	Strength
Ceylan et al. (2022)	RCOs	IPC vs. SHAM	10 elite male judo athletes	20	5	3 × 5 min	220	Alternate thighs (bilateral)	NA	pre-test	NO	Judo	15 s, 30 s, and 30 s test intervals to throw a similarly-sized partner as fast as possible using "ippon-seoi-nage" technique (10 s rest);	RM
Ceylan et al. (2023)	RCOs	IPC vs. SHAM	13 elite male judo athletes	18.6	5	3 × 5 min	180	Alternate thigh (unilateral)	1	pre-WU	submax	Judo	Judo Turn Task immediately followed by IPC; record turn metrics with no start CMJ; strength or end, plus 30 min and 60 min related markers.	
Cheng et al. (2021)	RCOs	IPC vs. CON	15 male college basketballPhysical performance players	21	3	4 × 5 min	220	Thighs (bilateral)	0.25	pre-WU	submax	Running	6 × 30 s Wingate-style sprints (4 min rest);	P_{avg} ; P_{peak}
Cheung et al. (2020)	RCOs	IPC vs. SHAM/CON	16 adults engaged in recreational activities(M: 8, FM: 8)	21	1	4 × 5 min	191	Alternate thigh (unilateral)	NA	pre-WU	submax	Cycling	Incremental exercise to exhaustion test: male participants start at 100 W, female participants at 75 W, increasing by 1 W every 3-4 s.	TC; $\dot{V}O_2$
Christiansen et al. (2022)	RCOs	IPC vs. SHAM	12 healthy males with physical performance active	28	1	4 × 5 min	220	Thighs (bilateral)	0.18	pre-WU	submax	Cycling	12 min rest after warm up, 4 min cycling test (simulated 4,000 metre individual pursuit).	$\dot{V}O_2$; P_{avg}
Clevidence et al. (2012)	RCOs	IPC vs. CON	12 male cyclists	26.7	3	3 × 5 min	220	Alternate thigh (unilateral)	0.083	pre-test	NA	Cycling	P_{peak} cycling at 30%, 50%, and 70% of P_{peak} for 5 min each, then cycling at 90% of P_{peak} until exhaustion.	$\dot{V}O_2$
Cocking et al. (2017)	RCOs	IPC vs. SHAM	14 amateur cyclists	29	3	4 × 5 min	220	Alternate arms and thighs (both sides)	NA	pre-test	NA	Cycling	1 h Timed Cycling Test.	P_{avg}

TABLE S4. Continue.

Study	Study design	Comparison	Participant population	Age	Experience level	IPC sets	Pressure (mmHg)	IPC limb	Interval (h)	Timing	WU level	Type of exercise	Exercises protocols	performance outcome measure
Cocking et al. (2018)	RCOs	IPC vs. SHAM	12 male cyclists	36	3	4 × 5 min	220	Thighs (bilateral)	0.33	pre-WU	submax	Cycling	375 kJ TT immediately after the warm up.	TC; $\dot{V}O_2$; P_{avg}
Crisafulli et al. (2011)	RCOs	IPC vs. SHAM/CON	17 healthy males	35.2	1	3 × 5 min	50 > SBP	Thighs (bilateral)	0.083	pre-WU	submax	Cycling	Incremental exercise to exhaustion test: Start at 25 W, increase by 25 W/min until exhaustion. Supramaximal test at 130% P_{peak} .	TC; $\dot{V}O_2$; P_{avg}
Cruz et al. (2016)	RCOs	IPC vs. SHAM	15 amateur male cyclists	28	1	4 × 5 min	220	Thighs (bilateral)	0.5	pre-WU	submax	Running	After 5 min rest. 60 s seated sprint with 7.5% body weight resistance.	MAOD; $\dot{V}O_2$; P_{peak}
Cruz et al. (2024)	RCOs	IPC vs. SHAM	10 healthy adult males	27	0	4 × 5 min	220	Thighs (bilateral)	0.75	pre-test	NO	RT	2 min intervals with 10 MVC, each lasting ~1.4 s.	Strength
Cruz et al. (2015)	RCOs	IPC vs. SHAM	12 amateur cyclists	28	3	4 × 5 min	220	Thighs (bilateral)	1.5	pre-WU	submax	Cycling	After 5 min rest. Incremental exercise to exhaustion test: increase to 100% P_{peak} until exhaustion or rpm drop > 5 for 5 s.	$\dot{V}O_2$
da Silva Telles et al. (2021)	RCOs	IPC vs. SHAM	16 healthy adults (M: 18, FM: 6)	24.8	2	4 × 5 min	220	Alternate arms (bilateral)	0.083	pre-WU	submax	RT	45° leg press RM test: 80% 1 RM	RM
da Silva Telles et al. (2022)	RCOs	IPC vs. SHAM/CON	16 active elderly women	68.1	1	3 × 5 min	132	Alternate arms (bilateral)	0.083	pre-warm-up	submax	Walking	6-min walk test	TC
Dantas et al. (2024)	RCOs	IPC vs. SHAM	21 trained males	21	1	3 × 5 min	220	Thighs (bilateral)	0	pre-WU	submax	Running	6 × 35 m maximal sprints (10 s rest).	TC; P_{avg} ; P_{peak}
de Groot et al. (2010)	RCOs	IPC vs. CON	15 healthy adults (M: 12, FM: 3)	27	3	3 × 5 min	220	Thighs (bilateral)	0.083	pre-test	NA	Cycling	Incremental exercise to exhaustion test: start at 50 W, increase by 50 W every 4 min, then by 150 W every 4 min, until exhaustion.	$\dot{V}O_2$; P_{peak}
de Santana et al. (2021)	RCOs	IPC vs. SHAM	24 healthy adults (M: 18, FM: 6)	25.8	1	3 × 5 min	220	Alternate thighs (bilateral)	4	pre-WU	submax	RT	45° leg press RM test: 50% RM, repeated with random 72-h intervals.	RM
de Souza et al. (2021)	RCOs	IPC vs. SHAM	9 healthy young males	22.4	1	3 × 5 min	SBP < 50	Thighs (bilateral)	0.13	pre-WU	submax	RT	Unilateral MVIC (10 s), rest interval of 3 min and 3 sets with 2-min rest of dynamic unilateral leg extension (75% 1RM)	RM; Strength

TABLE S4. Continue.

Study	Study design	Comparison	Participant population	Age	Experience level	IPC sets	Pressure (mmHg)	IPC limb	Interval (h)	Timing	WU level	Type of exercise	Exercises protocols	performance outcome measure
Ferreira et al. (2016)	RCTs	IPC vs. SHAM	23 college swimmers	23.9	2	3 × 5 min	220	Thighs (bilateral)	0.17	pre-WU	submax	Swimming	Rest for 5 min after warm-up. 6 × 50 m sprints (20 s rest), Borg scale 5–6, effort level 2–3.	TC
Foster et al. (2011)	RCOs	IPC vs. CON	8 experienced cyclists (M: 6, FM: 2)	39	3	4 × 5 min	SBP < 20	Thigh (unilateral)	1.5	post-warm-up and pre-test	submax	Cycling	4–5 km TT	TC
Gao et al. (2024)	RCOs	IPC vs. SHAM/CON	22 healthy males	26.8	1	3 × 5 min	220	Arms (bilateral)	0.5	pre-WU	submax	Cycling	5 min rest after warm-up. 5 sets of 10 s (40 s rest) maximal sprints;	P _{avg} ; P _{peak}
Gibson et al. (2013)	RCOs	IPC vs. SHAM/CON	25 healthy adults (M: 16, FM: 9)	22.9	2	3 × 5 min	220	Alternate thighs (bilateral)	0.25	pre-WU	submax	Running	submaximal 30 m sprints × 2; 3 times max sprints of 10, 20, and 30 m (1 min rest);	TC
Gibson et al. (2015)	RCOs	IPC vs. SHAM/CON	16 well-trained team athletes (M: 7, FM: 9)	24	2	3 × 5 min	220	Alternate thigh (unilateral)	0.083	pre-WU	submax	Running	2 × 3 sprints followed by 5 × 6 s max effort sprints with 7.5% body weight resistance.	P _{peak}
Goldsmith et al. (2024)	RCOs	IPC vs. SHAM/CON	10 recreationPhysical performance active participants (M: 5, FM: 5)	31.8	1	4 × 5 min	220	Thighs (bilateral)	0.16	pre-test	NA	Cycling	Incremental exercise to exhaustion test: (10 W/min) until exhaustion.	VO ₂ ; P _{peak}
Griffin et al. (2018)	RCOs	IPC vs. SHAM	12 amateur male athletes	30	3	4 × 5 min	220	Thighs (bilateral)		pre-WU	submax	Cycling	3 min high-intensity cycling at 110 rpm and 10 min recovery cycling.	VO ₂ ; P _{peak}
Griffin et al. (2019)	RCOs	IPC vs. SHAM	12 healthy males engaged in recreational team sports	22	3	4 × 5 min	220	Alternate thigh (bilateral)	0.25	pre-WU	submax	Running	Repeated sprints protocol: 3 × 6 shuttle sprints (15 m each), alternating between standing and seated recovery, with passive recovery between sets.	TC
Guilherme da Silva Telles et al. (2020)	RCOs	IPC vs. SHAM	16 healthy adult males	24.8	2	4 × 5 min	220	Thigh (unilateral)	0.75	pre-WU	submax	RT	3 sets of training at 80% 1RM until concentric failure.	RM
Halley et al. (2020)	RCOs	IPC vs. CON	8 well-trained male canoe athletes	21	4	4 × 5 min	220	Thighs (bilateral)	0.33 and 0.66	pre-WU	submax	rowing	1000 m rowing TT.	TC; VO ₂ ; P _{avg}
Halley et al. (2019)	RCOs	IPC vs. SHAM	11 resistance-trained males	23.1	1	3 × 5 min	220	Thighs (bilateral)	0.16	pre-WU	submax	RT	3 × 5 min (120°/s extension; 300°/s flexion) at 40 cycles per min.	Strength

TABLE S4. Continue.

Study	Study design	Comparison	Participant population	Age	Experience level	IPC sets	Pressure (mmHg)	IPC limb	Interval (h)	Timing	WU level	Type of exercise	Exercises protocols	performance outcome measure
Hittinger et al. (2015)	RCOs	IPC vs. CON	15 male cyclists and triathletes	29.9	2	4 × 5 min	SBP < 10–20	Thighs (bilateral)	0.75	pre-test	NA	Cycling	(normoxic and hypoxic): 10 min submaximal exercise at 55% $\dot{V}O_{2peak}$, increasing 30 W every 2 min until exhaustion.	P_{peak}
Huang et al. (2020)	RCOs	IPC vs. SHAM	14 healthy non-athletic males	26	1	3 × 5 min	SBP < 50	Thighs (bilateral)	0.083	pre-WU	submax	RT	3 × maximal isokinetic knee extensions at 30, 150, and 270 deg/s; 30 × isokinetic endurance reps at 180 deg/s.	Strength; P_{avg}
Jean-St-Michel et al. (2011)	RCTs	IPC vs. SHAM	16 elite swimmers (M: 8, FM: 8)	18.8	4	4 × 5 min	SBP < 15	Arm (unilateral)	0	pre-WU	submax	Swimming	100 m swimming	TC
Jessen et al. (2024)	RCOs	IPC vs. SHAM	11 healthy, well-trained young males	25	2	3 × 2 min	180	Thighs (bilateral)	0.16	pre-WU	sumax	Cycling	4 min TT;	P_{avg}
Kataoka et al. (2024)	RCOs	IPC vs. SHAM/CON	39 healthy adults	26.5	1	4 × 5 min	110–150% AOP	Arm (unilateral)	0.05	pre-test	NA	RT	2 × 75 s maximal isokinetic unilateral elbow flexion/extension (2 min rest). Intervals between tests: 3–10 days.	Strength; P_{avg}
Kaur et al. (2017)	RCOs	IPC vs. SHAM	18 runners (M: 12, FM: 6)	27	1	3 × 5 min	220	Thighs (bilateral)	0.25	pre-WU	sumax	Running	incremental submaximal (65–85% $\dot{V}O_{2max}$) treadmill running protocols 3 × 5 min	$\dot{V}O_2$
Kido et al. (2015)	RCOs	IPC vs. CON	15 healthy active males	24	1	3 × 5 min	> 300	Thighs (bilateral)	0.083	pre-test	NA	Cycling	Work-to-Work Test: gradual increase in intensity every 3 min by 30 W, reaching 90% GET and 90% of max.	TE; $\dot{V}O_2$
Kido et al. (2018)	RCOs	IPC vs. CON	13 healthy active males	22.5	1	3 × 5 min	250	Thighs (bilateral)	0.083	pre-test	NA	Cycling	Work-to-Work Test: low intensity: 30 W for 3 min; medium intensity: 90% GET for 4 min; high intensity: 70% $\dot{V}O_{2max}$ until exhaustion.	TE; $\dot{V}O_2$
Kilding et al. (2018)	RCOs	IPC vs. SHAM	8 healthy, well-trained male cyclists	27	3	4 × 5 min	200	Thighs (bilateral)	0.083	pre-WU	submax	Cycling	Incremental and square-wave exercise tests; 4 km cycling TT.	TC; $\dot{V}O_2$
Kjeld et al. (2014)	RCOs	IPC vs. CON	14 oarsmen (M: 10, FM: 4)	28	4	4 × 5 min	SBP < 40	Forearm (unilateral)	0.5	post-warm-up and pre-test	submax	rowing	1000 m rowing TT.	TC

TABLE S4. Continue.

Study	Study design	Comparison	Participant population	Age	Experience level	IPC sets	Pressure (mmHg)	IPC limb	Interval (h)	Timing	WU level	Type of exercise	Exercises protocols	performance outcome measure
Kraus et al. (2014)	RCOs	IPC vs. SHAM	43 young adults in leisure activities (M: 27, FM: 16)	22.7	1	4 × 5 min	NA	Arm (unilateral)	0.25	pre-test	NA	Cycling	4 × 30 s Wingate anaerobic test, 150 rpm, 9% body weight load, 2 min rest intervals.	P _{avg} ; P _{peak}
Lim et al. (2021)	RCOs	IPC vs. SHAM	8 Singapore national badminton players (M: 6, FM: 2)	23.1	4	4 × 5 min	250	Arm (bilateral)		pre-WU	submax	Badminton	50 min badminton specific program, with 30 min rest followed by CMJ, sprint test and Yo-Yo intermittent recovery test.	TC; Jump; P _{avg} ; P _{peak}
Linchner et al. (2021)	RCOs	IPC vs. SHAM	14 NCAA Division II athletes (M: 12, FM: 2)	20	3	3 × 5 min	100% AOP	Thighs (bilateral)	0	pre-WU	submax	Running; Jump	25 min performance test (vertical jump, reactive strength index, standing broad jump, 10 m sprint, agility).	TC; Jump
Lisbão et al. (2017)	RCOs	IPC vs. SHAM	11 male competitive swimmers	20	3	4 × 5 min	220	Thighs (bilateral), Arm (unilateral)	1, 2 and 8	pre-WU	submax	Swimming	50 m freestyle TT: 3 consecutive tests.	TC
Lopes et al. (2018)	RCOs	IPC vs. SHAM	15 healthy males	25	1	3 × 5 min	220	Thighs (bilateral)	0.17	pre-WU	max	Running	10 rest after warm-up. 3 sets of 6 × 15 m shuttle sprints (180° direction change), 20 s active recovery.	TC; $\dot{V}O_2$
MacDougall et al. (2023)	RCOs	IPC vs. CON	12 well-trained rock climbers (M: 9, FM: 3)	30.7	2	5 × 2 min	> 300	Arm (unilateral)	0.33	post-warm-up and pre-test	submax	Rock climbing	Constant-intensity climbing hangboard test until failure.	TE; Strength
Marocolo et al. (2015)	RCOs	IPC vs. SHAM/CON	15 amateur swimmers	21	2	4 × 5 min	220	Alternate arm (unilateral)	0.083	pre-WU	submax	Swimming	100 m freestyle test.	TC
Marocolo et al. (2016) (a)	RCOs	IPC vs. SHAM/CON	13 healthy males	25.9	2	4 × 5 min	220	Alternate thigh (unilateral)	0.083	pre-WU	submax	RT	3 × maximum leg extension (2 min rest) with the predetermined 12 RM load	RM
Marocolo et al. (2016) (b)	RCOs	IPC vs. SHAM	21 healthy males	27.3	2	4 × 5 min	220	Alternate arm and thigh (unilateral)	0.07	pre-WU	submax	RT	Resistance Training Test: 12 RM load bicep curl (20 reps), followed by 3 × leg extensions (60% 12 RM, 2 min rest);	RM
Montoye et al. (2020)	RCOs	IPC vs. SHAM	12 healthy adults (M: 5, FM: 7)	20.4	1	3 × 5 min	220	Thigh (unilateral)	0	pre-WU	submax	Running	2.4 km test	TC
Morley et al. (2023)	RCOs	IPC vs. CON	15 healthy and recreationPhysical performance active adults (M: 9, FM: 6)	27	1	4 × 5 min	stop arterial inflow	Thighs (bilateral)	0.083	pre-WU	submax	Cycling	4 km test	TC; P _{avg}
Mota et al. (2020)	RCOs	IPC vs. SHAM	20 healthy adult females	23.1	1	3 × 3 min + 2 min reperfusion	SBP < 50	Arms (bilateral)	0.1	pre-WU	submax	Arm crank exercise	speed _{max} 3 min arm cycling exercise.	P _{avg} ; P _{peak}

TABLE S4. Continue.

Study	Study design	Comparison	Participant population	Age	Experience level	IPC sets	Pressure (mmHg)	IPC limb	Interval (h)	Timing	WU level	Type of exercise	Exercises protocols	performance outcome measure
Muñoz-Gómez et al. (2023)	RCOs	IPC vs. SHAM	9 older adults	69.1	0	3 × 5 min	SBP < 50	Thighs (bilateral)	0.083	pre-test	NA	Walking	20 min walking at 65–75% HR _{max} , RPE scale 12–13.	TC; Strength
Paixão et al. (2014)	RCOs	IPC vs. SHAM	15 amateur cyclists	30.2	2	4 × 5 min	250	Alternate thigh (unilateral)	0.2	pre-WU	submax	Cycling	2 × Wingate Test: After each test, 30 s sprints at 0.10 kg/kg load (10 min rest).	P _{peak}
Pandorf et al. (2023)	RCOs	IPC vs. SHAM	16 university swimmers (M: 5, FM: 11)	22	3	3 × 5 min	40–220	Thighs (bilateral)	0.2	pre-WU	submax	Swimming	swimming TT (250 m/500 m).	TC
Paradis-Deschênes et al. (2016) (a)	RCOs	IPC vs. SHAM	10 strength-trained males	25	2	3 × 5 min	200	Right thigh (unilateral)	0.3	pre-WU	submax	RT	5 × 5 s maximal knee extension test (1 min rest).	Strength
Paradis-Deschênes et al. (2016) (b)	RCOs	IPC vs. SHAM	17 strength-trained adults (M: 9, FM: 8)	25	2	3 × 5 min	200	Right thigh (unilateral)	0.3	pre-WU	submax	RT	5 × 5 s maximal knee extension test (1 min rest).	Strength
Paradis-Deschênes et al. (2020)	RCOs	IPC vs. CON	9 well-trained male road cyclists, runners, and triathletes	16.4	3	3 × 5 min	220	Alternate thigh (unilateral)	0.43	pre-WU	submax	Cycling	2 sets 5 km TT;	TC
Patterson et al. (2015)	RCOs	IPC vs. SHAM	14 healthy males	22.9	0	4 × 5 min	220	Thighs (bilateral)	0.5	pre-WU	submax	Running	Repeated Sprints: 12 × 6 s sprints, 1.0 Nm/kg torque load.	$\dot{V}O_{2i}$; P _{peak} ; P _{avg}
Paull et al. (2019)	RCOs	IPC vs. SHAM	10 NCAA Division I middle- and long-distance runners (M: 6, FM: 4)	21	4	4 × 5 min	220	Arm (right side)	0.75	pre-WU	submax	Running	Running at 110% $\dot{V}O_{2max}$ (~20.3 km/h, 5% incline) for > 2 min to exhaustion.	TE; $\dot{V}O_2$
Pereira et al. (2020)	RCOs	IPC vs. SHAM/CON	20 healthy adults (M: 10, FM: 10)	28.5	0	3 × 5 min	225	Non-dominant leg thighs and upper arms	0	pre-test	NA	RT	MVC test lasting 3–4 s, performed at least twice (120 s rest).	TE
Pethick et al. (2021)	RCOs	IPC vs. SHAM	10 healthy adults (M: 6, FM: 4)	25.9	0	3 × 5 min	225	Thigh (unilateral)	0.33	pre-test	NA	RT	40% MVC intermittent isometric knee extension contractions (6 s, rest 4 s) to task failure	TE
Richard et al. (2018)	RCOs	IPC vs. SHAM	9 elite long track speed skaters (M: 7, FM: 2)	23.3	4	3 × 5 min	SBP < 30	Arms (bilateral)	1	pre-WU	submax	Skating	20–40 min individual race warm-up, followed by 1000 m ice TT.	TC
Rodrigues et al. (2023)	RCOs	IPC vs. SHAM/CON	15 resistance-trained males	29.9	2	3 × 5 min	170	Arms (unilateral))	0.17	pre-WU	submax	RT	1 RM test	Strength

TABLE S4. Continue.

Study	Study design	Comparison	Participant population	Age	Experience level	IPC sets	Pressure (mmHg)	IPC limb	Interval (h)	Timing	WU level	Type of exercise	Exercises protocols	performance outcome measure
Sabino-Carvalho et al. (2017)	RCOs	IPC vs. SHAM/CON	18 healthy adults (M: 14, FM: 4)	23.15	1	4 × 5 min	220	Alternate thigh (unilateral)	0.16	pre-test	NA	Running	8 km/h, +1 km/h/min to exhaustion. 6 min baseline, +1 km/h/stage to exhaustion. 2 min at 60% V _{peak} , +0.5 km/h to exhaustion.	TE; $\dot{V}O_2$
Salagas et al. (2022)	RCOs	IPC vs. CON	12 healthy males	25.8	1	1 × 5 min	100% AOP	Arms (bilateral)	0	post-warm-up and pre-test	max	RT	perform 4 × bench press at 60% of 1RM (each lasting 12 s, 12 s rest).	RM
Seeger et al. (2017)	RCOs	IPC vs. SHAM	12 healthy adults (M: 10, FM: 2)	31	2	4 × 5 min	220	Thighs (bilateral)	0 and 24	pre-WU	submax	Running	5 km TT.	TC
Slysz et al. (2018)	RCOs	IPC vs. CON	12 healthy males	22	1	3 × 5 min	220	Thighs (bilateral)	0.17	pre-WU	submax	Walking	30-second Wingate test and subsequent (after 25 minutes of rest) incremental maximal aerobic test	P _{peak}
Sutter et al. (2019)	RCTs	IPC vs. SHAM	69 healthy older adults	61.1	0	5 × 5 min	20 > SBP	Arms (bilateral)	0	pre-test	NA	Balance	Standing on a platform with feet facing forward, maintaining balance for as long as possible, each trial lasting 30 s.	Balance
Tanaka et al. (2020)	RCOs	IPC vs. CON	14 healthy adult males	22.1	0	3 × 5 min	300	Thigh (unilateral)	0.083	pre-test	NA	RT	20% MVC sustained isometric unilateral knee extension until failure.	TE
Tanaka et al. (2016)	RCOs	IPC vs. CON	12 healthy males	22	0	3 × 5 min	> 300	Thigh (unilateral)	0.083	pre-test	NA	RT	MVC Test: gradual torque increase to max, 3 × 3 s (1 min rest); Submaximal Fatigue Test: 20% MVC torque until failure.	Strength; TE
Telles et al. (2022)	RCOs	IPC vs. SHAM/CON	16 males with recreational training	27.8	1	4 × 5 min	220	Arms (bilateral)	0.17	pre-WU	submax	RT	3 × 3-5 reps at 60-80% perceived max (1 min rest) before strength testing.	Strength
Ter Beek et al. (2022)	RCOs	IPC vs. SHAM	14 healthy adult males	24.9	2	4 × 5 min	250	Thighs (bilateral)		pre-WU	submax	Cycling	Incremental exhaustion test: 105 W for 7 min, increasing by 35 W every 2 min at 70 rpm until exhaustion.	$\dot{V}O_2$; P _{peak}
Thompson et al. (2018)	RCOs	IPC vs. SHAM/CON	18 top Canadian university track and field sprinters (M: 10, FM: 8)	20.85	4	3 × 5 min	220	Thighs (bilateral)	0.25	post-warm-up and pre-test	submax	Running	4 × 20 m sprints (5 min rest).	TC

TABLE S4. Continue.

Study	Study design	Comparison	Participant population	Age	Experience level	IPC sets	Pressure (mmHg)	IPC limb	Interval (h)	Timing	WU level	Type of exercise	Exercises protocols	performance outcome measure
Tocco <i>et al.</i> (2015)	RCOs	IPC vs. SHAM	16 male skilled runners	34.6	3	3 × 5 min	220	Riternate thigh (unilateral)	0.25	pre-WU	submax	Running	5 km selfpaced run	VO ₂
Tomschi <i>et al.</i> (2018)	RCOs	IPC vs. SHAM	10 healthy males	24.3	0	4 × 5 min	120, 220	Right arm (unilateral)	0.083	pre-test	NA	Cycling	incremental power test at 60 rpm until exhaustion.	VO ₂ ; P _{avg}
Tumes <i>et al.</i> (2018)	RCOs	IPC vs. CON	16 male rowers at national and regional level	24	4	3 × 5, 3 × 10 min	220	Thigh (unilateral)	0.5	pre-WU	submax	Rowing	5 min rest after warm-up. 2000 m Rowing TT.	TC; VO ₂ ; P _{avg}
Urbanski <i>et al.</i> (2024)	RCOs	IPC vs. SHAM	43 physical performance active individuals (M: 24, FM: 19)	20	2	1 × 5 min	220	Upper and lower limbs simultaneously (unilateral)	0.083	post-warm-up and pre-test	submax	Rowing	500 m Physical performance-out rowing trial.	TC; P _{peak} ; P _{avg}
Valenzuela <i>et al.</i> (2021)	RCOs	IPC vs. SHAM	16 male healthy adults	23	1	3 × 5 min	220	Arms (bilateral)	0.5	pre-WU	submax	RT	resistance exercise: 3 × 3 reps to failure at 60% 1RM, 2 min passive rest between sets.	RM; Strength
Vangoe <i>et al.</i> (2020)	RCOs	IPC vs. CON	12 male well-trained cyclists	32	2	3 × 5 min	200	Thighs (bilateral)	0.05	pre-WU	submax	Cycling	1 km test.	TC; P _{peak} ; P _{avg}
Wiggins <i>et al.</i> (2019)	RCOs	IPC vs. SHAM	13 male athletes regularly engaging in endurance training	24	1	4 × 5 min	220	Thighs (bilateral)	0.17	pre-WU	submax	Cycling	6 min cycling at intensities 15% below anaerobic threshold and 85% VO _{2max} , then 5 km TT.	TC; VO ₂
Williams <i>et al.</i> (2021)	RCOs	IPC vs. SHAM	20 international and national level swimmers (M: 14, FM: 6)	20	5	4 × 5 min	194	Thighs (bilateral)	2 and 24	pre-WU	submax	Swimming	100 m and 200 m TT.	TC
Zhong <i>et al.</i> (2022)	RCTs	IPC vs. SHAM	79 healthy adult males	23.96	0	4 × 5 min	180	Arms (bilateral)	0.5	pre-WU	submax	Cycling	Phase 1: 4 km altitude simulation with 0.75 h hypoxic treatment, 4.25 h graded exercise test (VO _{2max}), 0.5 h recovery; Phase 2: 8 days post-IPC with direct physiological variable testing.	VO ₂

IPC: ischemic preconditioning; SHAM: sham intervention; CON: no intervention; vs.: versus; sets: Ischaemia and reperfusion duration for IPC; WU: warm-up; M: male; FM: female; NA: unknown; NO: no warm-up component; RT: resistance training; TC: Time to complete; TE: Time to exhausted; RM: maximum number of repetitions; TT: Time trial; CMJ: Countermovement Jump; s: second; min: minute; h: hour; P_{avg}: Average Power Output; P_{peak}: Peak Power Output; MVC: Maximum Voluntary Contraction; MIVC: Maximum Isotonic Voluntary Contraction; FSKT: Frequency Speed of Kick Test; m: meter; km: kilometer; W: watt; reps: repetitions; SBP: systolic blood pressure; AOP: arterial occlusion pressure;

ELECTRONIC SUPPLEMENTARY MATERIAL APPENDIX S5 (GOODNESS-OF-FIT AND CORRELATION COEFFICIENT COMPARISON RESULTS)**TABLE S5.** Comparative analysis of the goodness of fit for exercise performance with respect to the interval time of warm-up content without differentiation.

PHYSICAL PERFORMANCE (interval)	linear	Cubic Polynomial Model_2	Cubic Polynomial Model_3	Restricted Cubic Spline Model_4	Natural Cubic Spline Model	Restricted Cubic Spline Model_3
logLik:	-110.4756	-109.5485	-109.4249	-109.3402	-109.3402	-109.869
deviance:	220.9512	219.0969	218.8498	218.6804	218.6804	219.7379
AIC:	230.9512	231.0969	232.8498	232.6804	232.6804	231.7379
BIC:	249.3861	253.1984	258.611	258.4416	258.4416	253.8394
AICc:	231.1588	231.3896	233.2428	233.0734	233.0734	232.0306

TABLE S6. Comparative analysis of the goodness of fit between warm-up interval durations and exercise performance

pre-wu (interval)	linear	Cubic Polynomial Model_2	Cubic Polynomial Model_3	Restricted Cubic Spline Model_4	Natural Cubic Spline Model	Restricted Cubic Spline Model_3
logLik:	-37.98233	-37.19718	-37.19718	-36.96561	-36.9654	-37.60517
deviance:	75.96465	74.39437	74.39437	73.93121	73.93079	75.21034
AIC:	85.96465	86.39437	86.39437	87.93121	87.93079	87.21034
BIC:	102.32965	106.00152	106.00152	110.77005	110.76962	106.81749
AICc:	86.28211	86.84357	86.84357	88.53662	88.5362	87.65954

TABLE S7. Comparative analysis of the goodness of fit between intervals without warm-up and exercise performance

pre-test (interval)	linear	Cubic Polynomial Model_2	Cubic Polynomial Model_3	Restricted Cubic Spline Model_4	Natural Cubic Spline Model	Restricted Cubic Spline Model_3
logLik:	-59.00176	-58.77829	-58.22862	-57.57053	-57.56976	-58.50851
deviance:	118.00352	117.55658	116.45724	115.14107	115.13952	117.01701
AIC:	128.00352	129.55658	130.45724	129.14107	129.13952	129.01701
BIC:	139.91366	143.77326	146.9542	145.63803	145.63648	143.2337
AICc:	128.81433	130.72324	132.05724	130.74107	130.73952	130.18368

TABLE S8. Goodness-of-fit analysis of exercise performance across participant age groups

Age (Physical performance)	linear	Cubic Polynomial Model_2	Cubic Polynomial Model_3	Restricted Cubic Spline Model_4	Natural Cubic Spline Model	Restricted Cubic Spline Model_3
logLik:	-109.6076	-108.9525	-108.2293	-105.9413	-109.6076	-109.1073
deviance:	219.2153	217.9051	216.4586	211.8826	219.2153	218.2145
AIC:	229.2153	229.9051	230.4586	225.8826	229.2153	230.2145
BIC:	247.6502	252.0066	256.2198	251.6439	247.6502	252.316
AICc:	229.4229	230.1978	230.8516	226.2756	229.4229	230.5072

TABLE S9. Goodness-of-fit comparison of anaerobic performance across participant age groups

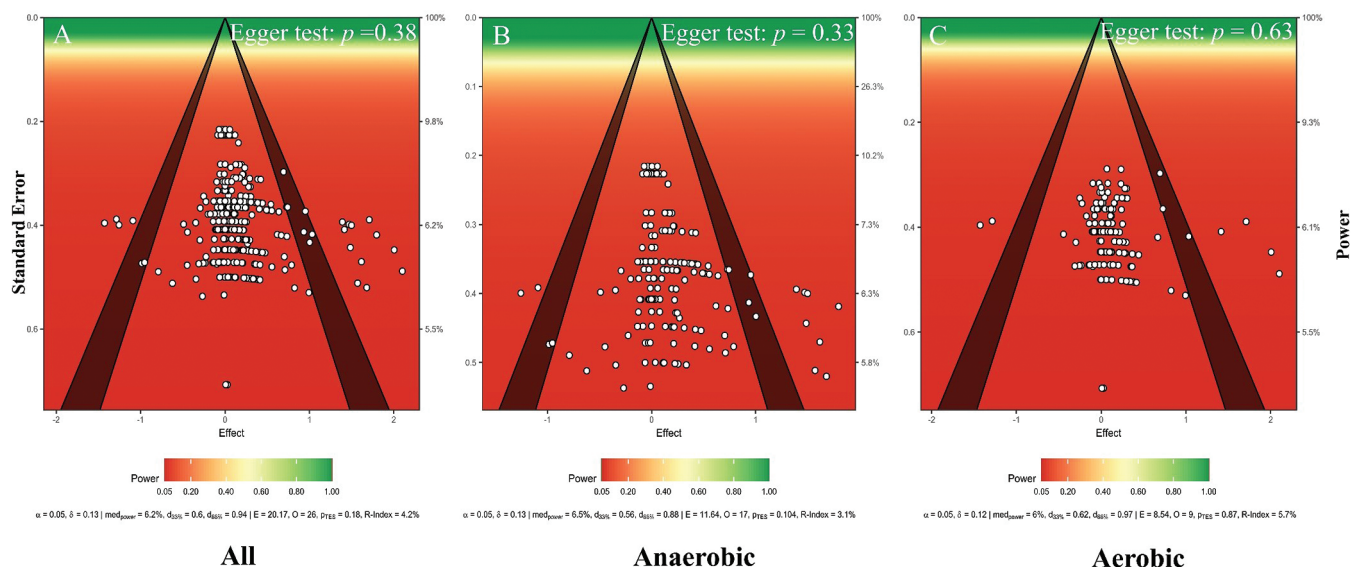
Age (anaerobic)	linear	Cubic Polynomial Model_2	Cubic Polynomial Model_3	Restricted Cubic Spline Model_4	Natural Cubic Spline Model	Restricted Cubic Spline Model_3
logLik:	-65.80637	-65.47321	-64.96391	-63.99098	-65.80637	-64.8716
deviance:	131.61274	130.94643	129.92783	127.98195	131.61274	129.7432
AIC:	141.61274	142.94643	143.92783	141.98195	141.61274	141.7432
BIC:	157.32106	161.76122	165.83712	163.89124	157.32106	160.558
AICc:	141.97637	143.46177	144.62348	142.67761	141.97637	142.2585

TABLE S10. Goodness-of-fit comparison of aerobic performance across participant age groups

Age (aerobic)	linear	Cubic Polynomial Model_2	Cubic Polynomial Model_3	Restricted Cubic Spline Model_4	Natural Cubic Spline Model	Restricted Cubic Spline Model_3
logLik:	-57.74554	-57.17875	-56.49745	-56.36723	-57.74554	-57.21918
deviance:	115.49108	114.35749	112.9949	112.73446	115.49108	114.43837
AIC:	123.49108	124.35749	124.9949	124.73446	123.49108	124.43837
BIC:	135.22898	138.99376	142.51479	142.25434	135.22898	139.07463
AICc:	123.78959	124.81204	125.64106	125.38061	123.78959	124.89291

TABLE S11. Comparison of the goodness of fit of effect sizes for different levels of meta-analyses

Last model results								
PHYSICAL PERFORMANCE(interval)								
	df	AIC	BIC	AICc	logLik	LRT	pval	QE
four-level	4	261.7094	276.6942	261.8392	-126.8547	NA	NA	426.5362
three-level	3	263.8613	275.0999	263.939	-128.9307	4.15198	0.0415859	426.5362
PHYSICAL PERFORMANCE(anaerobic)								
	df	AIC	BIC	AICc	logLik	LRT	pval	QE
four-level	4	132.7224	145.3123	132.9619	-62.36119	NA	NA	242.0826
three-level	3	137.6712	147.1137	137.814	-65.8356	6.948821	0.0083875	242.0826
PHYSICAL PERFORMANCE(aerobic)								
	df	AIC	BIC	AICc	logLik	LRT	pval	QE
three-level	3	123.3172	132.1421	123.4937	-58.65861	NA	NA	180.8781
two-level	2	132.6907	138.574	132.7783	-64.34536	11.37351	0.000745	180.8781

ELECTRONIC SUPPLEMENTARY MATERIAL APPENDIX S6 (STATISTICAL POWER ANALYSIS)**FIG. S3.** Statistical power of IPC on athletic performance and Egger's test results

Note: The vertical solid line represents the pooled effect size (Hedges $g = -0.50$ and -0.30), the vertical dash line represents the adjusted pooled effect size. Significance contours at .05 and .01 levels are noted by the shaded area. med_{power} indicates the median power of Physical performance included effect sizes. $d_{33\%}$ and $d_{66\%}$ indicate the true effect sizes necessary for achieving 33% and 66% levels of median power. E, O, and PTES show the results of a test of excess significance. R-index denotes the expected replicability of findings.

ELECTRONIC SUPPLEMENTARY MATERIAL APPENDIX S7 (PHYSICAL PERFORMANCE DETAILED RESULTS OF DATA ANALYSIS)**TABLE S12.** Effects of IPC on sport performance—Three or Four-level model

Outcome	Studies(K)	Effect size(n)	Effect size	95%CI	95%CI_adj	p-value	p-value_adj	t-value	Q test	I ² -Level 2	I ² -Level 3	I ² -Level 4	PI	p-Egger
Physical performance	90	314	0.1318	[0.0571; 0.2066]	[0.0719; 0.1918]	0.0006	< 0.0001	3.4705	426.536	0.00%	9.13%	5.74%	[-0.1787; 0.4424]	0.3854
Anaerobic	49	173	0.1451	[0.063; 0.2271]	[0.0469; 0.2432]	0.0009	0.004	3.5757	242.083	0.00%	13.64%	0.00%	[-0.1429; 0.4331]	0.3295
Aerobic	44	141	0.0994	[-0.0126; 0.2114]	[0.0101; 0.1887]	0.0816	0.0301	2.2517	180.878	0	0.1653	0	[-0.2741; 0.4728]	0.6324

K: number of studies; n: Total number of effects included; 95%CI: Unadjusted 95% confidence interval (range of effect size estimates); 95%CI_adj: Adjusted 95% confidence interval (corrected for multilevel models or heterogeneity);

p-value_adj: Adjusted p-value (e.g., corrected for multiple comparisons or model adjustments); t-value: t-test statistic (for testing significance of the effect size); Q test: Q statistic for heterogeneity test (assessing between-study heterogeneity).

I²-Level 2/3/4: Heterogeneity proportions in multilevel models; PI: Prediction Interval; p-Egger: Egger test p-value to detect publication bias (e.g. $p < 0.05$ for possible bias);

TABLE S13. Subgroup analyses of IPC on sport performance—Three or Four-level model (1)

Variable	Moderator	Studies (K)	Effect size(n)	Effect size	95%CI	95%CI_adj
Exercise type	aerobic	44	141	0.1254	[0.0169; 0.2339]	[0.0431; 0.2077]
	anaerobic	49	173	0.1368	[0.0414; 0.2322]	[0.0570; 0.2166]
Comparison	IPC vs. CON	33	95	0.223	[0.1152; 0.3309]	[0.0942; 0.3519]
	IPC vs. SHAM	73	219	0.0961	[0.0162; 0.1759]	[0.0345; 0.1576]
Sex	sexmale	55	182	0.2008	[0.1041; 0.2975]	[0.1192; 0.2824]
	sexmixed	29	97	0.0646	[-0.0569; 0.1862]	[-0.0003; 0.1295]
	sexNA	5	18	-0.112	[-0.4487; 0.2248]	[-0.7221; 0.4982]
	sexfemale	6	17	0.0845	[-0.1206; 0.2895]	[-0.0813; 0.2502]
Exprence_level	level2	24	76	0.1845	[0.0409; 0.3282]	[0.0419; 0.3272]
	level0	10	35	0.143	[-0.0992; 0.3852]	[0.0233; 0.2627]
	level1	29	116	0.1508	[0.0280; 0.2736]	[0.0283; 0.2734]
	level3	15	43	0.0819	[-0.1231; 0.2870]	[-0.0100; 0.1739]
	level4	9	37	0.0135	[-0.2370; 0.2640]	[-0.0602; 0.0872]
	level5	3	7	-0.0206	[-0.4335; 0.3922]	[-0.5265; 0.4852]
IPC_sets	4 × 5 min	43	157	0.107	[-0.0004; 0.2144]	[0.0201; 0.1938]
	1 × 5 min	2	7	0.6031	[0.1210; 1.0851]	[-6.6568; 7.8629]
	3 × 2 min	1	1	-0.0166	[-0.9129; 0.8798]	[NA; NA]
	3 × 10 min	1	3	0.1761	[-0.2101; 0.5623]	[-0.0273; 0.3794]
	3 × 3 min + 2 min reperfusion	1	2	-0.0613	[-0.6862; 0.5636]	[-0.0635; -0.0591]
	3 × 5 min	41	138	0.1422	[0.0280; 0.2565]	[0.0516; 0.2329]
	5 × 2 min	1	3	0.1333	[-0.6156; 0.8821]	[-0.7613; 1.0279]
	5 × 5 min	1	1	0.1584	[-0.4117; 0.7284]	[NA; NA]
	8 × 5 min	1	2	0.0191	[-0.4499; 0.4881]	[-0.0985; 0.1367]
Warm-up	NO	22	84	0.0987	[-0.0430; 0.2404]	[-0.0757; 0.2731]
	YES	70	230	0.1433	[0.0577; 0.2289]	[0.0662; 0.2204]

TABLE S13. Subgroup analyses of IPC on sport performance—Three or Four-level model (2)

Variable	p-value	p-value_adj	t-value	F-test	Q test	I ² -Level 2	I ² -Level 3	I ² -Level 4	p _{-diff}
Exercise type	0.0237	0.0038	2.2735	$F_{(2,312)} = 6.027$	426.533	0	0.0926	0.0583	0.8707
	0.0051	0.0013	2.8218						
Comparison	0.0001	0.0013	4.0702	$F_{(2,312)} = 8.752$	421.295	0	0.0756	0.0561	0.0221
	0.0185	0.0027	2.3672						
Sex	0.0001	0	4.0857	$F_{(4,310)} = 4.528$	419.73	0	0.0834	0.0613	intrcpt
	0.2963	0.0508	1.0462						0.0804
	0.5135	0.6334	-0.6542						0.08
	0.4183	0.245	0.8105						0.2537
Expereince_level	0.012	0.0137	2.5277	$F_{(6,308)} = 2.37$	424.114	0	0.097	0.0588	no difference
	0.2463	0.0248	1.1616						
	0.0162	0.0181	2.4171						
	0.4323	0.0762	0.7863						
	0.9154	0.6774	0.1063						
	0.9217	0.8603	-0.0983						
IPC_sets	0.0509	0.0173	1.9601	$F_{(9,305)} = 1.84$	421.29	0	0.0996	0.0608	intrcpt
	0.0144	0.4863	2.4619						0.049
	0.971	NA	-0.0364						
	0.3703	0.0685	0.8972						
	0.847	0.0018	-0.1931						
	0.0149	0.003	2.4491						
	0.7264	0.3094	0.3502						
	0.585	NA	0.5466						
	0.9361	0.6456	0.0802						
Warm-up	0.1716	0.2467	1.3703	$F_{(2,312)} = 6.156$	426.052	0	0.0945	0.0542	0.5884
	0.0011	0.0004	3.2928						

K: number of studies; n: Total number of effects included; 95%CI: Unadjusted 95% confidence interval (range of effect size estimates); 95%CI_adj: Adjusted 95% confidence interval (corrected for multilevel models or heterogeneity); p-value_adj: Adjusted p-value (e.g., corrected for multiple comparisons or model adjustments); t-value: t-test statistic (for testing significance of the effect size); Q test: Q statistic for heterogeneity test (assessing between-study heterogeneity); I²-Level 2/3: Heterogeneity proportions in multilevel models; PI: Prediction Interval; p-Egger: Egger test p-value to detect publication bias (e.g. $p < 0.05$ for possible bias); Moderator: Subgroup category (e.g., intervention type, population characteristics); F-test: F-statistic for ANOVA or model significance; p_{-diff}: p-value for subgroup differences; intrcpt: Intercept term in the model (baseline effect); NA: Data not available or not applicable; CON: Control group (no intervention); SHAM: Sham intervention group (sham or simulated intervention).

TABLE S14. Subgroup analyses of IPC on anaerobic sport performance—Three or Four-level model (1)

Variable	Moderator	Studies(K)	Effect size(n)	Effect size	95%CI	95%CI_adj
Comparison	IPC vs. CON	15	42	0.2165	[0.0659; 0.3672]	[0.0378; 0.3953]
	IPC vs. SHAM	45	131	0.1256	[0.0229; 0.2283]	[0.0390; 0.2122]
Sex	female	4	10	0.1085	[-0.1542; 0.3711]	[-0.2113; 0.4283]
	male	31	100	0.2212	[0.0932; 0.3493]	[0.1134; 0.3291]
	mixed	16	58	0.0877	[-0.0614; 0.2367]	[0.0071; 0.1682]
	NA	2	5	-0.261	[-0.7449; 0.2229]	[-6.7358; 6.2137]
Experience_level	level0	6	16	0.1568	[-0.1456; 0.4592]	[-0.0661; 0.3798]
	level1	16	72	0.1557	[-0.0044; 0.3158]	[0.0188; 0.2926]
	level2	15	51	0.2151	[0.0343; 0.3959]	[-0.0103; 0.4406]
	level3	4	14	0.1435	[-0.2234; 0.5104]	[-0.0827; 0.3697]
	level4	5	15	-0.0264	[-0.3623; 0.3095]	[-0.0519; -0.0010]
	level5	3	5	-0.0592	[-0.4860; 0.3677]	[-0.4253; 0.3070]
IPC_sets	1 × 5 min	1	1	1.6166	[0.6521; 2.5810]	[NA; NA]
	3 × 5 min	26	85	0.1279	[-0.0121; 0.2679]	[0.0438; 0.2119]
	4 × 5 min	21	86	0.1293	[-0.0133; 0.2720]	[-0.0162; 0.2749]
	5 × 5 min	1	1	0.1584	[-0.3853; 0.7020]	[NA; NA]
Warm-up	NO	9	35	0.0815	[-0.1290; 0.2920]	[-0.0569; 0.2199]
	YES	40	138	0.1629	[0.0517; 0.2740]	[0.0638; 0.2619]
Outcome	Balance	1	1	0.1584	[-0.3825; 0.6992]	[NA; NA]
	Jump	4	8	0.0526	[-0.2318; 0.3369]	[-0.4893; 0.5944]
	MAOD	1	1	-0.1275	[-0.6833; 0.4282]	[-0.4533; 0.1983]
	P	13	46	0.045	[-0.0873; 0.1774]	[-0.0542; 0.1443]
	RM	12	30	0.4262	[0.2188; 0.6337]	[0.1157; 0.7368]
	Strength	14	40	0.0617	[-0.0792; 0.2027]	[-0.0631; 0.1866]
	Time to complete	15	32	0.1148	[-0.0404; 0.2701]	[-0.0078; 0.2375]
	Time to failure	3	10	0.4555	[0.0073; 0.9036]	[-1.4668; 2.3777]
	$\dot{V}O_2$	3	5	-0.1383	[-0.4383; 0.1617]	[-0.9128; 0.6362]

TABLE S14. Subgroup analyses of IPC on anaerobic sport performance—Three or Four-level model (2)

Variable	p-value	p-value_adj	t-value	F-test	Q test	I ² -Level 2	I ² -Level 3	p _{diff}
Comparison	0.0051	0.021	2.8373	F (2 , 171) = 5.029	240.901	0	0.1326	0.2187
	0.0168	0.0056	2.4143					
Sex	0.4161	0.3615	0.8152	F (4 , 169) = 3.434	236.077	0	0.1246	no difference
	0.0008	0.0002	3.4119					
	0.2471	0.0356	1.1614					
	0.2884	0.6989	-1.0649					
Experience_level	0.3074	0.1248	1.0239	F (6 , 167) = 1.825	239.265	0	0.1471	no difference
	0.0566	0.0293	1.9198					
	0.02	0.0598	2.3493					
	0.4411	0.1336	0.7722					
	0.8767	0.0451	-0.1554					
	0.7847	0.5283	-0.2736					
IPC_sets	0.0011	NA	3.3089	F (4 , 169) = 4.433	232.091	0	0.1297	1 × 5
	0.0731	0.0046	1.8031					0.003
	0.0753	0.0778	1.7895					0.003
	0.566	NA	0.575					0.0101
Warm-up	0.4458	0.1909	0.7642	F (2 , 171) = 4.475	241.445	0	0.138	0.5007
	0.0043	0.002	2.8925					
Outcome	0.564	NA	0.5782	F (9 , 164) = 2.722	225.127	0	0.1244	
	0.7156	0.7711	0.365					
	0.6511	0.2524	-0.453					
	0.5026	0.3434	0.6719					
	0.0001	0.012	4.0565					
	0.3883	0.2958	0.8649					
	0.1461	0.0644	1.4603					
	0.0464	0.4032	2.0068					
	0.364	0.5566	-0.9103					

K: number of studies; n: Total number of effects included 95%CI: Unadjusted 95% confidence interval (range of effect size estimates); 95%CI_adj: Adjusted 95% confidence interval (corrected for multilevel models or heterogeneity); p-value_adj: Adjusted p-value (e.g., corrected for multiple comparisons or model adjustments); t-value: t-test statistic (for testing significance of the effect size); Q test: Q statistic for heterogeneity test (assessing between-study heterogeneity); I²-Level 2/3: Heterogeneity proportions in multilevel models; PI: Prediction Interval; Moderator: Subgroup category (e.g., intervention type, population characteristics); F-test: F-statistic for ANOVA or model significance; p-diff: p-value for subgroup differences; intrcpt: Intercept term in the model (baseline effect); NA: Data not available or not applicable; CON: Control group (no intervention); SHAM: Sham intervention group (sham or simulated intervention). MAOD: Maximum accumulative oxygen deficit; P: power output; RM: Maximum number of repetitions of the Exhaustion Test; $\dot{V}O_2$: oxygen uptake;

TABLE S15. Effects of IPC on aerobic sport performance—Three or Four-level model (1)

Variable	Moderator	Studies(K)	Effect size(n)	Effect size	95%CI	95%CI_adj
Comparison	IPC vs. CON	17	53	0.21	[0.0479; 0.3720]	[-0.0041; 0.4240]
	IPC vs. SHAM	31	88	0.0413	[-0.0858; 0.1684]	[-0.0318; 0.1145]
Sex	female	3	7	0.0989	[-0.2159; 0.4137]	[-0.3539; 0.5517]
	male	23	82	0.1483	[-0.0005; 0.2971]	[0.0098; 0.2868]
	mixed	15	39	0.0309	[-0.1643; 0.2260]	[-0.1062; 0.1679]
	NA	3	13	0.0391	[-0.4331; 0.5112]	[-0.2763; 0.3544]
Experence_level	level0	4	19	0.1089	[-0.2892; 0.5070]	[-0.0204; 0.2382]
	level1	13	44	0.1098	[-0.0821; 0.3016]	[-0.1577; 0.3772]
	level2	9	25	0.1322	[-0.1014; 0.3658]	[0.0389; 0.2255]
	level3	11	29	0.0574	[-0.1880; 0.3028]	[-0.0601; 0.1749]
	level4	5	22	0.0537	[-0.2942; 0.4017]	[-0.1403; 0.2478]
	level5	1	2	0.1552	[-0.4609; 0.7712]	[0.1445; 0.1659]
IPC_sets	1 × 5 min	1	6	0.2728	[-0.2436; 0.7892]	[-0.2386; 0.7842]
	3 × 10 min	1	3	0.143	[-0.3155; 0.6015]	[-0.2298; 0.5158]
	3 × 2 min	1	1	-0.0166	[-0.9374; 0.9042]	[NA; NA]
	3 × 3 min + 2 min reperfusion	1	2	-0.0613	[-0.6790; 0.5563]	[-0.0623; -0.0604]
	3 × 5 min	15	53	0.1298	[-0.0610; 0.3205]	[-0.0997; 0.3592]
	4 × 5 min	24	71	0.077	[-0.0782; 0.2322]	[-0.0120; 0.1661]
	5 × 2 min	1	3	0.1364	[-0.5965; 0.8693]	[-0.3581; 0.6309]
	8 × 5 min	1	2	-0.0084	[-0.5499; 0.5332]	[-0.1227; 0.1060]
Warm-up	NO	12	49	0.0907	[-0.1095; 0.2908]	[-0.2248; 0.4061]
	YES	33	92	0.1028	[-0.0265; 0.2320]	[-0.0013; 0.2069]
Outcome	Time to failure	8	11	0.5147	[0.2738; 0.7556]	[0.1570; 0.8724]
	P	16	30	0.098	[-0.0593; 0.2554]	[0.0035; 0.1925]
	Strength	4	19	0.026	[-0.2888; 0.3408]	[-0.2595; 0.3114]
	Time to complete	20	35	0.0728	[-0.0811; 0.2268]	[-0.1460; 0.2916]
	$\dot{V}O_2$	22	46	0.0131	[-0.1303; 0.1564]	[-0.1345; 0.1606]

K: number of studies; n: Total number of effects included; 95%CI: Unadjusted 95% confidence interval (range of effect size estimates); 95%CI_adj: Adjusted 95% confidence interval (corrected for multilevel models or heterogeneity); p-value_adj: Adjusted p-value (e.g., corrected for multiple comparisons or model adjustments); t-value: t-test statistic (for testing significance of the effect size); Q test: Q statistic for heterogeneity test (assessing between-study heterogeneity); I^2 -Level 2/3/4: Heterogeneity proportions in multilevel models; PI: Prediction Interval; Moderator: Subgroup category (e.g., intervention type, population characteristics); F-test: F-statistic for ANOVA or model significance; $p_{\text{-diff}}$: p-value for subgroup differences; intrcpt: Intercept term in the model (baseline effect); NA: Data not available or not applicable; CON: Control group (no intervention); SHAM: Sham intervention group (sham or simulated intervention); P: power output; $\dot{V}O_2$: oxygen uptake;

TABLE S15. Effects of IPC on aerobic sport performance—Three or Four-level model (2)

Variable	p-value	p-value_adj	t-value	F-test	Q test	I ² -Level 2	I ² -Level 3	p _{-diff}
Comparison	0.0115	0.054	2.5622	F (2 , 139) = 3.283	175.234	0	0.153	0.0638
	0.5214	0.2573	0.6428					
Sex	0.5354	0.4324	0.6213	F (4 , 137) = 1.016	179.682	0	0.1698	no difference
	0.0507	0.037	1.9713					
	0.755	0.6328	0.3126					
	0.8702	0.6423	0.1637					
	0.5895	0.0747	0.5409					
Experience_level	0.2598	0.3889	1.1316	F (6 , 135) = 0.564	180.55	0	0.171	no difference
	0.2649	0.0121	1.1194					
	0.6444	0.2965	0.4626					
	0.7604	0.4654	0.3055					
	0.6192	0.0034	0.4982					
IPC_sets	0.298	0.0933	1.0448	F (8 , 133) = 0.52	179.552	0	0.1771	no difference
	0.5384	0.2775	0.6168					
	0.9716	NA	-0.0356					
	0.8446	0.0008	-0.1964					
	0.1806	0.244	1.3458					
	0.328	0.0864	0.9817					
	0.7133	0.1769	0.3682					
	0.9756	0.8257	-0.0306					
Warm-up	0.3719	0.5391	0.8958	F (2 , 139) = 1.543	180.347	0	0.1658	no difference
	0.1182	0.0528	1.572					
Outcome	0	0.0106	4.2256	F (5 , 136) = 4.023	158.512	0	0.1275	
	0.2202	0.0428	1.2317					
	0.8706	0.7943	0.1632					
	0.3512	0.4961	0.9355					
	0.8573	0.8569	0.1801					

K: number of studies; n: Total number of effects included; 95%CI: Unadjusted 95% confidence interval (range of effect size estimates); 95%CI_adj: Adjusted 95% confidence interval (corrected for multilevel models or heterogeneity); p-value_adj: Adjusted p-value (e.g., corrected for multiple comparisons or model adjustments); t-value: t-test statistic (for testing significance of the effect size); Q test: Q statistic for heterogeneity test (assessing between-study heterogeneity); I²-Level 2/3/4: Heterogeneity proportions in multilevel models; PI: Prediction Interval; Moderator: Subgroup category (e.g., intervention type, population characteristics); F-test: F-statistic for ANOVA or model significance; p_{-diff}: p-value for subgroup differences; intrcpt: Intercept term in the model (baseline effect); NA: Data not available or not applicable; CON: Control group (no intervention); SHAM: Sham intervention group (sham or simulated intervention); P: power output; VO₂: oxygen uptake;

Model Results:

	estimate	se	tval	df	pval	ci.lb	ci.ub	
intrcpt	0.4262	0.1051	4.0565	164	<.0001	0.2188	0.6337	***
OutcomeBalance	-0.2679	0.2934	-0.9131	164	0.3625	-0.8471	0.3114	
OutcomeJump	-0.3737	0.1760	-2.1226	164	0.0353	-0.7212	-0.0261	*
OutcomeMAOD	-0.5537	0.2990	-1.8516	164	0.0659	-1.1442	0.0367	.
OutcomeP	-0.3812	0.1190	-3.2022	164	0.0016	-0.6162	-0.1461	**
OutcomeStrength	-0.3645	0.1173	-3.1068	164	0.0022	-0.5961	-0.1328	**
OutcomeTime to complete	-0.3114	0.1289	-2.4152	164	0.0168	-0.5659	-0.0568	*
OutcomeTime to failure	0.0293	0.2488	0.1176	164	0.9065	-0.4620	0.5205	
OutcomeVO2	-0.5645	0.1827	-3.0906	164	0.0023	-0.9252	-0.2039	**

FIG. S4. Subgroup analysis of anaerobic performance with "RM" as the intercept.

Model Results:

	estimate	se	tval	df	pval	ci.lb	ci.ub	
intrcpt	0.5147	0.1218	4.2256	136	<.0001	0.2738	0.7556	***
OutcomeP	-0.4167	0.1327	-3.1402	136	0.0021	-0.6791	-0.1543	**
OutcomeStrength	-0.4887	0.1803	-2.7105	136	0.0076	-0.8453	-0.1321	**
OutcomeTime to complete	-0.4419	0.1359	-3.2523	136	0.0014	-0.7105	-0.1732	**
OutcomeVO2	-0.5016	0.1262	-3.9741	136	0.0001	-0.7512	-0.2520	***

FIG. S5. Subgroup analysis of aerobic performance with "Time to failure" as the intercept.

ELECTRONIC SUPPLEMENTARY MATERIAL APPENDIX S8 (FUNNEL PLOTS WITH EGGER'S TEST FOR EXERCISE OUTCOMES ACROSS DIFFERENT ENERGY SYSTEMS)

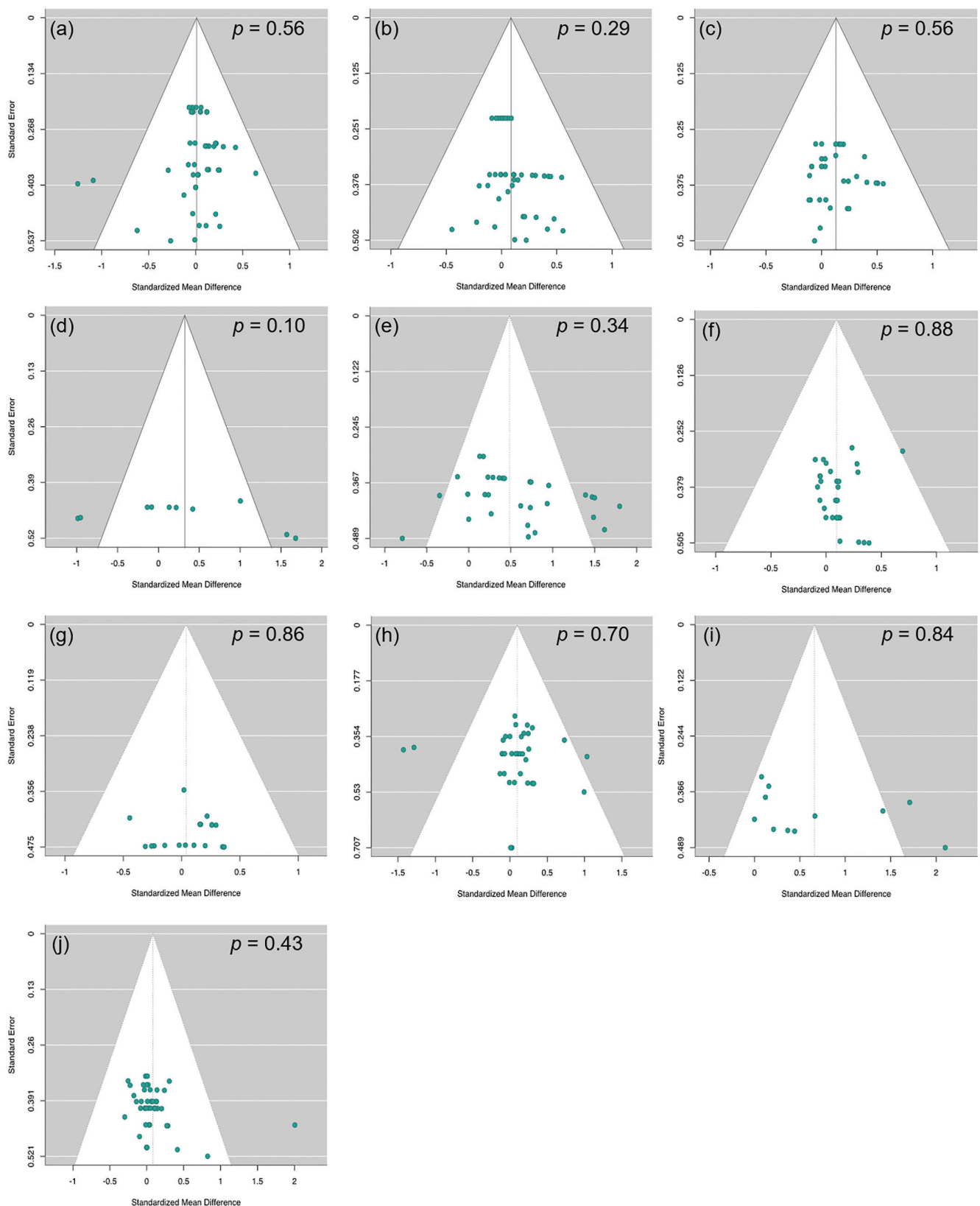


FIG. S6. Funnel plots with Egger's test for exercise outcomes across different energy systems.

(a)–(e): Funnel plots for anaerobic performance, representing power output, strength, time to complete, time to failure, and maximal number of repetitions, respectively; (f)–(j): Funnel plots for aerobic performance, representing power output, strength, time to complete, time to failure, and $\dot{V}O_2$, respectively. *P*-values correspond to the results of Egger's test, with values < 0.05 indicating the presence of publication bias.