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Effects of normobaric hyperoxic recovery after exercise on subsequent performance: a systematic review and meta-analysis with secondary physiological outcomes

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Abstract

Background

Normobaric hyperoxic recovery has been proposed as a post-exercise strategy to improve subsequent exercise performance, but the overall performance evidence and the consistency of accompanying physiological recovery markers remain unclear. This systematic review and meta-analysis primarily evaluated the effect of normobaric hyperoxic recovery on subsequent performance, with selected physiological outcomes interpreted as secondary and exploratory evidence.

Methods

We systematically reviewed studies examining normobaric hyperoxic recovery after exercise. Performance was prespecified as the primary outcome. Peripheral oxygen saturation (SpO_2), heart rate (HR), and blood

lactate (BLa) were treated as secondary outcomes. After full-text verification, 19 reports were retained, yielding 21 study entries for synthesis. Because many studies used crossover, repeated-measures, or within-subject designs and most did not report sufficient paired-variance information, the main quantitative syntheses used arm-level summary statistics and random-effects models with standardized mean differences (Hedges' g).

Results

The primary performance analysis included 16 study entries and estimated a small-to-moderate effect in favor of normobaric hyperoxic recovery (SMD = 0.42, 95% CI 0.22 to 0.63; I^2 = 0%). This estimate was not materially altered in leave-one-out, trim-and-fill, fail-safe N, and prespecified structural sensitivity analyses. For secondary outcomes, 10 study entries contributed to the BLa analysis, which showed no clear pooled effect (SMD = 0.14, 95% CI -0.15 to 0.43; I^2 = 0%). Although funnel-plot asymmetry was detected for BLa, trim-and-fill did not materially alter the pooled estimate. HR results were based on 2 exploratory study entries and showed no clear pooled effect (SMD = 0.29, 95% CI -0.35 to 0.93; I^2 = 0%). SpO_2-related outcomes were highly heterogeneous (I^2 = 90.0%), and this inconsistency persisted after sensitivity analyses, supporting narrative rather than pooled inferential interpretation.

Conclusions

Normobaric hyperoxic recovery was associated with a modest, directionally consistent effect in favor of subsequent performance. In contrast, the secondary physiological outcomes provided limited and inconsistent evidence. No clear pooled effect was observed for blood lactate, heart-rate findings were exploratory, and SpO_2 outcomes were too heterogeneous to support a stable pooled conclusion. Overall, the findings suggest a possible performance benefit of normobaric hyperoxic recovery, while physiological outcomes should be interpreted as descriptive and hypothesis-generating rather than as evidence of a consistent physiological recovery response.

Keywords

Normobaric hyperoxia; recovery; exercise performance; meta-analysis; blood lactate; oxygen saturation; heart rate

Introduction

Recovery between repeated exercise bouts is a central concern in sport and exercise science [1]. In many training and competition settings, athletes must reproduce high levels of force, power, speed, or endurance within

limited recovery periods [2]. Recovery strategies are therefore used to preserve subsequent performance. This applied perspective is consistent with broader recovery principles, in which recovery quality is considered integral to repeated-performance capacity and repeated-exercise performance [1, 2]. Oxygen-based recovery has attracted intermittent attention for decades, but its practical value remains uncertain [3].

One specific approach is normobaric hyperoxic recovery, in which oxygen-enriched gas is administered under normal barometric pressure during the post-exercise recovery period [4]. The rationale is that, compared with breathing room air, hyperoxic recovery may increase oxygen availability [5], accelerate reoxygenation, and improve readiness for a subsequent exercise bout [6]. These effects may be especially relevant when repeated high-intensity efforts are separated by incomplete recovery, particularly in settings where oxygen transport, oxygen uptake kinetics, and exercise-induced hypoxemia may influence recovery and subsequent performance [7]. Physiological plausibility alone, however, does not establish a meaningful performance benefit.

A further challenge is that studies of hyperoxic recovery have not focused on a single outcome domain. Some studies have assessed subsequent performance outcomes (e.g., power output, endurance time, and force recovery), but findings have been mixed or inconsistent across the literature [8-12]. Others examined physiological markers, including blood lactate, heart rate, or oxygen-saturation-related outcomes [13-17]. These endpoints are not interchangeable. Notably, earlier oxygen-inhalation studies reported limited or inconsistent recovery-related effects, and several did not demonstrate clear subsequent performance benefits [18-20].

Performance is the most directly relevant outcome for athletes, coaches, and applied practitioners [21], whereas physiological outcomes may provide descriptive physiological context without necessarily moving in parallel with performance [22]. The literature is also heterogeneous in design. Published studies include crossover, repeated-measures, within-subject, and parallel comparisons, as well as laboratory-based and sport-specific exercise modes [23-26]. Recovery protocols also varied with respect to passive versus active recovery, oxygen concentration, duration of exposure, and environmental conditions [27-30]. In addition, some studies compare hyperoxic recovery with standard normoxic recovery, whereas others use more complex control conditions. These features complicate evidence synthesis and likely contribute to the inconsistent interpretation of the field.

Some oxygen-based interventions are conceptually distinct from the review question addressed here. In particular, hypoxic recovery and hyperbaric oxygen should not be treated as equivalent to normobaric hyperoxic recovery because they differ in both physiological basis and practical

application [3]. Reviews that combine them risk obscuring the specific effect of interest. The present review therefore focused specifically on normobaric hyperoxic recovery after exercise rather than on oxygen-related interventions more broadly.

At the same time, the field now appears mature enough to support a performance-focused quantitative synthesis. A sufficient number of studies report post-recovery performance outcomes, whereas recurring physiological outcomes such as blood lactate, heart rate, and oxygen saturation remain more limited and heterogeneous. To our knowledge, however, no previous synthesis has clearly prioritized performance as the primary outcome while separating interpretation of physiological secondary outcomes according to their consistency and meta-analytic suitability. That distinction is important because it aligns the synthesis more closely with both practical relevance and methodological caution.

Accordingly, the primary aim of this systematic review and meta-analysis was to evaluate the effect of normobaric hyperoxic recovery after exercise on subsequent performance in humans. Peripheral oxygen saturation (SpO_2), heart rate (HR), and blood lactate (BLa) were evaluated as secondary outcomes to provide descriptive and hypothesis-generating context regarding physiological recovery. These secondary outcomes were not treated as equivalent inferential endpoints to performance, and their interpretation was determined according to the size, consistency, and heterogeneity of the available evidence.

Methods

Study design

This study was conducted as a performance-focused systematic review and meta-analysis of normobaric hyperoxic recovery after exercise, with selected physiological recovery outcomes evaluated as secondary and exploratory evidence. The review was reported in accordance with the PRISMA 2020 statement [31]. The review was not prospectively registered in PROSPERO because the review process had progressed beyond the stage of prospective registration before final manuscript preparation, and the review was instead conducted according to a pre-defined internal protocol informed by current systematic-review guidance [32].

Literature search

A structured literature search was performed in Google Scholar, Web of Science, SPORTDiscus, Scopus, PubMed, Embase, the Cochrane Library, and CINAHL from database inception to March 2, 2026. Search terms were designed to capture three core concepts: hyperoxic or oxygen-enriched

interventions, recovery-related conditions, and exercise- or sport-related contexts. Where appropriate, terms related to hyperbaric oxygen, hypoxic recovery, non-relevant clinical studies, and animal studies were used to exclude conceptually distinct interventions or populations during searching and screening; altitude-related normobaric hyperoxic recovery studies were not excluded when they otherwise met the eligibility criteria. The detailed search strategies for each source are provided in Supplementary Table S1.

Eligibility criteria

Studies were eligible if they involved human participants and examined normobaric hyperoxic recovery administered after exercise or between repeated exercise bouts. Normobaric hyperoxic recovery was defined as the administration of oxygen-enriched gas under normal barometric pressure during the recovery period. Interventions delivering a fraction of inspired oxygen above ambient air (>20.9% FiO_2) were eligible; no minimum oxygen concentration threshold was imposed because the included literature used a wide range of oxygen fractions. Eligible studies also required a comparator condition without hyperoxic recovery, at least one relevant post-exercise outcome, and sufficient quantitative information for extraction or derivation of summary statistics. Studies were excluded if they primarily evaluated hypoxic recovery rather than normobaric hyperoxic recovery, involved hyperbaric oxygen interventions, used non-human or in vitro models, were not original research, or did not report outcomes relevant to the review question. Performance was prespecified as the primary outcome. Secondary outcomes were peripheral oxygen saturation, heart rate, and blood lactate.

Study selection

Records identified through the search were screened in two stages: title/abstract screening followed by full-text assessment. Full texts were reviewed against the eligibility criteria, with particular attention to intervention type, recovery context, outcome definition, and study design. Studies initially considered but later found to involve hypoxic recovery, hyperbaric oxygen, or unsupported full-text evidence were removed from the verified included set.

After full-text verification, 19 reports were retained, yielding 21 study entries for synthesis after prespecified splitting of Maeda (1997) [16] by anaerobic-threshold subgroup and the altitude-comparison paper by Suchý et al. [27] into low-altitude and high-altitude entries.

Data extraction

Data were extracted from the full text, tables, and figures where necessary. When summary statistics were not reported in a directly usable form, values

were derived from standard errors or estimated from figures when justified and transparently documented. For each eligible study, we extracted, where available, the study identifier and year, participant characteristics, exercise protocol, recovery intervention and comparator, testing environment, design type, sample size, selected outcome measure, timepoint used for synthesis, and group-level summary data. When multiple outcomes or timepoints were reported within the same comparison, a single outcome and timepoint were selected for meta-analysis to avoid double counting. Selection prioritized, in order, the prespecified primary performance endpoint most directly reflecting the subsequent exercise bout, the post-recovery timepoint closest to the prespecified recovery assessment, the hyperoxic-versus-control comparison most directly matching the eligibility criteria, and outcomes with extractable mean and variance data. These criteria were applied before pooling to reduce selective inclusion of favorable results.

Outcome framework

The primary outcome was post-recovery performance, including measures such as power output, maximal force, endurance time, or sport-specific performance time. Performance outcomes were direction-aligned before synthesis so that positive effect sizes consistently favored hyperoxic recovery. Secondary outcomes were categorized as blood lactate, heart-rate-related outcomes, and oxygen-saturation-related outcomes. Because these outcomes differed in endpoint definition, measurement timing, and meta-analytic suitability, they were interpreted more cautiously than the primary performance outcome, and the final level of inference was determined separately for each secondary outcome domain.

Handling of multiple study entries

Prespecified study-splitting rules were applied to avoid inappropriate pooling across substantively distinct conditions. Maeda (1997) [16] was split into Higher AT and Lower AT entries. The altitude-comparison paper by Suchý et al. [27] was prespecified as two study entries for synthesis, representing the low-altitude and high-altitude conditions. Sperlich 2011 [12] and Sperlich 2012 [28] were treated as separate studies because they involved different participant settings and protocols. Yokoi 2014 was represented by two distinct articles rather than duplicate publication [29, 30]. For multi-arm or multi-condition studies, only the prespecified comparison relevant to the review question was retained in the main meta-analysis. For example, in Kay 2008 [33], the primary analysis retained 100% O_2 versus 21% O_2, while the 60% O_2 comparison was not included in the main pooled model.

Risk-of-bias assessment

Risk of bias was assessed using an adapted domain-based framework informed by the RoB 2 structure [34] and tailored to mixed exercise-recovery study designs, including parallel, crossover, repeated-measures, and within-subject designs. Five domains were evaluated: randomization process or order generation, deviations from intended interventions or condition-allocation concerns, missing outcome data, outcome measurement, and selection of the reported result. For crossover and repeated-measures studies, the framework additionally considered condition order, washout, and potential carryover concerns where applicable.

Each study was assigned a judgment of low risk, some concerns, or high risk, together with an overall judgment. Study-level judgments were summarized in a risk-of-bias table and visualized using ROBVIS traffic-light and summary plots.

Statistical analysis

The main quantitative synthesis used random-effects meta-analysis with standardized mean differences (Hedges' g) [35]. A random-effects model was selected because variation across studies was expected in participant populations, exercise modes, recovery protocols, timing, and outcome assessment. Potential sources of variation also included differences in oxygen fraction across interventions, which may influence physiological and performance responses. Many included studies used crossover, repeated-measures, or within-subject designs, but most did not report sufficient paired-variance information, within-subject correlation coefficients, or paired effect estimates to support a consistent paired-analysis framework across all studies. Accordingly, the main analyses were conducted using arm-level summary statistics as the most consistently available common metric. Hedges' g was used to reduce small-sample bias. This was considered the most feasible approach across the overall evidence base; however, because this framework does not fully exploit within-subject information from crossover designs, the pooled estimates should be interpreted as more informative about the direction and approximate consistency of the overall signal than about the precise absolute magnitude of effect. Heterogeneity was assessed using I^2 and tau^2. Where a sufficient number of comparisons was available, an exploratory subgroup analysis by environmental setting (sea level versus altitude-related conditions) was performed to examine a potential source of variation. Funnel plots and Egger's regression test [36, 37] were used to assess small-study effects when a sufficient number of comparisons were available. Where appropriate, trim-and-fill analysis [38] was used as an exploratory assessment of the potential influence of funnel-plot asymmetry on the pooled estimate, leave-one-out analysis was used to examine whether the primary result was driven by any single study, a fail-safe N was

calculated as an exploratory indicator of how many additional null-result studies would be required to render the pooled performance effect non-significant, and structural sensitivity analyses were used to test the influence of prespecified methodological concerns, including graph-derived data and atypical comparator conditions.

Primary outcome synthesis

Performance was synthesized as the principal inferential outcome of the review. The primary model pooled study-level performance comparisons using arm-level summary data and random-effects estimation. Additional prespecified structural sensitivity analyses examined exclusion of Kay 2008 [33], because the retained primary comparison relied on graph-derived values, and exclusion of Hauser 2014 [39], because the comparator involved hypoxic rather than standard normoxic recovery.

Secondary outcome synthesis

Secondary outcomes were synthesized separately by domain. For blood lactate (BLa), a pooled random-effects model was performed. Funnel-plot asymmetry was further explored using Egger's test and trim-and-fill analysis. For heart rate (HR), a pooled exploratory analysis was performed because the available studies used partially heterogeneous HR-derived endpoints, including heart-rate recovery and heart-rate decline during recovery. For SpO_2, pooled analysis was initially attempted. However, because substantial heterogeneity persisted despite sensitivity analyses, including exclusion of White 2013 [17] and leave-one-out analysis, the final interpretation was narrative rather than based on a stable pooled estimate.

Software

Meta-analyses and sensitivity analyses were performed in R using the meta package. Risk-of-bias visualizations were generated using ROBVIS.

Results

Study selection and study characteristics

The electronic search identified 3585 records from databases and web sources before duplicate removal, and an additional 9 records were identified through citation searching. After screening and full-text assessment, 19 reports describing eligible studies were retained, yielding 21 study entries after prespecified splitting of Maeda (1997) [16] by anaerobic-threshold subgroup and the altitude-comparison paper by Suchý et al. [27] into low-altitude and high-altitude entries; the separate repeated-anaerobic-exercise study by Suchý and Heller [11] was treated as

an independent report. The included studies covered a broad range of exercise-recovery paradigms, including repeated sprint protocols, Wingate-based anaerobic exercise, treadmill running, swimming and bench-swimming protocols, and track-running performance tests. Hyperoxic recovery was most commonly delivered as normobaric oxygen inhalation during passive or active recovery intervals, although oxygen concentration, recovery duration, and background environment varied across studies. Study characteristics are summarized in Table 1. The included evidence base also contained older oxygen-inhalation recovery experiments, but these reports generally provided limited methodological detail and should therefore be interpreted cautiously. The study-selection process is illustrated in Figure 1.

Primary outcome: performance

The primary meta-analysis included 16 study entries assessing performance-related outcomes. Consistent with the statistical approach described in the Methods, the main quantitative synthesis used arm-level summary statistics. The pooled random-effects analysis estimated a small-to-moderate effect in favor of normobaric hyperoxic recovery on performance (SMD = 0.42, 95% CI 0.22 to 0.63; Figure 2). Statistical heterogeneity was not detected statistically (I^2 = 0%); however, this should not be interpreted as evidence of clinical homogeneity because the included studies differed in exercise modality, oxygen dose, recovery duration, participant characteristics, and outcome definition. An exploratory subgroup analysis by environmental setting did not show a significant subgroup difference. Assessment of small-study effects did not indicate statistically significant funnel-plot asymmetry (Figure 3), and the pooled estimate remained materially unchanged in supplementary sensitivity analyses, including trim-and-fill, leave-one-out analysis, and fail-safe N assessment. Additional structural sensitivity analyses excluding Kay 2008 [33] and Hauser 2014 [39] also did not materially alter the pooled estimate, suggesting that the direction and approximate magnitude of the primary performance finding were not materially driven by these study-specific methodological concerns. The primary outcome dataset is summarized in Table 2.

Secondary outcomes

Blood lactate (BLa)

A total of 10 study entries contributed to the blood lactate analysis. The pooled random-effects model did not show a clear effect of hyperoxic recovery on blood lactate (SMD = 0.14, 95% CI -0.15 to 0.43; I^2 = 0%; Figure 4). However, funnel-plot asymmetry was observed and Egger’s test was significant, suggesting possible small-study effects. Trim-and-fill did not

impute missing studies and did not materially alter the pooled estimate. The BLa findings were therefore interpreted cautiously.

Heart rate (HR)

Two study entries contributed to the heart-rate synthesis. The pooled exploratory analysis did not show a clear effect of hyperoxic recovery on HR-related outcomes (SMD = 0.29, 95% CI -0.35 to 0.93; I^2 = 0%; Figure 5). Because the contributing studies used partially heterogeneous HR-derived endpoints, including heart-rate recovery and heart-rate decline during recovery, this analysis was treated as exploratory. Some included studies reporting heart-rate-related outcomes, particularly older recovery experiments, were retained descriptively in the review but were not included in the exploratory pooled HR model because their reported endpoints were not sufficiently compatible with the prespecified synthesis dataset.

SpO_2 / oxygen saturation

Five study entries were initially considered for SpO_2-related synthesis. The initial pooled model suggested an effect in favor of hyperoxic recovery; however, statistical heterogeneity was substantial, and the result was not considered sufficiently stable for inferential interpretation. Exclusion of White 2013 [17], which assessed recovery-to-baseline time rather than saturation level per se, did not meaningfully reduce heterogeneity. Leave-one-out analysis further indicated that no single study adequately explained the observed inconsistency. Taken together, these findings indicated that the SpO_2 evidence base was insufficiently homogeneous for a stable pooled conclusion. SpO_2 findings were therefore interpreted narratively rather than as a definitive pooled effect. Secondary outcome data are summarized in Table 3, and the overall outcome interpretation is summarized in Table 5.

Risk of bias

Risk of bias was assessed using an adapted domain-based framework informed by the RoB 2 structure and tailored to mixed exercise-recovery study designs, including parallel, crossover, repeated-measures, and within-subject designs. Five domains were evaluated: randomization process or order generation, deviations from intended interventions or condition-allocation concerns, missing outcome data, outcome measurement, and selection of the reported result. Overall, most studies were judged as low risk or some concerns, whereas high-risk judgments were concentrated in deviations from intended interventions and selection of the reported result. However, the relatively favorable ratings for several older studies should be interpreted cautiously because reporting of randomization

procedures, blinding, condition order, washout, and selective outcome reporting was often limited. These judgments therefore reflect the information available in the original reports rather than definitive evidence that all relevant bias concerns were absent. Study-level risk-of-bias judgments are summarized in Table 4, and ROBVIS traffic-light and summary plots are presented in Figure 6A–B.

Discussion

This systematic review and meta-analysis should be interpreted primarily as a performance-focused synthesis of normobaric hyperoxic recovery after exercise. The main analysis estimated a small-to-moderate effect in favor of normobaric hyperoxic recovery on subsequent performance, with the direction of effect remaining generally consistent across sensitivity analyses. In contrast, the secondary physiological outcomes provided limited and inconsistent evidence. No clear pooled effect was observed for blood lactate, heart-rate findings were exploratory, and SpO_2 outcomes were too heterogeneous to support a stable pooled inference. Therefore, the physiological outcomes should be viewed as descriptive and hypothesis-generating context rather than as evidence that normobaric hyperoxic recovery produces a consistent physiological recovery response across outcome domains.

One notable feature of the primary outcome was the consistency of the performance signal. The pooled effect estimate favored hyperoxic recovery, statistical heterogeneity was not detected, and the result remained materially unchanged after leave-one-out analysis, trim-and-fill assessment, fail-safe N analysis, and structural sensitivity analyses excluding Kay 2008 [33] and Hauser 2014 [39], noting that in Hauser 2014 the comparator involved hypoxic rather than normoxic recovery, which may affect comparability. This pattern is important because the included performance studies varied in participant background, exercise mode, and recovery implementation. Despite that variation, the overall direction of effect was stable, suggesting that the pooled estimate was not driven by a single influential study or one methodologically atypical comparison. Furthermore, in the included Porter cycling protocol [40], oxygen was administered beyond the recovery phase alone, while related work from the same group also examined oxygen supplementation in a repeated-sprint cycling context [41]. This should be considered when interpreting the specificity of conclusions regarding recovery-only interventions.

The performance finding is physiologically plausible, but the present review cannot establish a consistent mechanism. Hyperoxic recovery may improve oxygen availability or reoxygenation in some recovery settings, particularly when repeated high-intensity efforts are separated by short intervals [42]. However, the secondary outcomes did not provide a stable or consistent

physiological explanation for the performance effect. The performance benefit should therefore be interpreted as an empirical outcome-level finding rather than as evidence that normobaric hyperoxic recovery uniformly improves physiological recovery processes.

The secondary outcomes were more mixed. For blood lactate, the pooled analysis did not show a clear overall effect. Although statistical heterogeneity was not detected, funnel-plot asymmetry was observed and Egger's test was significant. Importantly, trim-and-fill did not materially alter the pooled estimate, suggesting that potential small-study effects did not fully explain the null overall result. Blood lactate is influenced by multiple factors beyond recovery gas composition alone, including exercise intensity, muscle mass recruited, sampling time, training status, and whether the outcome reflects production, clearance, or distribution rather than recovery status alone [43-45].

The heart-rate findings should be interpreted even more cautiously. Only a small number of comparisons were available, and the contributing studies did not assess exactly the same construct. One study reported heart-rate recovery, and one reported heart-rate decline during recovery. Although the exploratory pooled estimate did not suggest a clear effect, the limited evidence base and heterogeneity in endpoint definition constrain inference. Accordingly, heart-rate results should be viewed as descriptive and hypothesis-generating rather than confirmatory.

The SpO_2 results warrant particular caution. Although some individual studies suggested favorable effects of hyperoxic recovery on oxygen-saturation-related outcomes, the pooled synthesis showed substantial heterogeneity, and this heterogeneity persisted after exclusion of White 2013 [17] and after leave-one-out analysis. This indicates that the inconsistency was not attributable to a single outlier study. More likely, the problem reflects limited methodological homogeneity across studies, including differences in whether the endpoint reflected saturation level, recovery-to-baseline time, measurement timing, or recovery environment. Accordingly, SpO_2 was more appropriately interpreted narratively in the present review. The available evidence suggests that hyperoxic recovery may influence oxygenation-related recovery responses in some settings, but the literature remains too heterogeneous to support a stable pooled estimate.

These mixed secondary findings help frame the primary result appropriately. The present review does not show that hyperoxic recovery improves all physiological recovery markers in a uniform way. Instead, the evidence suggests a more selective pattern: performance appears to benefit at the pooled level, whereas the commonly reported physiological markers do not yet provide a simple or consistent explanation across studies. This

distinction reduces the risk of overstating the practical implications of hyperoxic recovery and supports interpreting the secondary physiological outcomes as descriptive and hypothesis-generating.

Several methodological issues should be considered when interpreting these findings. First, the review was not prospectively registered, which limits transparency regarding protocol-level decisions and means that the possibility of post hoc analytical choices cannot be fully excluded. To reduce this risk, the Methods explicitly specify the outcome hierarchy, study-splitting rules, comparison selection, and sensitivity analyses used in the review. Second, many included studies used crossover, repeated-measures, or within-subject designs, but most did not report sufficient paired-variance information to permit a unified paired-effect meta-analysis across all studies. The quantitative syntheses therefore relied on arm-level summary statistics. This approach was the most feasible common framework across the evidence base, but it does not fully exploit within-subject information and may affect the precision of effect estimates. Third, the included studies were clinically heterogeneous with respect to participant training status, exercise modality, oxygen concentration, recovery duration, timing of administration, recovery mode, environmental conditions, and performance endpoint. Therefore, the absence of statistical heterogeneity in the primary analysis should not be interpreted as evidence that the interventions or outcomes were clinically interchangeable, particularly because statistical tests for heterogeneity have limited power when the number of studies is small and individual sample sizes are modest, such that an I^2 of 0% may underestimate the true between-study variability. Fourth, some data were derived from standard errors or estimated from published figures, and some studies reported multiple potential outcomes or time points. Although prespecified selection rules were used to avoid duplicate inclusion within studies, these decisions introduce additional uncertainty. Fifth, risk-of-bias judgments for several older studies should be interpreted in light of limited reporting detail in the original reports, particularly for randomization, blinding, order effects, washout, and selective outcome reporting.

The review also has important strengths. It provides a focused synthesis of normobaric hyperoxic recovery rather than oxygen-related recovery interventions more broadly, thereby excluding hypoxic-recovery and hyperbaric-oxygen studies from the primary framework. This improves conceptual clarity relative to broader reviews that combine fundamentally different oxygen-related interventions. In addition, the review clearly distinguished the primary performance outcome from the secondary physiological outcomes rather than treating all post-exercise endpoints as equivalent.

The analysis was further strengthened by extensive sensitivity testing of the primary outcome and by a transparent decision process for handling studies that were not suitable for stable quantitative synthesis in secondary domains.

From a practical standpoint, the current evidence suggests that normobaric hyperoxic recovery may be most relevant in settings involving repeated high-intensity efforts separated by short recovery intervals, such as interval-based training, repeated sprint exercise, or competition formats with closely spaced bouts. A modest performance benefit could be practically relevant in some of these contexts, although the current evidence does not allow strong or broadly applicable recommendations. At the same time, the present findings do not support broad claims that hyperoxic recovery produces large or universal improvements in physiological recovery. Coaches, clinicians, and practitioners should therefore view hyperoxic recovery as a potentially useful but context-dependent strategy rather than as a universally effective recovery tool.

Future research should address the main weaknesses of the current evidence base. Future studies should report sufficient information for paired or crossover-aware effect estimation, including change-score variance or within-subject correlations where appropriate, so that future syntheses can make fuller use of within-subject designs. Greater standardization is also needed in the selection and reporting of recovery endpoints, especially for SpO_2 and heart-rate outcomes. In addition, future trials should distinguish more clearly between normoxic, hypoxic, and altitude-related control conditions and should justify the timing, dose, and delivery mode of hyperoxic exposure. Studies that integrate performance outcomes with physiological measures using consistent sampling schedules would be especially valuable for determining whether performance effects are accompanied by reproducible changes in specific recovery markers.

Conclusion

In conclusion, normobaric hyperoxic recovery was associated with a modest, directionally consistent effect in favor of subsequent performance. Evidence for secondary physiological outcomes was less consistent: no clear pooled effect was found for blood lactate, heart-rate findings were exploratory, and SpO_2-related outcomes were too heterogeneous for a stable pooled conclusion. Better-reported, methodologically consistent studies are needed to determine whether, how, and under what conditions physiological responses accompany any performance effect.

Abbreviations

AT, anaerobic threshold; BLa, blood lactate; CI, confidence interval; FiO_2, fraction of inspired oxygen; HR, heart rate; I^2, Higgins inconsistency statistic; PRISMA, Preferred Reporting Items for Systematic Reviews and Meta-Analyses; RoB 2, revised Cochrane risk-of-bias tool; ROBVIS, Risk-of-Bias Visualization; SaO_2, arterial oxygen saturation; SMD, standardized mean difference; SpO_2, peripheral oxygen saturation.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Clinical trial number

Not applicable.

Availability of data and materials

All data generated or analysed during this study are included in this published article and its supplementary information files.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

LYS conceived the review question, conducted the literature search, screened records, extracted data, performed the statistical analyses, prepared the figures and tables, and drafted the manuscript. WZT assisted with data extraction, study verification, and revision of the manuscript. ZMJ contributed to literature verification, data checking, and manuscript revision. LY assisted with data checking, table formatting, and reference verification. PQY contributed to figure organization, supplementary material checking, and manuscript polishing. YF supervised the study, contributed to the study design and methodological framework, and critically revised the manuscript. DXL contributed to the study design, interpretation of the

findings, and critical revision of the manuscript. All authors read and approved the final manuscript.

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Table 1. Characteristics of included studies investigating normobaric hyperoxic recovery after exercise

Study	Sample size (N)	Participants	Exercise protocol	Hyperoxic recovery intervention	Recovery mode	Test environment	Outcomes assessed
Daab 2025	28	Semi-professional male soccer players; 24.5 ± 3.6 y	Loughborough Intermittent Shuttle Test (simulated soccer match)	99.5% O_2 for 15 min immediately post-exercise and daily during recovery	Passive	Sea level	MVC, LDH, CK, CRP, perceptual fatigue, muscle soreness, Hooper Index
Suchý and Heller 2010 (Repeated anaerobic exercise)	10	Male ice hockey players; 21.1 ± 1.1 y	2 × 30-s Wingate cycle sprints	99.5% O_2 delivered as 2 × (8 × 2-s) inhalations during recovery	Mixed / NR	Sea level	Power, anaerobic capacity, blood lactate, heart rate
Kay 2008	12	Recreationally active males; 20–21 y	Two consecutive 30-s Wingate tests separated by 4-min recovery	60% and 100% O_2 during 4-min active recovery (vs 21% O_2)	Active (50-W cycling)	Sea level	Peak power, minimum power, mean power, total work, fatigue rate, time to peak power
Porter 2022	10	Recreationally active male students; 22.8 ± 4.5 y	10 × 15-s cycle sprints	100% O_2 during recovery across sprint sets	Passive	Sea level	Power, blood lactate
Peeling 2011	7	National-level kayak athletes; 5 male / 2 female; age NR	6 × 3-min maximal aerobic intervals	99.5% O_2 for 2 min during each recovery interval	Passive	Sea level	Power, speed, heart rate, blood lactate, SpO_2, RPE
Sperlich 2012	10	Well-trained male athletes; age NR	2 sets of 10 × 6-s cycle sprints	100% O_2 during 30-s inter-sprint recovery	Passive	Simulated altitude (15.4% O_2 background)	Power, SpO_2, blood lactate, heart rate, RPE

				and 4-min inter-set recovery			
Peeling 2012	8	Highly trained swimmers; 5 male / 3 female; 24 ± 4 y	20 × 200-m swimming	99.5% O_2, 2 × 10 min	Passive / static	Sea level	Time, blood lactate, heart rate, IL-6
Yokoi 2014 (J Phys Ther Sci)	11	Healthy males; 20 y (18–21)	Single-leg isometric knee extension at 70% MVIC to task failure, repeated after recovery	30% O_2 for 30 min	Passive	Sea level	MVIC, endurance time, sEMG, NIRS-derived oxygenation
Yokoi 2014 (JSCR)	12	Healthy physically active males; 20 y (18–21)	3 sets of 3 isometric quadriceps contractions at 70% MVIC	30% O_2, 2 × 15 min between sets	Passive (seated)	Sea level	MVIC, endurance time, blood lactate, VAS
Winter 1989	12	Professional male soccer players; 25.7 ± 1.2 y	Two treadmill bouts to exhaustion	100% O_2 for 4 min between bouts	Passive (seated)	Sea level	Endurance time, blood lactate, heart rate, VO_2
Hauser 2014	8	Male cross-country skiers and triathletes; 25 ± 3 y	3 × 3-min all-out double-poling bouts	100% O_2, 2 × 3 min	Active	Simulated altitude (16.5% O_2 background)	Power, blood lactate, SpO_2
Robbins 1992	13	Male athletes (runners/cyclists); 28 ± 2.0 y	2 × 5-min submaximal exercise followed by 1 maximal treadmill run	100% O_2 for 4 min between bouts	Active (walking)	Sea level	Endurance time, heart rate, VE, VO_2, RPE
Bjorgum 1966	6	Healthy male runners; 18–22 y	2 × 5-min treadmill running at approximately 8 mph	Oxygen inhalation for 1 min between bouts	Passive (seated)	Laboratory	Heart rate, recovery oxygen consumption, ventilation
Nummela	9	Well-trained 400-m	3 sets of 3 × 300-m	40% O_2 during	Passive	Sea level	Heart rate, SaO_2, blood

2002		runners/hurdlers; 23.5 ± 3.0 y	treadmill running	inter-run and inter-set recovery (1, 2, 4, 5, and 10 min)			lactate, pH, SBE, PO_2, PCO_2, RPE
Sperlich 2011	12	Elite male swimmers; 21 ± 3 y	5 × 40 maximal arm strokes (bench swimming)	100% O_2 during 6-min recovery intervals	Passive	Sea level	Power, fatigue index, pO_2, SO_2, pH, [H+], base excess, blood lactate, ROS, EMG, RPE
Kidwell 2026	18	Trained male aquatic athletes; 20.5 ± 1.4 y	Maximal 100-yard swim followed by maximal 50-yard freestyle sprint	98% O_2 for 5 s at the onset of a standardized 25-s recovery interval	Passive	Sea level	50-yard sprint time, RPE
Suchý 2010 (Low altitude)	10	Cross-country skiers; 7 male / 3 female; 18.6 ± 3.6 y	2 × 30-s Wingate cycle sprints	99.5% O_2 delivered as 8 × 2-s inhalations during recovery	NR	Low altitude (485 m)	Power, anaerobic capacity, fatigue index, blood lactate, heart rate
Suchý 2010 (High altitude)	10	Cross-country skiers; 7 male / 3 female; 18.6 ± 3.6 y	2 × 30-s Wingate cycle sprints	99.5% O_2 delivered as 8 × 2-s inhalations during recovery	NR	High altitude (1835 m)	Power, anaerobic capacity, fatigue index, blood lactate, heart rate
White 2013	10	Well-trained male endurance athletes; 22 ± 1 y	10 × 3-min treadmill running at 85% vVO_2peak	99.5% O_2 during 90-s inter-interval recovery plus 15 min post-exercise	Passive	Sea level	SpO_2, heart rate, blood lactate, RPE, TQRper, IL-6, F2-isoprostanes
Maeda 1997 (Higher AT)	7	Healthy male students; 20.4 ± 0.53 y	10-min cycling at 70% VO_2max	30%, 40%, 60%, 80%, and 100% O_2	Passive	Sea level	Blood lactate and cardiorespiratory recovery

				for 5–6 min			variables
Maeda 1997 (Lower AT)	7	Healthy male students; 21.7 ± 0.49 y	10-min cycling at 70% VO_2max	30%, 40%, 60%, 80%, and 100% O_2 for 5–6 min	Passive	Sea level	Blood lactate and cardiorespiratory recovery variables

Abbreviations: AT, anaerobic threshold; CK, creatine kinase; CRP, C-reactive protein; EMG, electromyography; F2-isoprostanes, F2-isoprostanes; HR, heart rate; IL-6, interleukin-6; LDH, lactate dehydrogenase; MVIC, maximal voluntary isometric contraction; MVC, maximal voluntary contraction; NIRS, near-infrared spectroscopy; NR, not reported; PCO_2, partial pressure of carbon dioxide; PO_2, partial pressure of oxygen; RPE, rating of perceived exertion; ROS, reactive oxygen species; SaO_2, arterial oxygen saturation; SBE, standard base excess; sEMG, surface electromyography; SO_2, oxygen saturation; SpO_2, peripheral oxygen saturation; TQRper, total quality of recovery (perceived); VAS, visual analogue scale; VE, minute ventilation; VO_2, oxygen uptake; vVO_2peak, velocity at peak oxygen uptake.

Notes:
A total of 19 reports were included, yielding 21 study entries after prespecified splitting of Maeda (1997) and the altitude-comparison study of Suchý (2010), with the repeated anaerobic exercise study by Suchý and Heller treated as a separate report.
For Bjorgum (1966), the analytic sample was restricted to the runner subgroup (N = 6) to avoid inflation from combining runners and non-runners; the intervention is conservatively described as oxygen inhalation because the oxygen fraction was not explicitly reported in the available full text.
Sperlich 2011 and Sperlich 2012 were treated as separate study entries because they involved different exercise protocols and participant settings.
Yokoi 2014 is represented by two distinct articles rather than duplicate publication.
Kay 2008 is presented as one three-condition crossover study in Table 1.
Some older studies were retained for qualitative characterization of the evidence base but did not contribute to all final quantitative syntheses because of outcome incompatibility or insufficient extractable summary data.

Table 2. Studies contributing to the primary performance meta-analysis and extracted summary data

Study	Year	Selected performance outcome	Time point used for synthesis	Favored direction	Analytic subgroup / setting	Study design	Hyperoxia n	Hyperoxia mean	Hyperoxia SD	Control n	Control mean	Control SD	Included in main meta-analysis	Paired-effect data available
Dab 2025	2025	MVC	15 min post-recovery	Higher is better	Sea level	Randomized double-blind crossover / repeated	28	816	136	28	711	126	Yes	No
Ka	2	Peak	Test	Hi	Sea	Crosso	12	114	277	12	10	20	Yes	No

y 2008 (100% vs 21%)	008	power	2	gher is better	level	ver		0	.1	05	7.8		
Kidwell 2026	2026	50-yard maximal swim time (s)	Post-recovery sprint	Lower is better	Sea level	Within-subject crossover	18	31.92	2.22	18	32.91	3.15	Yes	Yes
Peeling 2011	2011	Mean power	Mean across 6 sets	Higher is better	Sea level	Repeated-measures design	7	203	35	7	201	35	Yes	No
Peeling 2012	2012	200-m swim time trial	12-h post-recovery performance trial	Lower is better	Sea level	Counterbalanced repeated-measures, 3-condition	8	136.5	5.7	8	137.2	5.2	Yes	No
Porter 2022	2022	Mean power	Sprint 10 (NH vs NN)	Higher is better	Sea level	Within-participant repeated, 4-condition counterbalanced	10	456.8	121.7	10	502.6	99.8	Yes	No
Robbins 1992	1992	Time to exhaustion	Ex3 maximal treadmill bout after 4-min recovery period	Higher is better	Sea level	Crossover / repeated, randomized order	13	3.46	0.11	13	3.33	0.14	Yes	No

Sperlich 2011	2011	Mean power output	R2 Interval 5	Higher is better	Sea level	Crossover / repeated, randomized	12	207.2	45.8	12	198.9	42.2	Yes	No
Sperlich 2012	2012	Mean power output	Interval 5	Higher is better	Sea level	Crossover / repeated	10	549	117	10	530	145	Yes	No
Suchý 2010 (Low altitude)	2010	Mean power	2nd Wingate test	Higher is better	Sea/ Low altitude	Crossover / repeated, double-blind	10	742.3	171.2	10	713.8	171.9	Yes	No
Suchý and Heller 2010 (Repeated anaerobic exercise)	2010	Mean power decline (W)	1st-to-2nd Wingate change	Lower is better	Sea level	Crossover / repeated, double-blind	10	27.09	19.68	10	49.23	29.18	Yes	No
Winter 1989	1989	Time to exhaustion	Second treadmill bout after 4-min recovery	Higher is better	Sea level	Crossover / repeated, randomized double-blind	12	126	25.98	12	120	31.87	Yes	No
Yokoi 2014	2014	MVIC recovery	REC-MVIC-1	Higher is	Sea level	Crossover / repeated	11	99.8	11.28	11	89.7	9.62	Yes	No

(J Phys Ther Sci)		rate		better									
Yokoi 2014 (JSCR)	2014	MVIC recovery rate	T5	Higher is better	Sea level	Crossover / repeated	12	96.6	18.01	12	82.5	12.12	Yes	No
Hauser 2014	2014	Mean total power output	Pmean tot (overall)	Higher is better	Altitude-related	Crossover / repeated, single-blind	8	198.4	27.1	8	200.2	28.0	Yes	No
Suchý 2010 (High altitude)	2010	Mean power	2nd Wingate test	Higher is better	Altitude-related	Crossover / repeated, double-blind	10	691.1	138.3	10	655.9	128.0	Yes	No

Abbreviations:
AT, anaerobic threshold; JSCR, *Journal of Strength and Conditioning Research*; J Phys Ther Sci, *Journal of Physical Therapy Science*; MVC, maximal voluntary contraction; MVIC, maximal voluntary isometric contraction; REC-MVIC-1, first post-recovery MVIC assessment; SD, standard deviation; SE, standard error; SEM, standard error of the mean; T5, fifth post-recovery measurement time point.

Notes:

1. This table summarizes the studies contributing to the primary performance meta-analysis and the arm-level summary statistics extracted for synthesis. A total of 16 study entries contributed to the main synthesis.
2. Because many included studies used crossover, repeated-measures, or within-subject designs, but most reports did not provide sufficient paired-variance data or within-subject correlations, the primary meta-analysis was conducted using arm-level summary statistics in a common random-effects model.
3. Favored direction indicates whether higher or lower values reflect better performance. For time-based outcomes, lower values indicate better performance and effect directions were aligned accordingly during meta-analysis.
4. “Included in main meta-analysis” indicates whether the study contributed directly to the primary arm-based pooled analysis.
5. “Paired-effect data available” indicates whether a study reported sufficient information for a paired-effect or crossover-specific quantitative synthesis; in most cases, such information was not available.
6. For Kay 2008, only the prespecified comparison of 100% O_2 versus 21% O_2 was retained in the primary analysis; the 60% O_2 comparison was not included.

7. For Suchý 2010, the altitude-comparison study was represented as two separate entries (low altitude and high altitude) according to the prespecified study-splitting rule. The repeated anaerobic exercise study was retained as a separate study entry.
8. For Yokoi 2014, the *Journal of Physical Therapy Science* and *Journal of Strength and Conditioning Research* reports were treated as two distinct articles.
9. For Hauser 2014, the comparator was hypoxic recovery rather than standard normoxic recovery; accordingly, this study was retained in the main synthesis but additionally examined in sensitivity analysis.
10. For Kay 2008, the extracted performance values were estimated from the published figure, with error bars interpreted as standard errors.
11. For Yokoi 2014 and Winter 1989/Robbins 1992, some SD values were derived from reported SEM or SE.
12. Kidwell 2026 provided paired-result information that could have supported a paired-effect estimate, but it was retained within the common arm-based framework for consistency across studies.
13. The primary meta-analysis used standardized mean differences (Hedges' g) because performance outcomes were reported on different measurement scales.

Table 3. Secondary outcome data extraction and synthesis summary

Study	Year	Outcome domain	Selected measure	Time point used for synthesis	Favored direction	Analytic setting / environment	Design	Hypoxia condition	Control condition	Hypoxia group (n, mean ± SD)	Control group (n, mean ± SD)	Meta-analytic role / notes
Maeda 1997 (Higher AT)	1997	BLa	Blood lactate (mmol/L)	Post-exercise recovery endpoint used in final extraction	Lower is better	Sea level	Repeated / subgrouped by fitness	Hypoxic recovery	Control recovery	7, 2.55 ± 0.29	7, 3.11 ± 0.44	Included in pooled BLa analysis
Maeda 1997 (Lower AT)	1997	BLa	Blood lactate (mmol/L)	Post-exercise recovery endpoint used in final extraction	Lower is better	Sea level	Repeated / subgrouped by fitness	Hypoxic recovery	Control recovery	7, 3.89 ± 0.44	7, 4.55 ± 0.88	Included in pooled BLa analysis
White 2013	2013	BLa	Blood lactate (mmol/L)	Post-exercise endpoint used in final extraction	Lower is better	Sea level	Randomized single-blind repeated-measures	HYP	NORM	10, 5.0 ± 3.48	10, 5.5 ± 2.85	Included in pooled BLa analysis

Peeling 2011	2011	BLa	Blood lactate (mmol/L)	Endpoint used in final extraction	Lower is better	Sea level	Crossover / repeated	HYP	NORM	7, 5.2 ± 3.3	7, 4.8 ± 2.8	Included in pooled BLa analysis
Sperlich 2012	2012	BLa	Blood lactate (mmol/L)	Post-final sprint / recovery endpoint	Lower is better	Sea level	Crossover / repeated	HO	NO	10, 14.9 ± 3.2	10, 14.9 ± 3.2	Included in pooled BLa analysis
Yokoi 2014 (JSCR)	2014	BLa	Blood lactate (mmol/L)	Endpoint used in final extraction	Lower is better	Sea level	Crossover / repeated	Hyperoxic recovery	Control recovery	12, 5.4 ± 4.85	12, 4.8 ± 3.46	Included in pooled BLa analysis
Winter 1989	1989	BLa	Blood lactate (mmol/L)	Endpoint used in final extraction	Lower is better	Sea level	Crossover / repeated	O_2	Air	12, 8.6 ± 1.73	12, 8.3 ± 2.08	Included in pooled BLa analysis
Hauser 2014	2014	BLa	Blood lactate (mmol/L)	Endpoint used in final extraction	Lower is better	Simulated altitude (1800 m)	Crossover / repeated	Hyperoxic recovery	Hypoxic control recovery	8, 11.2 ± 1.8	8, 11.8 ± 2.9	Included in pooled BLa analysis; comparator not standard normoxia
Sperlich 2011	2011	BLa	Blood lactate (mmol/L)	Post-final interval / recovery endpoint	Lower is better	Sea level	Crossover / repeated, randomized	HOX	NOX	12, 11.8 ± 2.2	12, 11.8 ± 2.2	Included in pooled BLa analysis
Nummela 2002	2002	BLa	Blood lactate (mmol/L)	3rd set end (45 s run)	Lower is better	Sea level	Randomized crossover / repeated, 3-condition	RHOX	NOX	9, 15.2 ± 3.7	9, 15.6 ± 3.3	Included in pooled BLa analysis
White 2013	2013	HR	Heart rate recovery	Average recovery HR	Lower is bett	Sea level	Randomized single-blind	HYP	NORM	10, 124 ± 6.32	10, 125 ±	Included in pooled HR

			(bpm)	across interval session	er		repeated-measures				6.32	analysis; exploratory because endpoint definitions differed across studies Included in pooled HR analysis;
Nummela 2002	2002	HR	HRdec (beats·min^-1)	3rd set, first min recovery	Higher is better	Sea level	Randomized crossover / repeated, 3-condition	RHOX	NOX	9, 16 ± 8	9, 11 ± 13	exploratory because endpoint definitions differed across studies Included in quantitative exploration only; endpoint reflected
White 2013	2013	SpO_2	SpO_2 recovery time (s)	Post-exercise recovery-to-baseline time	Lower is better	Sea level	Randomized single-blind repeated-measures	HYP	NORM	10, 38 ± 9.49	10, 62 ± 9.49	recovery-to-baseline time rather than saturation level, and SpO_2 findings were ultimately interpre

											ted narrativ ely because heterog eneity remaine d substan tial
Spe rlic h 201 2	2 0 1 2	Sp O_2	SaO_2 (%)	Recover y endpoin t after hyperox ic vs normoxi c breathi ng	Hig her is bett er	Sea level	Crosso ver / repeate d	HO	NO	10, 99.8 ± 0.2	10, 95. 9 ± 0.4	Include d in quantit ative explora tion only; interpre ted narrativ ely in the final review because heterog eneity remaine d high
Ha use r 201 4	2 0 1 4	Sp O_2	SpO_2 (%)	Endpoi nt used in final extracti on	Hig her is bett er	Simu lated altitu de (180 0 m)	Crosso ver / repeate d	Hyp erox ic reco very	Hyp oxic con trol rec ove ry	8, 99.8 ± 0.3	8, 92. 5 ± 2.0	Include d in quantit ative explora tion only; compar ator was hypoxic rather than standar d normoxi c recover y, and the final interpre tation was narrativ e

Sperlich 2011	2011	SpO_2	SaO_2 (%)	Recovery endpoint after hyperoxic vs normoxic breathing	Higher is better	Sea level	Crossover / repeated, randomized	HOX	NOX	12, 99.9 ± 0.3	12, 97.2 ± 0.7	Included in quantitative exploration only; interpreted narratively in the final review because heterogeneity remained high
Nummela 2002	2002	SpO_2	SaO_2 (%)	3rd set end (45 s run)	Higher is better	Sea level	Randomized crossover / repeated, 3-condition	RHOX	NOX	9, 91.8 ± 3.7	9, 88.7 ± 2.0	Included in quantitative exploration only; interpreted narratively in the final review because heterogeneity remained high

Abbreviations:
AT, anaerobic threshold; BLa, blood lactate; HR, heart rate; HRdec, decrease in heart rate during recovery; HYP, hyperoxia; HO, hyperoxia; HOX, hyperoxic recovery; NO, normoxia; NOX, normoxic recovery/control; RHOX, hyperoxia during recovery only; SaO_2, arterial oxygen saturation; SD, standard deviation; SpO_2, peripheral oxygen saturation.

Notes:
This table summarizes the study-level data contributing to the secondary outcome synthesis.
Blood lactate (BLa) was retained as the pooled secondary outcome. Across 10 study entries, the pooled estimate was synthesized from the available eligible studies, and interpretation remained cautious because small-study effects were explored in the broader sensitivity analyses.
Heart rate (HR) was treated as an exploratory pooled outcome. Across 2 study entries, the synthesis should be interpreted as exploratory only because the included studies assessed partially heterogeneous HR-derived endpoints and the evidence base was very small.
SpO_2 was quantitatively explored across 5 study entries, but the final interpretation was narrative because heterogeneity remained substantial. The initial pooled analysis showed $I^2 = 90.0\%$; exclusion of White 2013 did not reduce heterogeneity ($I^2 = 92.5\%$), and leave-one-out analyses showed that

heterogeneity remained high regardless of which single study was omitted. Accordingly, no single study alone explained the inconsistency.
Direction of benefit indicates whether lower or higher values reflect a more favorable recovery profile for that outcome.
For multicontrast crossover studies, only the prespecified hyperoxic recovery versus control comparison was retained.
Intervention and comparator labels were retained as reported or abbreviated in the original studies; abbreviations are defined above.

Table 4. Risk-of-bias assessment of the included studies

Study	D1. Randomization / order generation	D2. Deviations from intended intervention / condition allocation concerns	D3. Missing outcome data	D4. Outcome measurement	D5. Selective reporting	Overall judgement
Daab 2025	Low	Low	Low	Low	Low	Low
Suchý and Heller 2010 (Repeated anaerobic exercise)	Some concerns	Low	Low	Low	Some concerns	Some concerns
Nummela 2002	Low	Some concerns	Low	Low	Some concerns	Some concerns
Kay 2008	Low	Some concerns	Low	Low	Low	Some concerns
Porter 2022	Low	Low	Low	Low	Low	Low
Peeling 2011	Low	High	Low	High	Low	High
Sperlich 2012	Low	Some concerns	Low	Low	Low	Some concerns
Peeling 2012	Low	Some concerns	Low	Low	Low	Some concerns
Yokoi 2014 (J Phys Ther Sci)	Low	Low	Low	Low	Low	Low
Yokoi 2014 (JSCR)	Low	Low	Low	Low	Low	Low
Winter 1989	Low	Low	Low	Low	Low	Low
Hauser 2014	Low	Low	Low	Low	Low	Low
Robbins 1992	Low	Low	Low	Low	Low	Low

Suchý 2010 (Low altitude)	Low	Low	Low	Low	Low	Low
Suchý 2010 (High altitude)	Low	Low	Low	Low	Low	Low
White 2013	Low	Low	Low	Low	Low	Low
Sperlich 2011	Low	Low	Low	Low	Low	Low
Kidwell 2026	Low	Low	Some concerns	Some concerns	Low	Some concerns
Maeda 1997 (Higher AT)	High	High	Low	Low	Some concerns	High
Maeda 1997 (Lower AT)	High	High	Low	Low	Some concerns	High
Bjorgum 1966	Low	Some concerns	Low	Low	Some concerns	Some concerns

Abbreviations: D1, bias arising from the randomization process / condition-order generation; D2, bias due to deviations from intended interventions or condition-allocation concerns; D3, bias due to missing outcome data; D4, bias in outcome measurement; D5, bias in selection of the reported result.

Notes:
Risk of bias was assessed using an adapted domain-based framework suitable for exercise-recovery studies that included parallel, crossover, repeated-measures, and within-subject designs.
For crossover and repeated-measures studies, D1 and D2 incorporated concerns related to condition order, randomization, and potential carryover or washout issues where applicable.
“Some concerns” indicates that at least one domain raised a potential methodological issue but the study was not judged to be at overall high risk of bias.
“High” overall judgement indicates that the study was considered vulnerable to substantial bias in at least one important domain.
This table reflects the final 21-study risk-of-bias set used for ROBVIS visualization. For older studies, risk-of-bias judgments should be interpreted in light of limited reporting detail; a low-risk judgment indicates that no clear domain-specific concern was identified from the available report, not that all possible risks of bias were definitively absent.

Table 5. Summary of findings and interpretation by outcome

Outcome	Studies contributing to synthesis	Synthesis approach	Main pooled result	Heterogeneity / sensitivity analyses	Final interpretation
Performance	16 study entries	Random-effects meta-analysis using arm-level summary	SMD = 0.42 (95% CI 0.22 to 0.63)	I^2 = 0%; leave-one-out and prespecified exclusion analyses did	Normobaric hyperoxic recovery was associated with a small-to-modera

		statistics and standardized mean differences (Hedges' g)		not materially change the result; trim-and-fill did not materially alter the pooled estimate; fail-safe N was 59; Egger's test was not significant	te benefit for subsequent performance, and sensitivity analyses did not materially change the direction or approximate magnitude of the estimate
Blood lactate (BLa)	10 study entries	Random-effects meta-analysis using standardized mean differences	The pooled estimate was synthesized from the available eligible studies; no clear pooled effect on blood lactate was identified	I^2 = 0%; Egger's test suggested asymmetry; trim-and-fill showed k0 = 0 and did not materially change the pooled estimate	No clear pooled effect on blood lactate was identified; interpretation should remain cautious because of the asymmetry signal despite stable trim-and-fill results
Heart rate (HR)	2 study entries	Exploratory random-effects meta-analysis using standardized mean differences	The pooled estimate was exploratory and did not support a clear effect on heart rate	I^2 = 0%; interpretation limited by the very small evidence base and heterogeneity in endpoint definitions across studies	No clear pooled effect on heart rate was identified; this outcome should be considered exploratory only
Peripheral oxygen saturation (SpO_2)	5 study entries	Quantitative exploration followed by narrative synthesis	An initial pooled estimate favored hyperoxic recovery, but this estimate was not retained for inferential interpretation because of marked heterogeneity	Initial I^2 = 90.0%; exclusion of White 2013 did not resolve heterogeneity (I^2 = 92.5%); leave-one-out analyses showed that heterogeneity remained high regardless of which single study was omitted	SpO_2 findings should be interpreted narratively rather than as a stable pooled conclusion

Abbreviations:
BLa, blood lactate; HR, heart rate; I^2, Higgins inconsistency statistic; SMD, standardized mean difference; SpO_2, peripheral oxygen saturation.

Notes:
The primary performance synthesis was based on arm-level summary statistics because most included crossover or repeated-measures studies did not report sufficient paired-variance data or within-subject correlations for a paired-effect meta-analysis.
For performance outcomes, positive standardized mean differences favor normobaric hyperoxic recovery after alignment of effect direction across different performance measures.
For secondary outcomes, effect estimates should be interpreted in the context of heterogeneous endpoint definitions and recovery time points across studies.
For SpO_2, a quantitative pooled estimate was explored initially, but the final interpretation was based on narrative synthesis because substantial heterogeneity persisted after sensitivity analyses.
Sensitivity statements are based on the completed sensitivity analyses, including leave-one-out analysis, trim-and-fill, fail-safe N, and prespecified exclusion analyses where applicable.

Figure 1. PRISMA 2020 flow diagram of study selection. The electronic search identified 3585 records from databases and web sources, and an additional 9 records were identified through citation searching. After duplicate removal, title/abstract screening, and full-text assessment, 19 reports were retained. These 19 reports yielded 21 study entries for synthesis after prespecified splitting of Maeda 1997 by anaerobic-threshold subgroup and the Suchý 2010 altitude-comparison study into low-altitude and high-altitude entries.

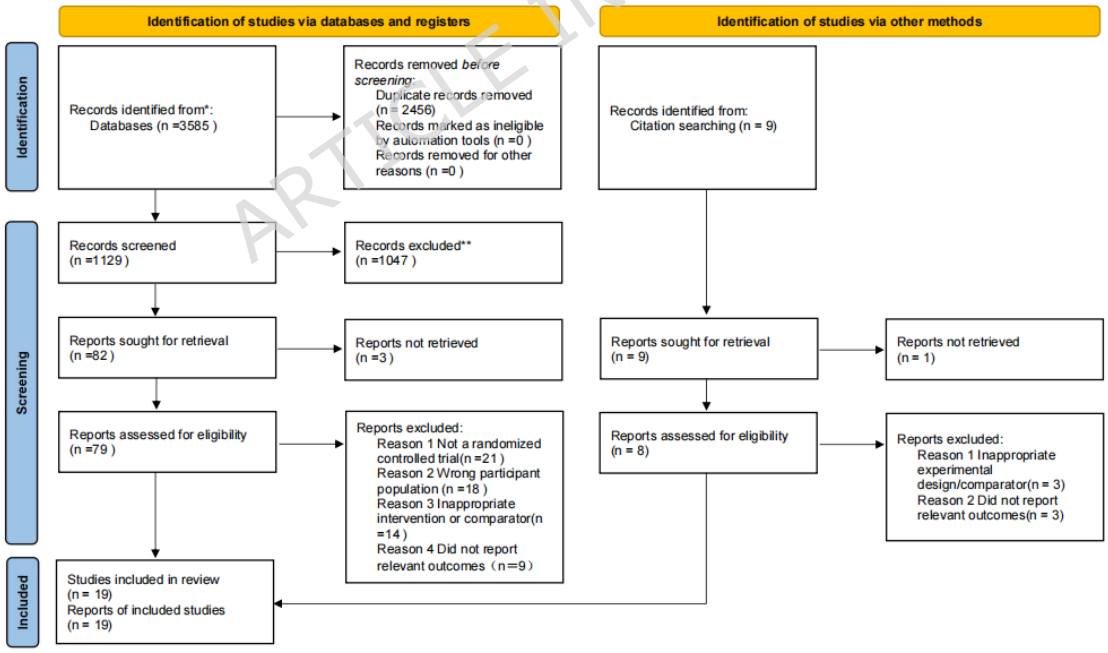

Figure 2. Forest plot of the primary performance meta-analysis. The pooled random-effects model estimated a small-to-moderate effect in favor of normobaric hyperoxic recovery on subsequent performance (SMD = 0.42, 95% CI 0.22 to 0.63; I^2 = 0%). Positive standardized mean differences favor

hyperoxic recovery after alignment of effect direction across different performance measures.

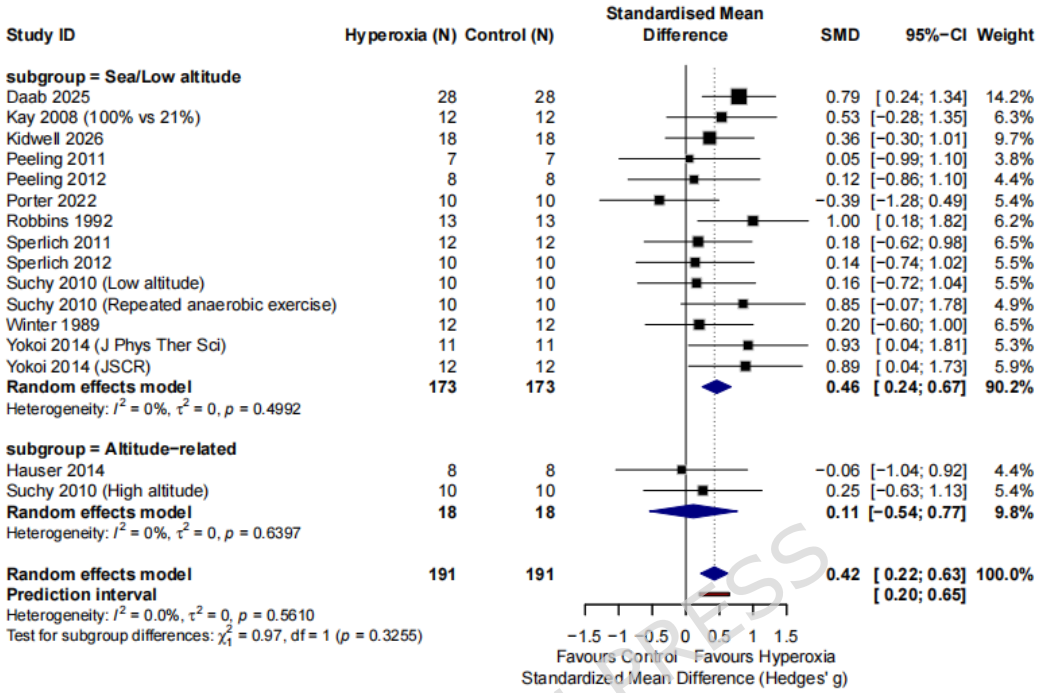

Figure 3. Funnel plot for the primary performance outcome. Visual inspection did not indicate marked asymmetry, consistent with the absence of statistically significant evidence for small-study effects in the primary performance analysis.

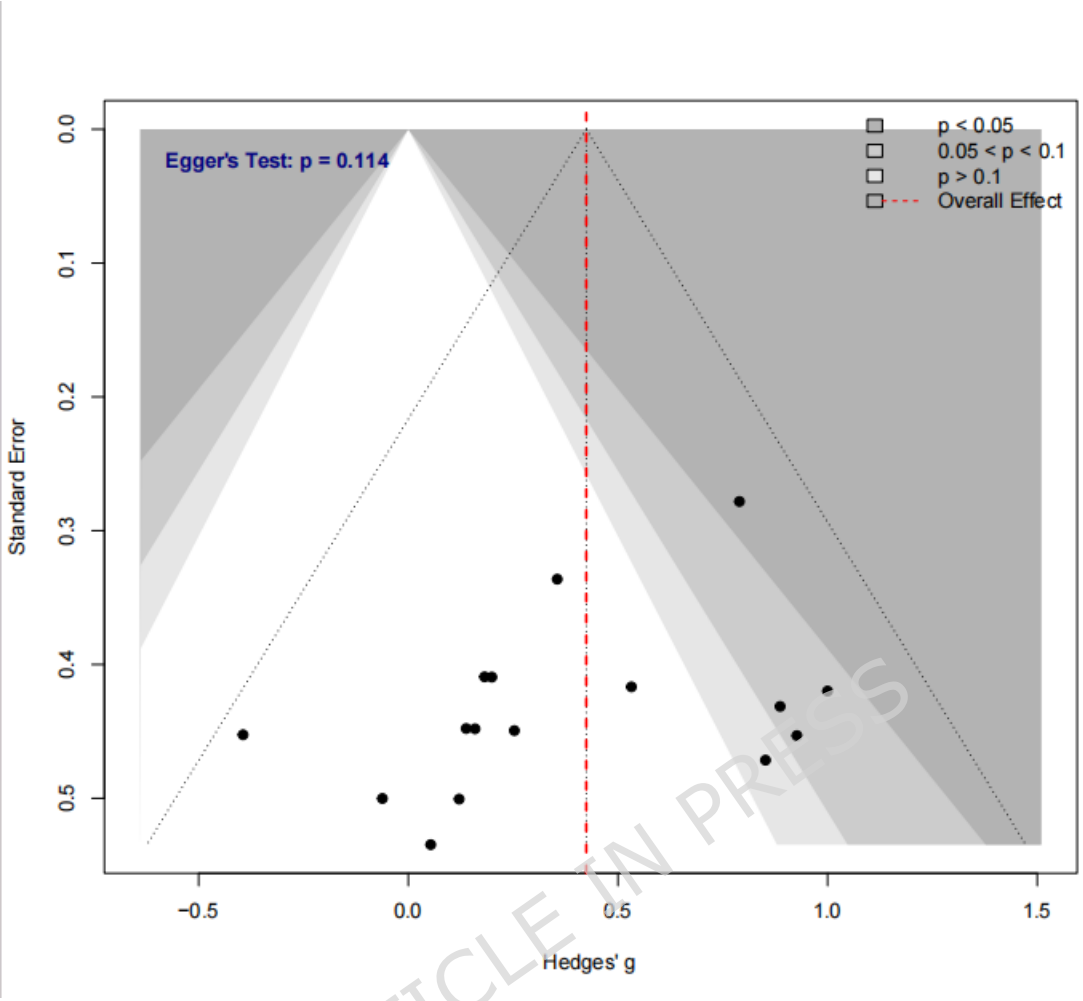

Figure 4. Forest plot of the blood lactate (BLa) meta-analysis. The pooled random-effects model did not show a clear effect of hyperoxic recovery on blood lactate (SMD = 0.14, 95% CI -0.15 to 0.43; I^2 = 0%). Lower blood lactate values were treated as more favorable during direction alignment.

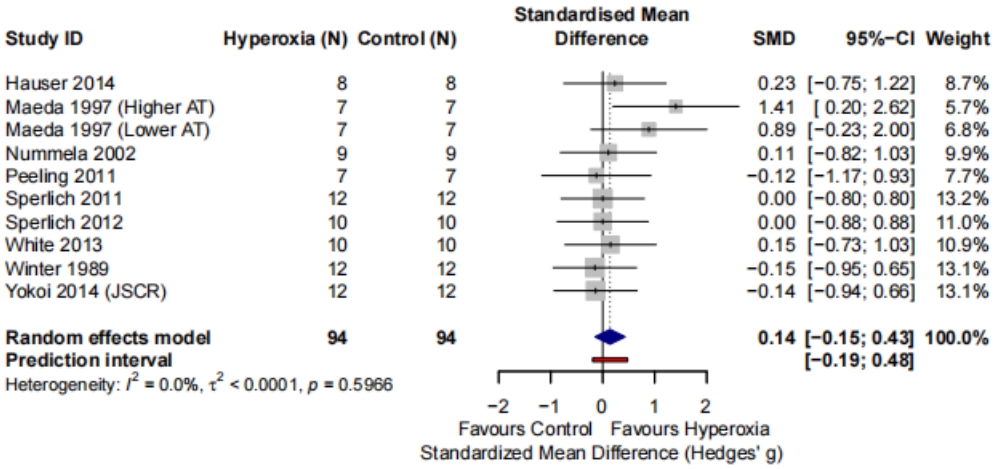

Figure 5. Forest plot of the exploratory heart-rate (HR) meta-analysis. The pooled exploratory analysis did not show a clear effect of hyperoxic recovery on HR-related outcomes (SMD = 0.29, 95% CI -0.35 to 0.93; I^2 = 0%). Because the contributing studies used partially heterogeneous HR-derived endpoints, this figure should be interpreted as exploratory only.

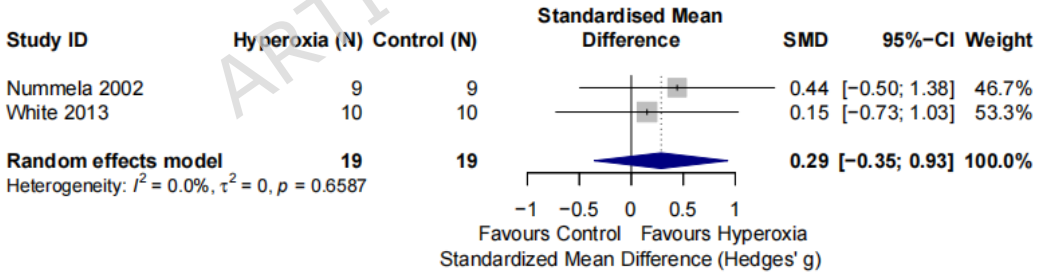

Figure 6A–B. ROBVIS risk-of-bias visualizations for included studies. Figure 6A shows the traffic-light plot presenting study-level judgments across the five adapted risk-of-bias domains. Figure 6B shows the summary plot of the proportion of studies judged as low risk, some concerns, or high risk across domains. Judgments were based on the adapted domain-based framework used in this review.