

Review Article

Impact of the administration type for normobaric hypoxia on the maximal aerobic capacity: A systematic review and meta-analysis

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ABSTRACT

Purpose: Normobaric hypoxia (NH) is a frequent strategy for training under hypoxic conditions that can be administered through different equipment, including face masks or hypoxic chambers/tents. Nonetheless, the versatility of administration methods may influence the outcomes.

Methods: Web of Science, Scopus, SPORTDiscus and PubMed/MEDLINE were searched to identify studies assessing the effect of NH administered by face mask or chamber/tent equipment on maximal oxygen uptake ($\dot{V}O_{2max}$) after a training period. An overall meta-analysis and sub-analysis of total program session volume (low, moderate, high), participants' training level (trained, active, sedentary), and the severity of hypoxia (moderate, severe) were conducted to explore the effects of the NH-administration system.

Results: Eighteen studies were included. Compared with normoxia, NH showed a moderate global improvement in $\dot{V}O_{2max}$ (standardized mean difference [SMD] = 0.74; $p = 0.06$), favoring the chamber/tent (SMD = 1.30; $p < 0.01$) over the face mask. Sub-analysis showed a very large effect in support of the hypoxic chamber/tent among sedentary individuals and training programs with a high volume of sessions. Severe hypoxia did not yield conclusive findings in $\dot{V}O_{2max}$ improvements, although the chamber/tent proved more effective (SMD = 1.42; $p < 0.01$) than the face mask under moderate hypoxia.

Conclusions: Chambers/tents may slightly accentuate the benefit of NH on aerobic performance, particularly in participants with limited training experience following a high volume of sessions under moderate hypoxia. However, the variability of sub-analysis factors (session volume, participants' training level, and methodological approaches) between studies using each type of hypoxia-generating equipment may influence this result.

1. Introduction

Hypoxia training is an important resource in optimizing sports performance.¹ It encompasses exposure to hypoxia (terrestrial or artificial) of varying severity and strategies depending on the desired objective.^{2,3} It is crucial to discriminate between passive exposure to hypoxia (such as resting or sleeping under hypoxic conditions) and exercise in hypoxia, where physical activity is performed in a low-oxygen environment. These modalities elicit distinct physiological adaptations and should be considered separately when designing training protocols and interpreting outcomes.^{3–5} The reduction in the inspired fraction of oxygen (F_iO_2) triggers several physiological responses in the body's organs and systems, including upregulated erythropoiesis, augmented capillary density, and enhanced mitochondrial bioenergetics, which collectively

optimize oxygen delivery, diffusion, and cellular utilization.^{6,7} These physiological responses, particularly those at the muscular level, lead to structural and metabolic adaptations in muscle fibers, such as enhanced oxidative enzyme activity and greater fatigue resistance,^{7,8} which collectively contribute to improving maximal oxygen uptake ($\dot{V}O_{2max}$).

Recent technological advancements have led to the development of innovative equipment that can replicate the physiological impact of high altitudes. These instruments either lower the pressure of inspired air (hypobaric hypoxia chambers) or diminish the oxygen concentration by introducing additional nitrogen or oxygen extraction methods (normobaric hypoxia [NH] from the use of hypoxia-generating systems).^{9,10} Examples of such equipment include masks, chambers, marquees, and tents for training¹¹ or sleeping.¹² The emergence of this artificial hypoxia-generating equipment on the market has improved accessibility to hypoxia during training and has solved logistical problems for

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Abbreviations	
c	bias correction factor for small samples
CO ₂	carbon dioxide
CI	confidence interval
d	standardized effect size coefficient
df	degrees of freedom
FiO ₂	inspired fraction of oxygen
G1-4	group number
H-AE	hypoxic-absolute exercise
HAT	hypoxic-absolute exercise
HC	hypoxia control
HET	hypoxia exercise training
HI	hypoxia intensive
HIGH	high intensity training
HIT	high-intensity interval training
HM	hypoxia moderate
H-RE	hypoxic-relative exercise
HR	heart rate
hrLT	heart rate at the lactate threshold
HRmax	maximal heart rate
HRRmax	heart rate reserve maximum
HRT	hypoxic-relative exercise
I ²	I squared statistic
LLTH	live-low train-high
LOW	low intensity training
MAP	maximal aerobic power
MICT	moderate intensity continuous training
N	normoxia
n	sample size
NC	normoxia control
N-E	normoxic exercise
NET	normoxia exercise training
NH	normobaric hypoxia
NI	normoxia intensive
NM	normoxia moderate
NT	normoxia exercise
p	p value
PaO ₂	alveolar oxygen pressure
Pmax	maximal power
PO	power output
PPO	peak power output
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analysis
Q	test statistic for the test of heterogeneity
RCT	Randomized controlled trials
ROS	reactive oxygen species
RoB 2	Revised Cochrane risk-of-bias tool for randomized trials
RSA	repeated sprint ability
S ²	variance
\bar{S}	Pooled standard deviation
SD	standard deviation
SMD	standardized mean difference
$\dot{V}O_{2max}$	maximal oxygen uptake
v $\dot{V}O_{2max}$	velocity at maximal oxygen consumption
VT2	second ventilatory threshold
vVT2	velocity at the second ventilatory threshold
W	watts
Wmax	maximal work capacity
WRLT	workload at lactate threshold
\bar{z}	meanZ - z value
1 RM	one-repetition maximum
Δ	mean differences between post-pre in NH

athletes by promoting new training strategies, such as live-low train-high (LLTH).^{2,13} While LLTH is primarily known for enhancing repeated sprint ability (RSA), evidence suggests it can also improve $\dot{V}O_{2max}$ by increasing ventilatory efficiency, muscle oxygen extraction, and mitochondrial function, thereby supporting aerobic adaptations.^{3,14} In this context, NH-generating equipment includes different types of hypoxia-generating systems, many of them portable, that allow it to be administered in various ways, such as a connection through a face mask or by using small rooms, chambers, or tents (in this review, chamber/tent is used as a generic term to refer to these modalities). Physical exercise in a hypoxia chamber/tent is normally accompanied by progressive alteration of environmental conditions of temperature, relative humidity, and the carbon dioxide (CO₂) level, which significantly increases when the exercise reaches a sufficient intensity and duration.^{9,15} This fact could affect the athlete's performance, considering the combination of exercise and hypoxia with other environmental stressors.^{15,16} Conversely, using a hypoxia-generating device connected via a face mask almost guarantees the quality and composition of the inspired air; however, practical constraints, such as tube length and chamber volume, may limit its applicability to resting conditions or exercise performed on an ergometer, compared to the broader movement possibilities within a chamber or tent. Therefore, hypoxia chambers/tents or face masks imply different intervention contexts that could affect the training conditions, which warrants the need for further investigation.

Several studies have compared strategies involving normobaric hypoxia with normoxia (N), and their impact on the aerobic capacity.^{17,18} However, no review has differentiated and compared different types of NH-delivery equipment used to establish hypoxia. Therefore, the objective of the present study was to carry out a systematic review

and meta-analysis to address the effect of the type of equipment used to develop the systemic NH condition (face mask vs hypoxia chamber/tent) on aerobic performance, assessed by $\dot{V}O_{2max}$, after a training period. This investigation hypothesizes that the modality of systemic NH-delivery equipment influences the magnitude of $\dot{V}O_{2max}$ improvements following an exercise intervention period, with greater enhancements expected when using a hypoxia chamber/tent compared to a face mask.

2. Methods

2.1. Literature search

This review was carried out following the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA)¹⁹ guidelines. To reduce duplication of effort and publication bias, this study was registered in PROSPERO on 19 January 2024 (<https://www.crd.york.ac.uk/prospero/>; registration code - CRD42024497962). On 21 April 2025, Web of Science, Scopus, SPORTDiscus and PubMed/MEDLINE (main collections) were searched with the keywords 'hypoxia' AND 'exercise' AND 'cardiorespiratory fitness' OR ' $\dot{V}O_{2max}$ ' AND 'randomized controlled trial', as the terms used to construct the search strategy for each database (Supplemental Fig. S7). In addition, studies with the term 'intermittent hypoxic or hypoxia' were collected. The search results were stored in EndNote basic (Web of Science; Clarivate Analytics, New York, NY, USA). Two authors (C.B. and S.P.) carried out a pre-selection of the articles and extracted data corresponding to the application of hypoxia with a face mask or chamber/tent. A third researcher (B.F.) intervened in the case of discrepancies between C.B. and S.P. at any point in the

process. Only articles published in Journal Citation Reports–indexed journals that performed on humans and exclusively with artificial NH-generating equipment were retained.

2.2. Eligibility criteria

Preselected studies that met the following criteria were included in the analysis - (1) aerobic performance–focused studies conducted in systemic NH delivered by a face mask and/or hypoxia chamber/tent for a minimum period of 2 weeks; (2) healthy populations aged between 18 and 45 years; (3) clear specification of the FiO₂ used, or failing that, the altitude equivalent, to assess the severity of hypoxia; and (4) studies that included a control group in N for comparison; (5) publications were limited by English language.

Several groups of studies were excluded - (1) descriptive studies; (2) studies with participants residing at altitudes > 1 000 m above sea level; (3) non-original or incomplete publications; (4) studies that did not specify the evaluation procedure of the variable selected for analysis ($\dot{V}O_{2\max}$); (5) studies that applied terrestrial, local or systemic hypoxia induced by procedures other than those specified; and (6) studies for which it was not possible to access the numerical data in the results.

2.3. Data encoding

The following data were extracted to a spreadsheet - (1) the duration of the training program; (2) the type of design (intragroup or intergroup); (3) the size and characteristics of the sample (age, gender and the participants' training level [trained, active or sedentary]); (4) the severity of hypoxia (moderate [14.3%–16% FiO₂] or severe (11%–14.3% FiO₂)); (5) the duration of exposure to hypoxia in minutes; (6) the characteristics of the intervention program, namely sessions per week, the number of weeks and the intensity; (7) the description, mean and standard deviation (SD) of $\dot{V}O_{2\max}$ (ml·kg⁻¹·min⁻¹); and (8) the type of NH-generating equipment (face mask and/or hypoxia chamber/tent).

Potential confounding from covariates was assessed with sub-analysis of the data regarding the severity of hypoxia (moderate = 14.3%–16% FiO₂; severe = 11%–14.3% FiO₂), the participants' training level (trained = athletes or following a supervised training regimen; active = non-specifically trained or physically or recreationally active; sedentary = no regular physical activity or exercise frequency ≤ once weekly, and a duration < 20 min) and the total program session volume (low < 10 sessions; moderate = 10–19 sessions; high > 19 sessions). The coding files were collated by the authors to refine the criteria.

2.4. Quality criteria

Due to the specificity of the review topic, quality control criteria were included in the analysis following the recommendations of Downs and Black.²⁰ The following aspects were evaluated - (1) in the case of an intragroup design, the specification of the washout period between the evaluations or interventions; (2) randomization and counterbalancing of the distribution of the participants in the evaluation groups or conditions according to the design used; (3) the use of double-blind design; and (4) the indication of the effect size.

2.5. Risk of bias assessment

The risk of bias of the included studies in this systematic review was determined independently by two reviewers (S.P. and C.B.) and was evaluated using specific scales depending on the type of study, following the instructions given by the Cochrane Handbook for Systematic Reviews of Intervention²¹ and the National Institutes of Health.²²

Randomized controlled trials (RCTs) were evaluated by using the Revised Cochrane risk-of-bias tool for randomized trials (RoB 2).²³ This common tool assesses bias in five distinct domains - the randomization

process, intended interventions, missing data, measurements, and results.

2.6. Statistical analysis

The studies included in the meta-analysis were analyzed as intergroup (NH vs N group) randomized measures for $\dot{V}O_{2\max}$ according to the objective of the intervention and are expressed as the standardized mean difference (SMD) and its 90% confidence interval (CI). Sub-analysis was performed to determine possible confounding effects of the type of equipment, the severity of hypoxia, the total program session volume, and the participant's training level. The standardized effect size coefficient (*d*) in RCTs was calculated as the mean difference between the pre–post change in the NH group, ($\bar{X}_{\text{post, NH}} - \bar{X}_{\text{pre, NH}}$) and the N group ($\bar{X}_{\text{pre, N}} - \bar{X}_{\text{pos, N}}$) divided by the mean pooled baseline standard deviation (\bar{S}_{pre})²⁴:

$$d = c(df_{NH}, N) \cdot [(\bar{X}_{\text{post, NH}} - \bar{X}_{\text{pre, NH}}) - (\bar{X}_{\text{post, N}} - \bar{X}_{\text{pre, N}})] / (\bar{S}_{\text{pre}}) \bar{S}_{\text{pre}} = \sqrt{((n_{NH} - 1) \cdot S^2_{\text{pre, H}} + (n_{N} - 1) \cdot S^2_{\text{pre, N}}) / (n_{NH} + n_{N} - 2)}$$

Where *df* is degrees of freedom, *n* is sample size and *c*, the coefficient included as a correction factor for small samples $c(df_{NH}, N)$ ²⁵.

$$c(df_{NH}, N) = 1 - 3 / (4(n_{NH} + n_{N} - 2) - 1)$$

For the weighting of the studies, the inverse variance method was used in both cases. Likewise, the raw mean difference (not standardized) was calculated for the RCTs, ($\bar{X}_{\text{post, NH}} - \bar{X}_{\text{pre, NH}} - (\bar{X}_{\text{post, N}} - \bar{X}_{\text{pre, N}})$), by using the weights obtained in the standardized meta-analysis to estimate the pooled mean difference for each result.

The data was analyzed using a multi-level random-effects model to account for multiple effects nested within groups, studies, and participants (three-level analysis).²⁶ This approach allows one to control the bias of combining several measures from the same study. According to DerSimonian and Laird,²⁷ independent effect size coefficients and their results were combined and analyzed by using a random-effects model. The weighted standardized mean change from baseline to the end of the intervention was the pooled effect size for the outcome.

Consistent with previous meta-analytic approaches,²⁸ we chose to avoid drawing binary conclusions via traditional null-hypothesis significance testing, given the documented issues with this statistical method.^{29–31} To estimate statistical heterogeneity, the *Q* test was performed, and the *I* squared statistic (*I*²) was calculated; heterogeneity was considered moderate if *I*² = 30%–60% (*p* < 0.1). The SMD value classification was 'trivial' (≤ 0.20), 'small' (0.21–0.50), 'moderate' (0.51–0.80), 'large' (> 0.80), and 'very large' (> 1.20).³² A positive SMD favors the training program performed under NH. Potential publication bias was assessed with Egger's test³³ by using the standard errors of the effect size, as estimated from a funnel plot through the trim-and-fill test. Statistical analysis was carried out using the Metafor package³⁴ of the R statistical program.³⁵

3. Results

3.1. Search results

Fig. 1 presents the PRISMA flowchart of the search. The initial database search yielded a total of 657 identified studies, which were reduced to 589 after removing duplicates. Of the 243 articles selected for review, only 22 met the inclusion criteria and were included in the meta-analysis. Four of these studies, Roels et al.,³⁶ Millet et al.,³⁷ Ponsot et al.³⁸ and Zoll et al.³⁹ were redundant because they came from the same experiment, thereby providing duplicate data. Finally, 18 studies met the pre-determined inclusion criteria.

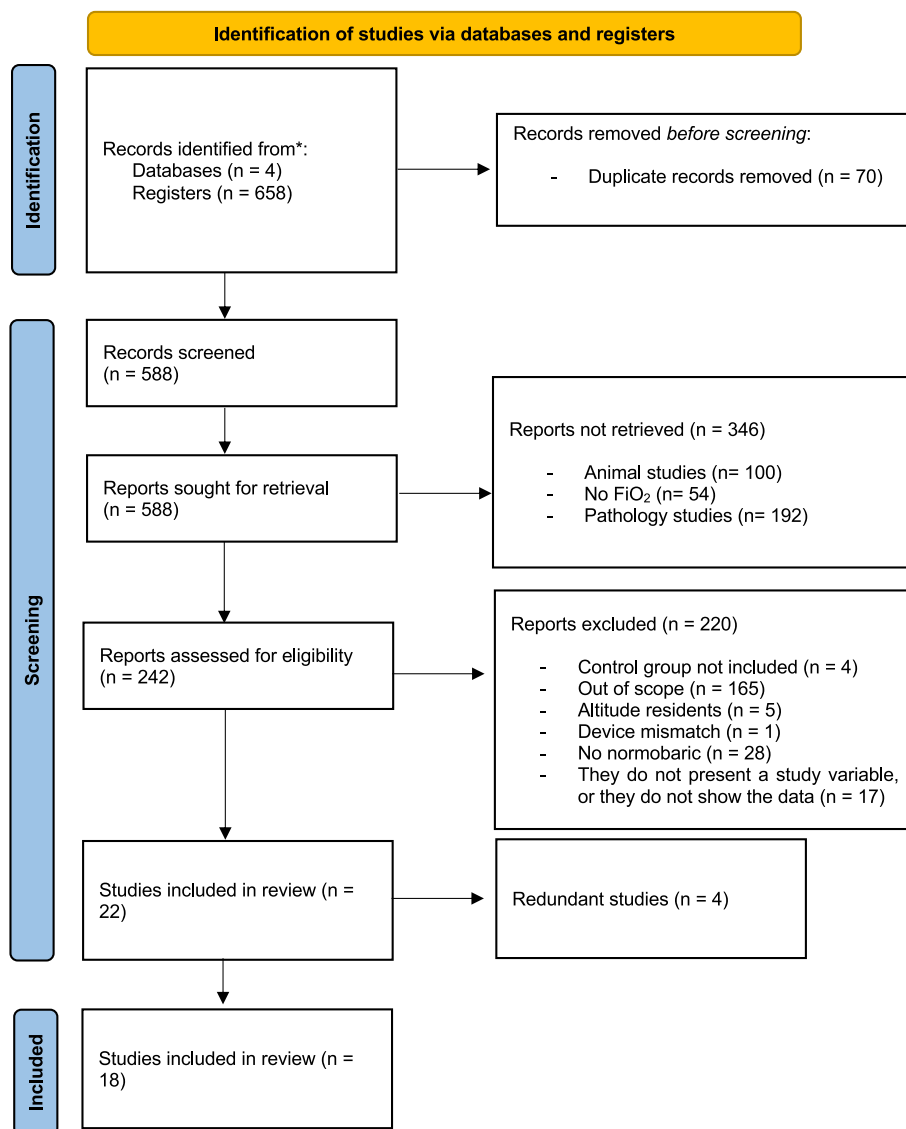


Fig. 1. Flowchart of the search and selection of studies.

3.2. Study characteristics

The studies included in the meta-analysis consisted of a total of 562 participants (15 women and 547 men), of whom 26.69% ($n = 150$) were classified as trained, 27.05% ($n = 152$) as active, and 46.26% ($n = 260$) as sedentary. The distribution of the studies included in the meta-analysis by NH-administration equipment was balanced between the use of a face mask ($n = 8$)^{36,40–46} and a hypoxic chamber/tent ($n = 10$).^{11,47–55} The vast majority of the studies used moderate hypoxia (15 of the studies; $\geq 14.3\%$ FiO₂); the remaining studies used severe hypoxia (3 of the studies; $< 14.3\%$ FiO₂).

The general characteristics of the included studies are summarized in Table 1 for face masks and Table 2 for chambers/tents. The training programs applied ranged from 2 to 5 days/week for 3–8 weeks. The exposure times to hypoxia ranged from 25 to 80 min/session. The hypoxia sessions were programmed in sustained exposure, coinciding in those cases with the duration of the training session (30–80 min).

The included studies had a sample size of 13–60 participants, with intervention groups of 6–20 participants. Five^{50–54} were carried out using a hypoxia chamber/tent and yielded a positive result in favor of the use of intermittent NH. Twelve^{40–45,47–49,56} studies did not show differences between conditions, of which three^{47–49} were carried out in a

hypoxia chamber/tent, and nine^{40–46,55,56} used a face mask. Only one study¹¹ carried out in a chamber/tent revealed a negative result regarding the use of intermittent NH.

3.3. Meta-analysis

The results are presented as the *SMD* final versus initial value (post vs pre) after the intervention program between the environmental conditions (NH vs N). The absence of studies comparing both hypoxia-generating equipment prevents the inclusion of this factor in the meta-analysis.

The global analysis presented mean differences in $\dot{V}O_{2\max}$ largely favoring the NH condition over the N condition (*SMD* = 0.74; 90% *CI*: [0.10; 1.37]; $p = 0.06$). Sub-analysis of the type of device (Fig. 2) revealed a large, significant effect favoring NH when using a chamber/tent (*SMD* = 1.30; 90% *CI*: [0.55; 2.06]; $p < 0.001$). Conversely, no changes of interest were found between conditions when using a face mask (*SMD* = -0.03; 90% *CI*: [-0.99; 0.92]; $p = 0.96$). Heterogeneity between the studies was high for $\dot{V}O_{2\max}$ between the environmental conditions ($I^2 = 94.0\%$).

The sub-analysis for the total program session volume (Table 3 and Supplemental Fig. S1) showed a very large effect on $\dot{V}O_{2\max}$ when

Table 1
Main characteristics of studies using normobaric hypoxia face mask included in the meta-analysis.

Author and publication date	Sample	NH FiO ₂ (device)	N° of sessions (n° of weeks)	Methods	Test protocol (device)	ṠO ₂ max (mL·min ⁻¹ ·kg ⁻¹) NH vs N
Akgül et al., 2023 ⁴⁴	n = 32. Active G1: N-HIT = 8 G2: N- MICT = 8 G3: H-HIT = 8 G4: H-MICT = 8	15.4% (Everest Summit II-Altitude Generator)	3 (8)	RW: 4-7 × 30-s Wingate “all-out” sprints (4 min of rest) 7.5% of the body weight MICT: 25–40 min running at 70%–80% of HRmax	Incremental test to exhaustion (treadmill)	=
Bailey et al., 2000 ³⁸	n = 32. Active G1: N (n = 14), G2: NH (n = 18).	16% (Hans Rudolph, 2 400 series)	12 (4)	Supervised cycling exercise Week 1–2: 20 min at 70%–75% of HR _{max} Week 3–4: 30 min at 80%–85% of HRmax	Incremental test to exhaustion (cycle ergometer)	=
Dufour et al., 2006 ³⁹	n = 18. Trained G1: N (n = 9), G2: NH (n = 9).	14.5% (Altitrainer 200®)	12 (6)	10-min warm-up at 60% ṠO ₂ max (< VT1), followed by two periods at VT2, separated by 5-min recovery at 60% ṠO ₂ max.	Incremental test to exhaustion (treadmill)	=
Lecoultre et al., 2009 ⁴⁰	n = 14. Trained G1: N (n = 7), G2: NH (n = 7).	14.4% (Altitrainer 200®)	12 (4)	Warm-up and cool-down: 15 min of light-to moderate intensity cycling exercise. 1 st HIT session: short (30 s–2 min) cycling intervals performed at subjects' MAP. The 2 nd HIT: longer intervals (6–12 min), performed at VT2. 3 rd session: after 5 min warm-up, continuous cycling (100 min) at 80%–100% PO associated with VT1.	Incremental test to exhaustion (cycle ergometer)	=
Nakamoto et al., 2016 ⁴¹	n = 30. Trained N = 12 H = 18	16% (Altitrainer 200®)	12 (6)	Each training session began with a 10-min warm-up at 60% of v ṠO ₂ max, followed by two periods at a velocity at which training HR was most of the time at hrLT of the hrLT test, with a range of 5% from the target HR	Incremental test to exhaustion (treadmill)	=
Roels et al., 2007 ³⁴	n = 19. Trained G1: N = 9 G2: H = 10	14.5% (Altitrainer 200®)	9 (3)	1 st 3 wk: continuous training session: 60 min at 60% of ṠO ₂ max; and interval training session: three sets of 2 min at 100% PPO.	Incremental test to exhaustion under normoxic and hypoxic conditions (cycle ergometer)	=
Vogt et al., 2001 ⁴²	n = 30. Active G1: N-high = 8 G2: N- low = 8 G3: H-high = 7 G4: H-low = 7	12.6% (nd)	30 (6)	Endurance; cycling: (high: 4–6 mM; low: 2–3 mM blood lactate level)	Incremental test to exhaustion (cycle ergometer)	=
Wang et al., 2019 ⁴³	n = 17. Recreational G1: N (n = 8), G2: NH (n = 9).	14.2% (Everest Summit II, Hypoxico, Inc., New York, NY)	8 (2)	Standardised warm-up (without the mask) and several short warm-up sprints (with the mask) 3 sets of 5 10-s all-out repeated-sprints (7.5% body mass loading), 20 s active recovery periods. A 5 min recovery between sets, and 10 min recovery period	Incremental test to exhaustion (cycle ergometer)	=

FiO₂: inspired fraction of oxygen; G1-4: group number; HIT: high-intensity interval training; HR: heart rate; hrLT: heart rate at the lactate threshold; HRmax: maximal heart rate; MAP: maximal aerobic power; MICT: moderate intensity continuous training; mM: millimoles; N: normoxia; nd: none declared; NH: normobaric hypoxia; Pmax: maximal power; PO: power output; PPO: peak power output; ṠO₂max: maximal oxygen uptake; v ṠO₂max: velocity at maximal oxygen consumption; VT2: second ventilatory threshold; vVT2: velocity at the second ventilatory threshold; † increase; ‡ decrease; = no significant change.

training in NH for those studies that included more than 19 sessions (*SMD* = 1.68; 90% *CI*: [0.64; 2.72]; *p* = 0.01). The sub-analysis examining the type of administration equipment depending on the total program session volume presented a small non-significant effect for training programs with a high volume of sessions when using a face mask (*SMD* = 0.30; 90% *CI*: [−0.04; 0.64]; *p* = 0.15). By contrast, the hypoxic chamber/tent displayed a very large effect for studies with > 19 training sessions (*SMD* = 2.22; 90% *CI*: [0.96; 3.48]; *p* < 0.01).

The sub-analysis for the participants' training level (Table 3 and Supplemental Fig. S2) showed a moderate (*SMD* = 0.76; 90% *CI*: [−0.23; 1.74]; *p* = 0.21) to very large (*SMD* = 1.39; 90% *CI*: [0.56; 2.22]; *p* = 0.01) effect on ṠO₂max under the NH condition for active or sedentary participants. The sub-analysis for the participants' training level showed a significant moderate effect when training in a chamber/tent for trained participants (*SMD* = 0.66; 90% *CI*: [0.08; 1.23]; *p* = 0.06), and a very large effect for both sedentary (*SMD* = 1.61; 90% *CI*: [0.63; 2.60]; *p* = 0.01) and active (*SMD* = 1.26; 90% *CI*: [−0.53; 3.05]; *p* = 0.25) participants.

The sub-analysis for the severity of hypoxia (Table 3 and Supplemental Fig. S3) revealed a large effect on ṠO₂max when using moderate hypoxia with respect to N condition (*SMD* = 0.84; 90% *CI*: [0.06; 1.61]; *p* = 0.07). The sub-analysis examining the type of administration

equipment depending on severity of the hypoxia showed a very large effect favouring ṠO₂max gains when training in a chamber/tent (*SMD* = 1.42; 90% *CI*: [0.60; 2.24]; *p* < 0.01). Conversely, despite the limited number of studies included when using severe hypoxia, small non-significant effect was observed favoring the NH condition (*SMD* = 0.30; 90% *CI*: [−0.05; 0.64]; *p* = 0.16).

3.4. Risk of bias and quality of databases

Two independent authors evaluated the risk of bias using the Cochrane RoB 2 for the 18 RCTs (Supplemental Fig. S4).²³ Overall, most of the included studies showed “some concerns” of bias in the overall assessment. The main methodological quality issue was the randomization process domain for 17 of the 18 studies (93.75%). Only 1 of the 18 studies showed a low risk of bias (Supplemental Fig. S5).⁴⁵ Additionally, the standard errors of the effect size estimated as a predictor of publication bias indicated that the studies are symmetrically distributed (*r* = 2.66; *p* = 0.397), which contradicts the funnel plot (Supplemental Fig. S6).

4. Discussion

The main purpose of this meta-analysis was to determine the influ-

Table 2
Main characteristics of studies using normobaric hypoxia chamber/tent included in the meta-analysis.

Author and publication date	Sample	NH FiO ₂ (device)	N° of sessions (n° of weeks)	Methods	Test protocol (device)	$\dot{V}O_{2max}$ (mL·min ⁻¹ ·kg ⁻¹) NH vs N
Andresen et al., 2022 ⁹	N = 28 G1: NM (n = 7), G2: HM (n = 7), G3: NI (n = 7), G4: HI (n = 7).	15.4% (chamber/tent, Hypoxic Training Systems, Hypoxico, New York)	9 (3)	For the NM/HM group, each training session consisted of a constant workload of about 50% Pmax: 100 min (week 1), 110 min (week 2), and 120 min (week 3) For the NI/HI group, each training session consisted of 24.73 min at intense 60 s cycles at 100% Pmax interrupted by 75 s cycles at 10% Pmax.	Incremental test to exhaustion (cycle ergometer)	↓
Czuba et al., 2017 ⁴⁵	n = 15. Trained G1: N (n = 7), G2: NH (n = 8).	15.5% (nd)	8 (2)	4 microcycles. Warm-up and cool-down: 10 min, 45–55 min main part. Exercise upper limb rotator (50 W, 80 rpm, 60 s). Then, 30 s max. Effort on the rotator (load of 0.4 Nm·kg ⁻¹). After a 30 s rest, 3 min ride on the cycle ergometer (50% $\dot{V}O_{2maxhyp}$ / $\dot{V}O_{2max}$). Another 2 min exercise bout (95% $\dot{V}O_{2maxhyp}$ / $\dot{V}O_{2max}$). And 3 min (50% $\dot{V}O_{2maxhyp}$ / $\dot{V}O_{2max}$).	Ramp test (cycle ergometer)	=
Czuba et al., 2019 ⁴⁶	n = 14. Trained G1: N (n = 7), G2: NH (n = 7).	16.5% (nd)	9 (3)	Running exercise. 15 min general warm-up (70% of workload at lactate threshold WRLThyp/WRLT), a 40- to 50-min main part, and a 5-min cool-down (60% WRLThyp/WRLT). The main part of the workout consisted of four 7 min (1 st week), 8 min (2 nd week), or 9 min (3 rd week) bouts at 100% of WRLThyp/WRLT separated by 2 min of active recovery. After the warm-up and during the rest between the bouts, the athlete aimed at the target in the standing position with a sporting rifle (20 s). one-legged HIIT sessions 4 × 4 min one-legged 90% of the HRmax achieved during the incremental cycling test (work/rest ratio 1:1).	Incremental test to exhaustion (treadmill)	=
Menz et al., 2016 ⁵³	n = 13. Active G1: NG (n = 6), G2: HG (n = 7).	12.6% (nd)	3 (3)	5 min warm-up at N (running at 8.5 km·h ⁻¹ + stretching). Also, a specific warm-up (3 sets, 10 repetitions at 50% 6 RM, 1 min rest, 8 repetitions at 75% of 6 RM, 2 min rest, and repetitions to failure 6 RM load). Training program: 2–4 sets; 6 reps, 90%–100% 6 RM	Incremental test to exhaustion (cycle ergometer)	=
Ramos-Campo et al., 2018 ⁴⁷	n = 28. Active G1: N (n = 13), G2: NH (n = 15).	15% (chamber/tent, CAT-12, Colorado Altitude Training, USA)	16 (2)	Each subject performed a HET 2 days before and 2 days after the intervention. The HET: 3 min warm-up 50 W, 30 min 100 W, 3 min recovery 50 W (FiO ₂ : 12%). Intervention: The subjects trained on a bicycle ergometer, 30 min/day at 60% of $\dot{V}O_{2max}$ (NH: FiO ₂ 15%).	Incremental test to exhaustion (treadmill)	=
Wang et al., 2015 ⁴⁸	n = 40. Sedentary G1: NET (n = 20), G2: HET (n = 20).	12%–15% (chamber/tent, Colorado Mountain Room™, Boulder, CO.)	25 (5)	The subjects trained on a bicycle ergometer (N or NH at rest; or were trained on a bicycle ergometer at 50%Wmax N (NT), 50%HRRmax at NH (HRT), or 50%Wmax at NH (HAT) for 30 min/day.	Incremental test to exhaustion (cycle ergometer)	↑
Wang et al., 2017 ⁴⁹	n = 60. Sedentary. G1: HAT (n = 12), G2: HRT (n = 12), G3: NT (n = 12), G4: HC (n = 12), G5: NC (n = 12).	15% (chamber/tent, Colorado Mountain Room™, Boulder, CO.)	20 (5)	The subjects trained on a bicycle ergometer, 30 min·day ⁻¹ at 60% of $\dot{V}O_{2max}$.	Incremental test to exhaustion (cycle ergometer)	↑ (compared to NT and HRT)
Wang et al., 2014 ⁵⁰	n = 40. Sedentary G1: N (n = 20), G2: NH (n = 20).	15% (chamber/tent, Colorado Mountain Room™, Boulder, CO)	25 (5)	The subjects trained on a bicycle ergometer (N-C or H-C at rest; or were trained on a bicycle ergometer at 50%Wmax N (N-E), 50%HRRmax at NH (H-RE), or 50%Wmax at NH (H-AE) for 30 min·day ⁻¹ .	Incremental test to exhaustion (cycle ergometer)	↑
Wang et al., 2011 ⁵¹	n = 60. Sedentary. G1: H-AE (n = 12), G2: H-RE (n = 12), G3: N-E (n = 12), G4: H-C (n = 12), G5: N-C (n = 12).	15% (chamber/tent, Colorado Mountain Room™, Boulder, CO.)	20 (5)	Each subject performed N and NH (FiO ₂ 12%) continuous exercise (bicycle ergometer 3 min warm-up 50 W, 20 min 100 W, 3 min recovery 50 W) on the 3 rd and 2 nd day before and on the 3 rd and 2 nd day after intervention. Intervention: The subjects trained on a bicycle ergometer (N-C or H-C at rest; or were trained on a bicycle ergometer at 50%Wmax N (N-E), 50% HRRmax at NH (H-RE), or 50%Wmax at NH (H-AE) for 30 min·day ⁻¹ .	Incremental test to exhaustion (cycle ergometer)	↑ (compared to N-E)
Wang et al., 2010 ⁵²	n = 60. Sedentary. G1: H-AE (n = 12), G2: H-RE (n = 12), G3: N-E (n = 12), G4: H-C (n = 12), G5: N-C (n = 12).	12%–15% (chamber/tent, Colorado Mountain Room™, Boulder, CO.)	20 (5)		Incremental test to exhaustion (cycle ergometer)	↑ (compared to N-E)

FiO₂: fraction of inspired oxygen; G1-5: group number; H-AE: hypoxic-absolute exercise; HAT: hypoxic-absolute exercise; HC: hypoxia control; HET: hypoxia exercise training; HI: hypoxia intensive; HIIT: high intensity interval training; HM: hypoxia moderate; H-RE: hypoxic-relative exercise; HRmax: maximal heart rate; HRRmax: heart rate reserve maximum; HRT: hypoxic-relative exercise; N: normoxia; NC: normoxia control; nd: none declared; NET: normoxia exercise training; N-E: normoxic exercise; NH: normobaric hypoxia; NI: normoxia intensive; NM: normoxia moderate; NT: normoxia exercise; Pmax: maximal power; 1 RM: one-repetition maximum; $\dot{V}O_{2max}$: maximal oxygen uptake; W: watts; Wmax: maximal work capacity; WRLT: workload at lactate threshold; ↑ increase; ↓ decrease; = no significant change.

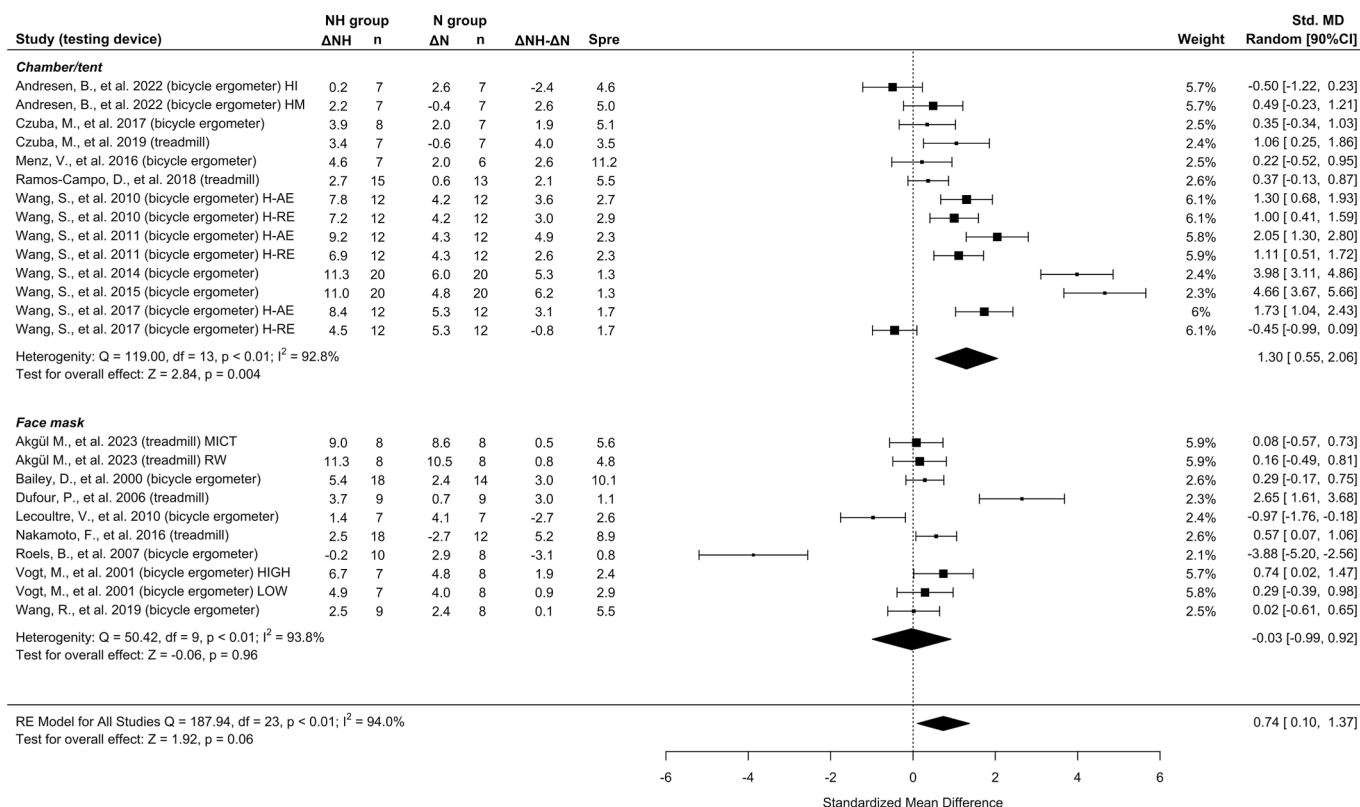


Fig. 2. Forest plot of the standardized mean differences between conditions (normobaric hypoxic [NH] group vs. normoxic [N] group) on maximal oxygen uptake ($\dot{V}O_{2max}$) grouped by the type of device used (chamber/tent and face mask). Δ - mean differences between post-pre in NH; n - sample size; Spre - mean baseline standard deviation; Std. MD - standard mean difference; Random - random effect's model; CI; confidence interval; Q - test statistic for the test of heterogeneity; df - degrees of freedom; p; p value; I² - I squared statistic; Z - z value; HM - hypoxia with moderate intensity; HI - hypoxia with intensive intensity; H-AE - hypoxic-absolute load exercise; H-RE - hypoxic-relative load exercise; HIGH - high intensity training; LOW - low intensity training.

ence of the type of equipment used to administer the NH condition (face mask vs hypoxia chamber/tent) on maximal aerobic performance. The results showed that an intermittent NH training period had a positive impact on $\dot{V}O_{2max}$ compared with N, which was more favorable when using a hypoxia chamber/tent ($SMD = 1.30$; $p < 0.001$). However, the high variability in the total program session volume and the participants' training level between the studies conducted with each type of hypoxia-generating equipment seems to influence this result. It is noteworthy that training protocols designed to enhance aerobic performance were slightly more frequently implemented in studies using a chamber/tent compared with a face mask to enhance $\dot{V}O_{2max}$. Moreover, the lack of key information about the hypoxia-generating equipment in the method section of the available studies – for example, the dimensions of the chamber/tent or the flow rate of the hypoxia-generating equipment – makes it difficult to assess the air quality and, therefore, the net physiological stress the participants experienced, limiting the conclusions drawn in this study.

Aerobic training under hypoxic conditions is expected to improve $\dot{V}O_{2max}$ at sea level mainly due to convective oxygen delivery adaptations.^{57,58} Combining aerobic exercise with hypoxia reduces alveolar oxygen pressure (PaO₂), leading to tissue hypoxia and exacerbating local muscle stress through increased reactive oxygen species (ROS) and

metabolite accumulation.⁵⁹ Consequently, this effect triggers several adaptive metabolic and angiogenic responses to maintain an optimal oxygen supply and to preserve muscle health.⁶⁰ The results of this meta-analysis revealed a moderate benefit of $\dot{V}O_{2max}$ when training in NH ($SMD = 0.74$). Moreover, compared with a face mask, a chamber/tent yielded a favorable, very large effect on $\dot{V}O_{2max}$ (hypoxia chamber/tent - $SMD = 1.30$; 90% CI: [0.55; 2.06]; face mask - $SMD = -0.03$; 90% CI: [-0.99; 0.92]) (Fig. 2).

A priori, compared with the use of a face mask, intense and prolonged exercise in a hypoxia chamber/tent, often of small size and with a low flow rate, is associated with elevated CO₂, humidity, and temperature inside it,⁶¹ making it difficult to keep the hypoxemia level stable, and potentially affecting performance.⁹ Ortiz-Prado et al.⁶² reported an association between rebreathing air with a high CO₂ concentration and a reduction in PaO₂.¹⁶ Contrary to face masks that favor continuous air replacement and help preserve the quality of inspired hypoxic air, this effect can be particularly pronounced in chambers/tents with small dimensions and limited air ventilation systems.¹⁵ However, considering the prevailing trend in most of the included studies that exhibited moderate to low intensities (Table 2), adding an adverse environment may provide higher but tolerable physiological stress. Thus, the interplay between the adverse conditions when using an NH chamber/tent

Table 3
Results of the subgroup meta-analyses.

Subgroup analysis	n	Classification	SMD (90% CI)	p value
Total training volumen				
Low (< 10 sessions)	7	Overall	-0.27 [-1.30; 0.76]	0.66
	2	Face mask	-1.87 [-5.07; -1.33]	0.34
	5	Chamber/tent	0.30 [-0.09; 0.76]	0.21
Moderate (10–19 sessions)	5	Overall	0.53 [-0.33; 1.39]	0.31
	4	Face mask	0.59 [-0.57; 1.74]	0.40
	1	Chamber/tent	–	–
High (> 19 sessions)	12	Overall	1.68 [0.64; 2.72]	0.01
	4	Face mask	0.30 [-0.04; 0.64]	0.15
	8	Chamber/tent	2.22 [0.96; 3.48]	< 0.01
Participants training level				
Sedentary	9	Overall	1.39 [0.56; 2.22]	< 0.01
	2	Face mask	0.50 [0.01; 1.00]	0.10
	7	Chamber/tent	1.61 [0.63; 2.60]	0.01
Active	9	Overall	0.76 [-0.23; 1.74]	0.21
	4	Face mask	0.17 [-0.12; 0.46]	0.35
	5	Chamber/tent	1.26 [-0.53; 3.05]	0.25
Trained	6	Overall	0.00 [-1.41; 1.42]	1.00
	4	Face mask	-0.37 [-2.58; 1.83]	0.78
	2	Chamber/tent	0.66 [0.08; 1.23]	0.06
Severity of the hypoxia				
Moderate (14.3%–16% FiO ₂)	20	Overall	0.84 [0.06; 1.61]	0.07
	7	Face mask	-0.16 [-1.51; 1.20]	0.85
	13	Chamber/tent	1.42 [0.60; 2.24]	< 0.01
Severe (< 14.3%–11% FiO ₂)	4	Overall	0.30 [-0.05; 0.64]	0.16
	3	Face mask	0.32 [-0.07; 0.71]	0.18
	1	Chamber/tent	–	–

Note: Negative values denote favouring of normoxia training and positive values indicate favouring of hypoxic training.

Abbreviations: n: number of groups, 90%CI = 90% confidence interval; SMD = standardized mean difference; p-value ($p < 0.010$).

during exercise may lead to further physiological adaptations that are intricately associated with enhanced aerobic performance. Additional comparative studies may test this hypothesis.

There was a clear relationship between the improvement in aerobic performance and training programs with a high volume of sessions in NH ($SMD = 1.68$; $p = 0.01$) compared with N (Table 3 and Supplemental Fig. S1). The sub-analysis of programs with a high volume of sessions revealed a very large increase in $\dot{V}O_{2max}$ in favor of chambers/tents ($SMD = 2.22$; $p < 0.001$), with no clear impact on $\dot{V}O_{2max}$ improvement when using face masks ($SMD = 0.30$; $p < 0.15$). Noteworthy, in the chamber/tent group, both NH and N groups exceeded the minimal clinically important difference for $\dot{V}O_{2max}$ ($3.5 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$),⁶³ with mean improvements of 8.29 and $4.80 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$, respectively. Furthermore, the NH group using the chamber/tent system showed a mean $\dot{V}O_{2max}$ increase of $3.5 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ compared to the N group, highlighting a clinically relevant additional benefit. Regarding the sub-analysis of the training programs with a low volume of sessions, a very large decrease in $\dot{V}O_{2max}$ was observed when a face mask was used, whereas no changes of interest were found with chamber/tent use. In particular, Roels et al.³⁶ analyzed the effect of a 3-week training program of two high-intensity interval-training sessions (2 sets of $3 \times 2 \text{ min}$; 100% of the peak power output) interspersed with three continuous aerobic sessions (60 min; 60% $\dot{V}O_{2max}$) in N or moderate NH in endurance-trained athletes. NH was administered with a face mask.

According to other studies, this protocol can limit the impact on $\dot{V}O_{2max}$ and hematological variables in endurance-trained athletes, even though performance improvements may occur.^{3,64} Additionally, the low volume of sessions and training load intensity used by Roels et al.³⁶ may represent an insufficient stimulus for inducing changes in $\dot{V}O_{2max}$, rather than the impact of the use of a face mask itself in highly trained athletes.

Compared with N, the sub-analysis of the participants' initial training level yielded a moderate to very large effect of NH on $\dot{V}O_{2max}$ in active ($SMD = 0.76$; $p = 0.21$) and sedentary ($SMD = 1.39$; $p = 0.01$) populations (Table 3 and Supplemental Fig. S2). Consistent with other studies,^{65–67} populations with low initial $\dot{V}O_{2max}$ are more sensitive to aerobic adaptations. Although there was a very large increase in $\dot{V}O_{2max}$ in favor of chamber/tent equipment, the impact of different hypoxia-generating equipment could not be compared due to the limited number of studies using face masks ($n = 1$).⁴⁴ Because enhancements in aerobic performance could not be exclusively attributed to the type of NH administration in the active population, the results revealed a large positive impact benefiting chambers/tents ($SMD = 1.26$; $p = 0.25$) in a trained group compared with the face mask. Roels et al.³⁶ reported this same observation. The elevated training level of the participants and the peculiar methodology applied may have contributed to enhancing mechanical performance due to peripheral muscle-fibre adaptations,^{68,69} regardless of $\dot{V}O_{2max}$.

The present meta-analysis revealed a large effect on $\dot{V}O_{2max}$ when using moderate hypoxia ($SMD = 0.84$; $p = 0.07$) (Table 3 and Supplemental Fig. S3). Consistent with the results discussed previously, training under moderate hypoxia in a chamber/tent may induce a greater impact on aerobic performance ($SMD = 1.42$; $p < 0.01$) compared with the same exercise using a face mask delivery system ($SMD = -0.16$; $p < 0.85$). It is noteworthy that, within the chamber/tent group, the moderate hypoxia group was predominantly composed of sedentary individuals who underwent a high number of training sessions.^{50–54} Nevertheless, our findings suggest that moderate hypoxia may offer an optimal balance between physiological stress and training load, thereby facilitating meaningful aerobic adaptations.

Separately, the sub-analysis for severe hypoxia revealed a non-significant increase in $\dot{V}O_{2max}$ compared to the N condition ($SMD = 0.32$; $p = 0.18$), with findings limited to only three studies. The results could only be derived for the use of face masks, with two of the contributions coming from the same study,^{44,45} and one from a chamber/tent,⁵⁵ which limits the possibility of extracting robust comparative results between NH delivery modalities. This imbalance precluded meaningful comparisons between face mask and chamber/tent NH administration methods under severe hypoxic conditions, thereby limiting the strength of the conclusions drawn for this subgroup. Exposure to severe hypoxia is characterized by marked arterial desaturation and potentially exacerbates perceived exertion,⁷⁰ which may compromise aerobic exercise tolerance and impact training intensity and volume⁷¹ to a greater extent than moderate hypoxia. Notably, considerable variability was observed across the studies employing severe hypoxia, both in terms of participant characteristics and training programs and frequencies.^{44,45,55} Despite such variability, the consistent factor across these interventions was the application of intermittent severe hypoxia, which may have disrupted the balance between hypoxic dose, training intensity, and fitness level, ultimately limiting the potential $\dot{V}O_{2max}$ enhancement. Therefore, further studies are needed to investigate the impact of severe hypoxia on aerobic performance improvements and to allow differentiation of the effects associated with the type of hypoxic delivery system.

5. Limitations

The current investigation presents some potential limitations - (1) The wide variability in training methodologies across studies limits the

ability to isolate the effects of specific training parameters and reduces the strength of the conclusions. Although subgroup analyses were performed for variables such as training status, total training volume, and hypoxia severity, the scope of these analyses was restricted, which inherently limits the depth of interpretation; (2) due to the scarcity of studies within certain subgroup analyses, conclusions drawn from these small subgroups should be considered exploratory; (3) the lack of information on the training conditions concerning air quality inside the chamber/tent; (4) insufficient reporting of the physical dimensions of the hypoxia chambers/tents in the available studies, nor do they provide data corresponding to the flow rate capacity of the hypoxia-generating system, the FiO₂ measurement error, and the variation in temperature, relative humidity, and CO₂ during the training; (5) a significant portion of our data in the NH chamber/tent condition is sourced from a single research group (Table 2), which may contribute to potential bias due to differences from the other studies (e.g., equipment, procedures, population, among others); and (6) the use of unclear randomization procedures and limited blinding, as detected in some studies, could introduce risks of selection and performance bias, potentially affecting the internal validity of the findings.

6. Conclusions

This review presents evidence of the impact of different NH-administration equipment on maximal aerobic capacity following a training period. The results favor NH chambers/tents for enhancing aerobic performance, particularly in sedentary individuals engaged in high total program session volume (> 19 sessions) under moderate intermittent hypoxia. Furthermore, the high variability in both factors, in addition to the methodological differences in the training protocols across the included studies, could have contributed to the observed outcomes and should be taken into account when interpreting the results. Nevertheless, these findings also highlight the need to include in future research a detailed description of the NH chamber/tent dimensions and the characteristics of the hypoxic simulator, flow rating, and respiratory air conditions during the exercise intervention. Providing this information would allow researchers to discriminate the potential impact that air quality could have on physiological response for each type of hypoxia-generating equipment, regardless of the performance.

CRedit authorship contribution statement

Sergio Pérez-Regalado: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Cristina Benavente:** Writing – review & editing, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Filipa Almeida:** Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization. **Belén Feriiche:** Writing – review & editing, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Availability of data and materials

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.smhs.2025.09.007>.

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