Effects of Repeated-Sprint Training in Hypoxia on Sea-Level Performance: A Meta-Analysis

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Effects of repeated-sprint training in hypoxia on sea-level performance: a meta-analysis

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Abstract:	Background. Repeated-sprint training in hypoxia (RSH) is a recent intervention with numerous studies reporting effects on sea-level physical performance outcomes that are debated. No previous study had meta-analyzed the effects of RSH. Objective. We systematically reviewed the literature and meta-analyzed the effects of RSH vs. repeated-sprint training in normoxia (RSN) on key components of sea-level physical performance; i.e., best and mean (all sprint) performance during repeated-sprint exercise and aerobic capacity (i.e., maximal oxygen uptake, VO2max). Methods. The PubMed/MEDLINE, SportDiscus®, ProQuest, and Web of Science online databases were searched for original articles - published up to July 2016 - assessing changes in physical performance following RSH and RSN. The meta-analysis was conducted to determine the standardized mean difference (SMD) between the effects of RSH vs. RSN on sea-level performance outcomes. Results. After systematic review, 9 controlled studies were selected, including a total of 202 individuals (mean age 22.6 ± 6.1 years, 180 males). After data pooling, mean performance during repeated sprints (SMD = 0.46, 95% confidence interval (CI) -0.02, 0.93; P = 0.05) was further enhanced with RSH when compared with RSN. Although non-significant, additional benefits were also observed for best repeated-sprint performance (SMD = 0.31, 95% CI -0.03, 0.89; P = 0.30) and VO2max (SMD = 0.18, 95% CI -0.25, 0.61; P = 0.41). Conclusion. Based on current scientific literature, RSH induces greater improvement for mean repeated-sprint performance during sea-level repeated sprinting than RSN. The additional benefit observed for best repeated-sprint performance and VO2max for RSH vs. RSN was not significantly different.
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ABSTRACT

Background. Repeated-sprint training in hypoxia (RSH) is a recent intervention with numerous studies reporting effects on sea-level physical performance outcomes that are debated. No previous study had meta-analyzed the effects of RSH.

Objective. We systematically reviewed the literature and meta-analyzed the effects of RSH *vs*. repeated-sprint training in normoxia (RSN) on key components of sea-level physical performance; *i.e.*, best and mean (all sprint) performance during repeated-sprint exercise and aerobic capacity (*i.e.*, maximal oxygen uptake, VO_2max).

Methods. The PubMed/MEDLINE, SportDiscus®, ProQuest, and Web of Science online databases were searched for original articles – published up to July 2016 – assessing changes in physical performance following RSH and RSN. The meta-analysis was conducted to determine the standardized mean difference (SMD) between the effects of RSH *vs*. RSN on sea-level performance outcomes.

Results. After systematic review, 9 controlled studies were selected, including a total of 202 individuals (mean age 22.6 ± 6.1 years, 180 males). After data pooling, mean performance during repeated sprints (SMD = 0.46, 95% confidence interval (CI) -0.02, 0.93; P = 0.05) was further enhanced with RSH when compared with RSN. Although non-significant, additional benefits were also observed for best repeated-sprint performance (SMD = 0.31, 95% CI -0.03, 0.89; P = 0.30) and VO_2max (SMD = 0.18, 95% CI -0.25, 0.61; P = 0.41).

Conclusion. Based on current scientific literature, RSH induces greater improvement for mean repeated-sprint performance during sea-level repeated sprinting than RSN. The additional benefit

observed for best repeated-sprint performance and VO_2max for RSH *vs*. RSN was not significantly different.

Key points

- Repeated-sprint training in hypoxia (RSH) is a recent hypoxic training method aimed at improving physical performance. Its effectiveness on repeated-sprint ability is clear when compared with control (*i.e.*, no repeated-sprint training) but is debated when compared with repeated-sprint training in normoxia (RSN).
- This meta-analytic review shows that RSH in reference to RSN is more efficient to significantly improve mean repeated-sprint performance while an additional positive (but non-significant) effect on best repeated-sprint and maximal oxygen uptake (VO_2max) is reported.
- RSH requires sport-specific adjustment of the main training variables including length/duration of sprint and recovery intervals, exercise:recovery ratio, inter-set recovery duration and/or session frequency. Further investigations manipulating these variables are needed to improve RSH prescription and shed more light on the postulated underlying mechanisms (*i.e.*, compensatory vasodilatation, micro-vascular oxygen delivery (fast-twitch fibers) and specific skeletal muscle molecular adaptations).

1. Introduction

In elite sport, the difference in performance between athletes is tiny [1]. In order to gain a competitive edge, the majority of elite endurance athletes such as distance runners or road cyclists are regularly training in altitude/hypoxia via different available strategies [2-4]. The traditional panorama of hypoxic/altitude training [2] has recently been updated [3, 5] to reflect the development of innovative hypoxic interventions currently used by team- and or racquet-sport athletes [6]. The implementation of these methods has been facilitated by technological advances and development of a new generation of hypoxic devices (*e.g.*, normobaric hypoxic chamber, nitrogen-enriching or O_2-filtering portable devices, mobile inflatable hypoxic marquees) [7].

Nowadays, 'live low-train high' (LLTH) methods are increasingly popular. In particular the so-called 'repeated-sprint training in hypoxia' (RSH) [8], which is based on the repetition of 'all-out' efforts of short (≤ 30 s) duration interspersed with short incomplete recoveries, is acquiring unprecedented attractiveness. This model differs from the traditional 'intermittent hypoxic training' since exercise intensity is maximal, thereby allowing a high fast-twitch fibers recruitment [8-12]. In 2013, when compared to similar repeated-sprint training in normoxia (RSN), the pioneer RSH study demonstrated larger maximal repeated sprinting performance improvement and fatigue resistance in normoxia [9]. With a quite low 'hypoxic dose', RSH is unlikely to stimulate the erythropoietic pathway [13, 14]. Rather its efficacy relies on specific skeletal muscle tissue adaptations mediated by an oxygen-sensing pathway (*i.e.*, hypoxic inducible factors) [15-18], likely to be fiber-type specific [8].

Although a recent systematic review [19] has discussed the efficacy of LLTH to enhance sea-level physical performance, the effectiveness of RSH is passionately debated [20, 21] with critics' main concerns relating to fatigue criteria definition and/or repeated-sprint test control [22, 23]. However, the growing interest for implementing RSH in different sports at an elite or professional level (*e.g.*, Roland Garros Tennis Academy, Welsh national rugby team, Swedish National Wintersport Centre, French alpine and cross-country ski national teams) highlights the question of the effectiveness of RSH and therefore underlines the importance of a meta-analytic review of RSH. Therefore, we systematically reviewed and meta-analyzed the effects of RSH on best and mean performance during repeated sprinting and aerobic capacity (*i.e.*, maximal oxygen uptake, VO_2max).

2. Methods

2.1 Literature Search

The review and analysis was conducted in accordance with PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-analyses) statement guidelines [24]. A systematic search of the research literature was conducted for randomized controlled trials studying the effects of RSH interventions on sea-level physical performance. The search included articles published up to July 2016 using PubMed/MEDLINE, SportDiscus®, ProQuest, and Web of Science online databases. The following terms were searched for in 'all fields' – [(hypoxi* OR normobar* OR altitude) AND (repeated sprint train* OR high-intensity intermittent train*) while the terms (patients OR obes*) were excluded (using NOT). Analysis was restricted to 'English language' and original research articles published in peer-reviewed journals. Reference lists from retrieved studies as well as from recent reviews [19, 25-28] were also reviewed.

2.2 Inclusion and Exclusion Criteria

To compare and quantify the effects of RSH *vs*. RSN in improving sea-level physical performance outcomes, the following inclusion criteria were considered: (1) single- or double-blinded and placebo-controlled or cross-over design (*i.e.*, with at least an intervention group completing RSN); (2) trained (*i.e.*, regular training load > 2 h.week^{-1}) participants; (3) training intensity classified as 'all out', 'maximal' or 'supramaximal'; (4) sprint duration ≤ 30 s, recovery duration ≤ 60 s; (5) intervention duration ≥ 2 weeks and (6) physical performance testing (laboratory or field; including at least repeated-sprint ability (RSA) or aerobic capacity from which VO_2max could be determined) performed under normoxic conditions. Exclusion criteria were: (1) prior acclimatization/acclimation to hypoxia; (2) absence of physical performance measurement; (3) lack of a RSN group in the experimental design and/or (3) animal subjects.

2.3 Data extraction

A search of electronic databases and a scan of articles' reference list revealed 125 relevant studies (Fig. 1). Based on duplicates removal and screening of the title or abstract, 103 articles were dismissed. Twenty-two full-text articles were evaluated, and 9 were included for the meta-analysis. Each study was read and coded for descriptive variables: sex, training status, altitude level, intervention duration and frequency, training protocol.

Physical performance data were extracted in the forms of pre- (baseline) and post-training intervention (within 1-5 days; RSH *vs*. RSN) means, standard deviations (SDs), and sample sizes for RSH and RSN conditions. In studies that reported intermediate and post-intervention values, only post- values were recorded and compared with baseline. Data were collected directly from tables or within the text of the selected studies where possible or using Graph digitizing software (DigitizeIt, Germany) in studies where plots only were published. Dependent variables included best (*i.e.*, fastest sprint time or highest power output [usually corresponding to the initial sprint] recorded/achieved during the RSA test) and mean (*i.e.*, averaged sprint time or power output recorded/maintained throughout the test) RSA performances during repeated sprints. With the open-loop design, values were recalculated for an equal number of sprints performed by both groups, in order to allow comparison with the closed-loop design. Aerobic capacity was considered using direct (*i.e.*, VO_2max or peak oxygen uptake [VO_2peak]) or estimated (data were calculated from field test, *e.g.*, distance covered during Yo-Yo intermittent recovery test level 1/2 or velocity at VO_2max) measurements of VO_2max.

2.4 Data Analysis

Meta-analysis was conducted using comprehensive meta-analysis software (version 2, Biostat, Inc., Englewood, NJ, USA) in order to aggregate, via a random-effects model [29], the standardized mean difference (SMD) between the effects of RSH *vs*. RSN on physical performance. Use of the SMD summary statistic allowed all effect sizes to be transformed into an uniform scale, which was then interpreted according to Cohen's conventional criteria [30] with SMDs of <0.2, 0.2-0.3, 0.5, and 0.8 representing trivial, small, medium, and large effect sizes, respectively. Heterogeneity was determined using the I^2 value, with values of 25, 50 and 75 indicating low, moderate and high heterogeneity, respectively [29]. Study characteristics are presented as mean ± SD unless otherwise stated. Potential publication bias was evaluated using

Begg and Mazumdar's rank correlation and Egger's regression tests [31], with asymmetry examination of funnel plots. A P value ≤ 0.05 was considered statistically significant.

3. Results

3.1 Study Characteristics and Publication Bias

Participants along with training characteristics for the meta-analyzed studies are displayed in Table 1. A total of 7 studies comprised only male [9, 32-37], one study included only female [38], and another one recruited both sexes [39]. The mean number of participants was 26 ± 12. Participants' age, height and body weight were 22.6 ± 6.1 years, 175.8 ± 7.6 cm and 71.3 ± 10.8 kg, respectively.

The mode of exercise primarily involved running (four studies; overground and/or treadmill runs; [34-37]) and cycling (four studies; ergocycle [9, 33, 37, 38]); and one study used double-poling [39]. Training intervention average duration was 3.7 ± 1.3 weeks with 2.6 ± 0.6 sessions per week. Exercise protocol consisted of 3 ± 1 sets, 7 ± 4 repetitions, 8 ± 2 s of effort duration with 27 ± 8 s of recovery and 7± 5 min of inter-set rest.

Regarding testing, four different exercise modes (*i.e.*, overground and treadmill running, cycling, double-poling) were used. These RSA protocols also differed in terms of number of sprint repetitions (*i.e.*, from 6 to 10 repetitions for closed-loop design), duration/length of efforts (*i.e.*, 7-10 s or 20-30 m) as well as recovery time (*i.e.*, 20-30 s) and type (*i.e.*, passive or active). Similarly, aerobic capacity was assessed using either direct (from expired gas during laboratory-based incremental protocols) or estimated (from distance covered during field-based high-intensity intermittent protocols or velocity at VO_2max during field incremental protocols) measurements of VO_2max.

Visual examination of the funnel plots (not presented), Begg and Mazumdar's rank correlation test ($P \geq 0.11$) and the Egger's regression test ($P \geq 0.36$) did not indicate the presence of potential publication bias for the SMDs in best and mean performance during repeated sprinting and VO_2max in the studies included in the meta-analysis.

3.2 Meta-analysis

The forest plots depicting the individual SMD and associated 95% confidence interval (CI) and random-effects model for RSA best performance, mean RSA performance and VO_2max are shown in Figs. 2, 3 and 4, respectively.

Following data pooling, the SMD for mean RSA outcome was 0.46 (95% CI -0.02, 0.93), providing a significant small to moderate effect ($P = 0.05$) in favor of RSH *vs*. RSN, as shown in Fig. 3. Likewise, the effect on best RSA performance was higher with RSH compared with RSN (SMD = 0.31, 95% CI -0.27, 0.89; small to moderate effect; $P = 0.30$) (Fig. 2). In addition, there was a trivial non-significant effect of RSH *vs*. RSN on VO_2max improvement (SMD = 0.18, 95% CI -0.25, 0.61; $P = 0.41$) (Fig. 4). Heterogeneity was not detected among studies assessing best ($I^2 = 11.14\%$) and mean RSA outcomes ($I^2 = 6.19\%$) or VO_2max ($I^2 = 0.00\%$).

4. Discussion

The aggregated findings indicate that RSH is more effective than RSN for improving best (SMD = 0.31, small to moderate beneficial effect) and mean (SMD = 0.46, small to moderate beneficial effect) RSA outcomes, as well as VO_2max (SMD = 0.18, trivial beneficial effect).

Irrespective of the repeated-sprint training components (*i.e.*, exercise modality and exercise:recovery ratio) or participants' background, the results of this meta-analysis confirm the respective conclusions of the majority of both best and mean RSA studies (6 out of 9 studies for best RSA performance; 8 out of 9 studies for mean RSA performance) which were that RSH has a small to moderately greater beneficial effect than RSN on RSA outcomes (Figs. 2 and 3). Faiss et al. [9, 39] first showed that RSH delays task failure during a RSA test to exhaustion in trained cyclists and elite cross-country skiers (*i.e.*, +40% and +58% for the number of sprints performed post RSH *vs*. RSN). Their results also showed that RSH was as efficient as RSN for improving power output on a single sprint (5-7%) but with fatigue resistance being improved during sea-level repeated sprinting post-RSH only [9]. In the present systematic review, we recalculated from their results the peak (+4 and +5% relative to RSN) and mean (+5% and +12% relative to RSN) power outputs at the same number of sprints performed for pre-post comparisons of the effects of RSH and RSN (*i.e.*, 9th sprint in Faiss et al. [9] and 11th sprint in Faiss et al. [39]). This approach further pinpoints the putative benefit of RSH relative to RSN and allows comparison with other RSH studies. Because different RSA outcomes (*i.e.*, peak, mean power outputs or best time; mean or total time; sprint decrement, fatigue index) were used in the different RSH studies, this meta-analysis reinforces these findings as, from all included studies, we carefully reported best and mean RSA performance across an equivalent number of sprints performed for both RSH and RSN groups.

Our understanding of the physiological adaptations mediating physical performance enhancement in response to normoxic RSA is growing [25-27]. However, research about the underpinning mechanisms associated with the novel RSH method is still in its infancy. A solid ground suggests that RSH mechanisms likely differ from those associated to 'intermittent hypoxic training' [16-18]. With maximal intensity efforts performed in hypoxia, an enhanced oxygen utilization (via improved blood perfusion level) and an improved behavior of fast-twitch fibers are expected compared with similar training at sea-level [9, 39]. Pending confirmatory research, this could be based on at least three mechanisms: firstly, the compensatory vasodilatation with an induced nitric oxide (NO)-dependent increase in muscle blood flow aiming to match the increased oxygen demand at the muscular level when exercising in hypoxia [40, 41]; secondly, a greater micro-vascular oxygen delivery to fast-twitch fibers [42] mainly due to their higher fractional oxygen extraction [43]; thirdly, specific molecular adaptations arising from the oxygen-sensing pathway [15-18]. In support, previous animal model studies have highlighted phenotypic changes in favor of fast-twitch glycolytic fibers after hypoxia but not normoxia [10, 11]. Furthermore, and despite reporting no additive effect on performance, Montero & Lundby [44] demonstrated a marked RSH-induced increase in skeletal muscle concentration of total hemoglobin/myoglobin (considered an index of blood perfusion) compared with RSN and therefore confirmed similar findings on muscle oxygenation [9, 39]. While peak muscle perfusion is not reached with RSN [45], RSH should be associated with elevated muscle blood flow and eventually an increased endothelial shear stress, which in turn may stimulate angiogenesis in skeletal muscle [46, 47]. One cannot rule out that other potential mechanisms may be at play: it is known that, at the muscular level, waste metabolites accumulation and energy supply are essential limiting factors for RSA [25]. During repeated sprints, phosphocreatine breakdown is very high [48] and inorganic phosphate (Pi) accumulates in muscle. Since increased Pi levels may participate in decreasing the ability for force production, especially in fast-twitch fibers recruited during such fatiguing exercise [49], improved waste metabolites removal when blood flow is raised [50] (as reported post-RSH [9]) might delay fatigue during a RSA test.

A trivial beneficial effect of RSH on aerobic capacity (Fig. 4) compared with RSN was noted (5 out of 8 studies in RSH *vs*. RSN). Although calculations were based on the results of different field-based tests and not systematically from directly measured VO_2max values, this observation remains practically relevant. However, this variable may not always reflect improvement in the sport-specific aerobic component. While Brocherie et al. [35] failed to show any additional RSH-related effect on velocity at VO_2max using a modified version of the University of Montreal Track Test (*i.e.*, the VAMEVAL maximal incremental running test) [51], sport-specific aerobic tests such as Yo-Yo intermittent recovery tests [52] may be more appropriate. Reportedly, a 4-weeks treadmill RSH induced a +33% improvement in Yo-Yo intermittent recovery test level 1 compared with RSN (+14%) [36]. This would indicate that RSH may induce higher muscular oxidative activity rather than non-oxidative metabolism compared with RSN. Furthermore, a combination of methods improving RSA (using RSH) and VO_2max (via hemoglobin mass improvement through 'live high-train low' training camps) could optimize the benefits of acute and prolonged hypoxic stress [34] as proposed earlier [3].

Although the heterogeneity of the outcomes was low, a potential limitation of this meta-analysis concerns the different training and testing protocols used among the analyzed studies. The duration of RSH interventions ranged 2-5 weeks with 2-3 sessions per week. Further, training protocols considerably differed with 1-5 sets, 4-10 repetitions, 5-10 s efforts, 20-45 s recovery and 4.5-10 min inter-set duration, which may account for inconsistent findings. This may have impacted the physiological adaptations and/or physical performance, influenced by the various tests used (*e.g.*, four different modes of testing [overground and treadmill running, cycling, double-poling] and the wide ranging exercise:recovery ratio), in the absence of a 'gold standard' for RSA test. Additionally, apart from the study by Brocherie et al. [34], the current literature has not yet investigated the delayed effects (*i.e.*, after few weeks) of RSH interventions.

5. Protocol recommendations

Bearing in mind that effectiveness and adherence to RSH protocols are undoubtedly specific and individual, suggested recommendations are provided in Table 2. With a protocol resembling the actual recommendations, Brocherie et al. [53] demonstrated that RSH appears sufficient in severity, duration and/or frequency to elicit a significant hypoxic 'acclimation', with psycho-physiological responses (*i.e.*, overall peripheral discomfort, difficulty breathing and lower-limb discomfort) not negatively altered in comparison with RSN. With the great variation in exercise:recovery ratio among the RSH protocols, the recommendations made in Table 2 regarding exercise and recovery duration, as well as number of sets and repetitions, do not preclude longer duration (*e.g.*, ≥ 30 s recovery) RSH protocols (including different number of sets and repetitions) being potentially more appropriate for specific physiological (*e.g.*, oxidative *vs.* glycolytic component) and physical development (*e.g.*, VO_2max). Regarding recovery type, applying active recovery (*i.e.*, at low-to-moderate intensity) under hypoxic conditions may not be the most efficient. Hence, it may alter performance of subsequent sprint efforts, in particular via a slowing down of muscle re-oxygenation rate [9] and could lead to premature fatigue. In support, a previous study [54] conducted in normoxia indicated that active recovery (*i.e.*, 50% of velocity at VO_2max) induced a lower replenishment of oxygen in myoglobin and hemoglobin and a reduced rate of phosphocreatine resynthesis from the previous intense effort. Furthermore, exercise mode (*e.g.*, cycling or running) selection may also impact the magnitude of sport-specific fitness improvements. On the one hand, the non-weight-bearing nature of stationary cycling, coupled with minimal eccentric contraction of leg muscles, seems to mitigate risk of injury and discomfort [28]. On the other hand, neuromuscular fatigue is higher in cycling- *vs.* running-RSA modes [55]. Taking these factors into consideration, well-designed protocols using sport-specific conditions and/or ecological settings [34, 56, 57] would allow more effective application of research findings in field conditions. Improved understanding of operative mechanisms is also still needed. We also acknowledge that other variations of RSH could be even more effective for specific sports or playing position. Therefore, our recommendations should be seen as a starting point and we encourage practitioners to challenge and refine them as appropriate.

6. Perspectives

Given the small number of RSH studies conducted to date, there are still important questions that need to be addressed. These include the question of the optimal combination of variables such as sprint length (m)/duration (s), exercise:recovery ratio (from 1:2 through 1:5), inter-set recovery duration, number of sets and/or repetitions, and/or session frequency and their effects on physiological adaptations and related physical improvements, whether ‘anaerobic’ and/or ‘aerobic’. This may also provide valuable insights in terms of participants’ adherence to training, delayed onset muscle soreness and injury occurrence, and may allow specific prescription guidelines to be recommended. In this view, a particular focus on elite intermittent-sport athletes may be helpful. Furthermore, as RSH is generally combined with other sea-level conditioning training (*e.g.*, resistance, aerobic), determining the optimal arrangement of these different types of training is also warranted because the interaction between several approaches is unknown. Finally, to deepen our understanding of the physiological mechanisms underlying RSH, comparisons of different hypoxic stresses (*i.e.*, normobaric [all studies were conducted in this environment] *vs*. hypobaric hypoxia) and different environmental stresses (*i.e.*, hypoxic *vs*. heat *vs*. control) need to be conducted.

7. Conclusion

The current meta-analysis provides evidence that RSH is an effective training strategy for improving sport-specific physical performance among athletes and induces greater gains in RSA than RSN. Indeed, RSH induces small to moderately greater best and mean RSA performance improvements than RSN among endurance and team-sport athletes. The additional benefit observed for VO_2max was trivially higher for RSH *vs*. RSN.

Compliance with Ethical Standards

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Conflicts of interest

Franck Brocherie, Olivier Girard, Raphaël Faiss and Grégoire P. Millet declare that they have no conflicts of interest relevant to the content of this review.

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Figures legend

Fig. 1. Flow chart of study selection.

Fig. 2. Forest plot of the standardized mean difference (SMD) between the effect of repeated-sprint training performed in hypoxia (RSH) *vs*. normoxia (RSN) and/or control on best RSA performance. *Squares* represent the SMD for each study. The *diamond* represents the pooled SMD for all studies. *95% CI*, 95% confidence interval; *df*, degrees of freedom; *IV*, inverse variance. Std, standardized; RSA, repeated-sprint ability.

Fig. 3. Forest plot of the standardized mean difference (SMD) between the effect of repeated-sprint training performed in hypoxia (RSH) *vs*. normoxia (RSN) and/or control on mean RSA performance. *Squares* represent the SMD for each study. The *diamond* represents the pooled SMD for all studies. *95% CI*, 95% confidence interval; *df*, degrees of freedom; *IV*, inverse variance. Std, standardized; RSA, repeated-sprint ability.

Fig. 4. Forest plot of the standardized mean difference (SMD) between the effect of repeated-sprint training performed in hypoxia (RSH) *vs*. normoxia (RSN) and/or control on maximal oxygen uptake (VO_2max). *Squares* represent the SMD for each study. The *diamond* represents the pooled SMD for all studies. *95% CI*, 95% confidence interval; *df*, degrees of freedom; *IV*, inverse variance. Std, standardized; RSA, repeated-sprint ability.

Table 1. Summary of the participants and training characteristics for the meta-analyzed studies (in chronological order).

References	Design	Participants M or F (RSH, RSN)	Training status	Altitude level$^{a, b}$	Intervention	Training protocol	Testing mode	
					Duration × frequency (weeks × sessions per week)	Sets × reps × duration, intra- and inter-set rest	RSA	Aerobic
Faiss et al. [9]	Parallel, single-blind	M (20, 20)	Moderately trained cyclists	3000m	4 × 2	3 × 5 × 10 s, 20 s cycling, 5 min	10 s 'all-out' ergocycle sprints; 20 s active recovery until task failure^{c}	3 min 'all-out' ergocycle
Galvin et al. [32]	Parallel, single-blind	M (15, 15)	Academy rugby union and rugby league players	3500 m	4 × 3	1 × 10 × 6 s, 30 s treadmill, 4.5 min	10 × 20 m treadmill sprints; 30 s passive recovery	YYIR1
Gatterer et al. [31]	Parallel, single-blind	M (5, 5)	Adolescent footballers	3000 m	5 × 1.5	3 × 5 × 10s, 20s overground shuttle runs, 5 min	6 × 40 m shuttle-run sprints^{d}; 20s passive recovery	YYIR2
Faiss et al. [38]	Parallel, double-blind	M(11), F (6); (9, 8)	Elite cross-country skiers	3000 m	2 × 3	4 × 5 × 10s, 20s double-poling, 4.5-9.5 min	10 s 'all-out' double-poling sprints; 20 s recovery until task failure	3 × 3 min 'all-out' team-sprint simulation; 3 min active recovery
Brocherie et al. [33]	Parallel, double-blind	M (8, 8)	Adolescent footballers	2900 m	5 × 2	5 × 4 × 5 s, 45s treadmill and overgound shuttles, 5 min	10 × 30 m running sprints; 30 s passive recovery	VAMEVAL
Kasai et al. [37]	Parallel, single-blind	F (16, 16)	College lacrosse players	3000 m	4 × 2	2 × 10 × 7s, 30 s cycling, 10-20 min	10 × 7 s ergocycle sprints; 30 s passive recovery	Graded ergocycle power
Goods et al. [36]	Parallel, single blind	M (9, 10)	Semi-elite AFL players	3000 m	5 × 3	3 × 7 × 5s, 15-35s cycling, 5 min	3 × 6 × 20 m sprints; 25 s recovery^{e} 3 × 6 × 4 s ergocycle sprints; 25 s recovery^{e}	20 m shuttle-run test
Brocherie et al. [34]	Parallel, double-blind	M (11, 12)	Elite field hockey players	3000 m	2 × 3	4 × 5 × 5s, 25 s overground, 5 min	8 × 20 m sprints, 20 s passive recovery	YYIR2
Montero & Lundby. [35]	Cross-over, double blind	M (15)	Moderately trained endurance athletes	3000 m	4 × 3	4 × 5 × 10s, 20 s cycling, 5 min	10 s'all-out' ergocycle sprints ; 20 s active recovery until task failure^{c}	Incremental ergocycle test Time-trial ergocycle test

AFL, Australian Football League; M, males; F, females; Reps, repetitions; RSA, repeated-sprint ability; RSH, repeated-sprint training in hypoxia; RSN, repeated-sprint training in normoxia; YYIR1 and 2, Yo-Yo intermittent recovery tests level 1 and 2; VAMEVAL, maximal incremental running test, modified version of the University of Montreal Track Test.

[a] Where (simulated) altitude was not reported, we estimated it according to the fraction of inspired oxygen (FiO_2).

[b] All studies were conducted in normobaric hypoxia.

[c] Values were recalculated for an equal number of sprints performed by both RSH and RSN groups.

[d] 20 m back and forth.

[e] Only the first set of RSA test was considered.

Table 2. Protocol recommendations for repeated-sprint training in hypoxia (RSH).

Frequency	2-3 sessions per week.
Periodization	Blocks of 2-5 weeks.
Duration	~60 min (including warm-up and cool-down).
Modality	Sport-specific (overground/treadmill, ergocycle, double-poling ergometer, etc.).
Intensity	Exercise = maximal, supra-maximal, 'all-out' efforts. Inter-sprints recovery = passive. Inter-sets rest = passive.
Interval times	Exercise = 3-4 sets of 4-7 × 4-15-s intervals. Inter-sprints recovery ≤ 30 s. Exercise:recovery ratio = 1:2 to 1:5. Inter-sets rest = 3-5 min.

Figure 1

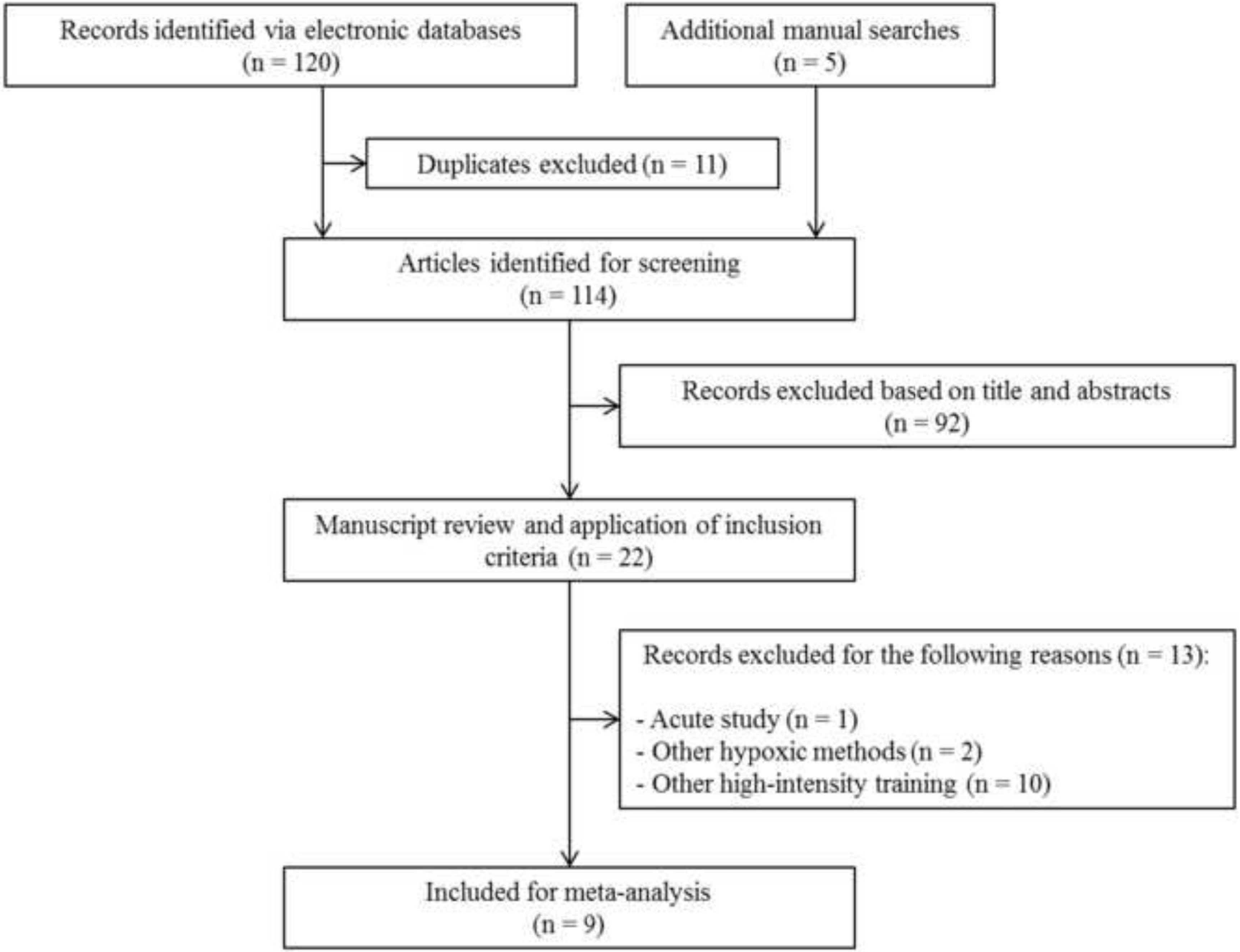
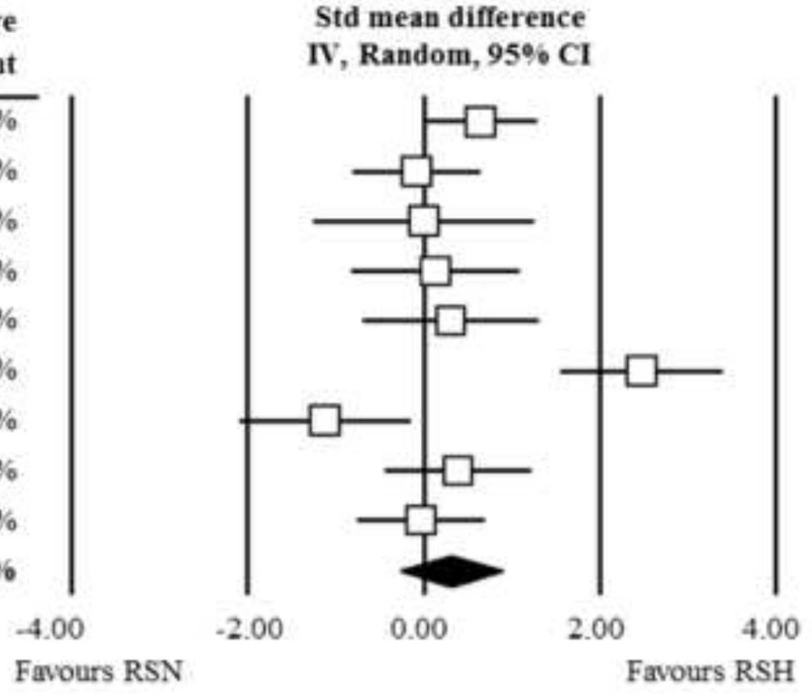

Records identified via electronic databases (n = 120)
Additional manual searches (n = 5)
Duplicates excluded (n = 11)
Articles identified for screening (n = 114)
Records excluded based on title and abstracts (n = 92)
Manuscript review and application of inclusion criteria (n = 22)
Records excluded for the following reasons (n = 13):
- Acute study (n = 1)
- Other hypoxic methods (n = 2)
- Other high-intensity training (n = 10)
Included for meta-analysis (n = 9)

Figure 2

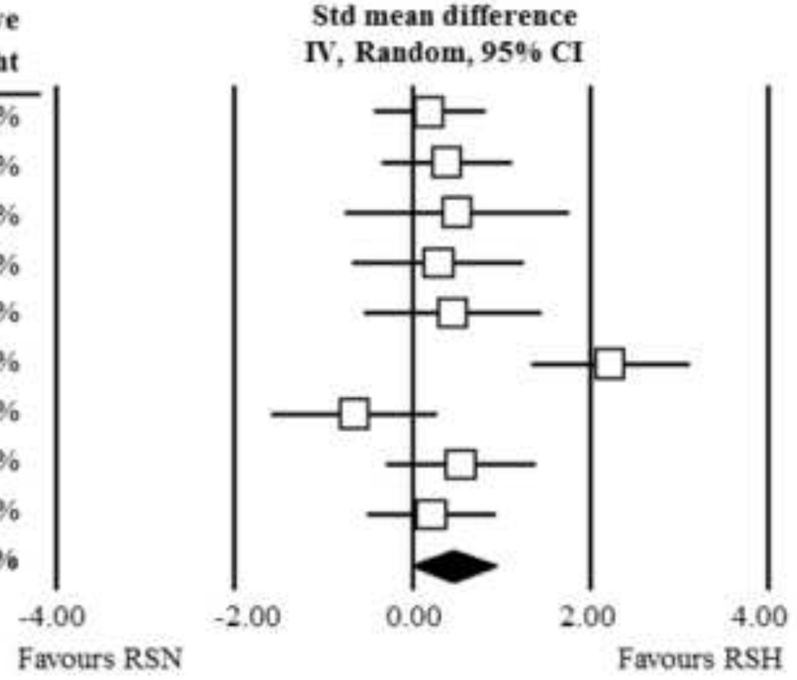
Study	SMD	[95% CI]	Relative weight
Faiss et al. [9]	0.638	[0.002, 1.273]	12.7%
Galvin et al. [36]	-0.080	[-0.796, 0.636]	12.2%
Gatterer et al. [37]	0.000	[-1.240, 1.240]	8.8%
Faiss et al. [39]	0.129	[-0.824, 1.082]	10.6%
Brocherie et al. [35]	0.300	[-0.685, 1.285]	10.5%
Kasai et al. [38]	2.473	[1.553, 3.394]	10.9%
Goods et al. [32]	-1.122	[-2.091, -0.154]	10.6%
Brocherie et al. [34]	0.385	[-0.441, 1.211]	11.5%
Montero & Lundby [33]	-0.036	[-1.051, 0.978]	12.2%
Combined	**0.307**	**[-0.272, 0.885]**	**100.0%**

Heterogeneity: $Tau^2 = 0.00$; $df = 8$ ($P = 0.53$); $I^2 = 11.14$

Test for overall effect: $Z = 1.04$ ($P = 0.30$)



Study	SMD	[95% CI]	Relative weight
Faiss et al. [9]	0.192	[-0.430, 0.813]	13.6%
Galvin et al. [36]	0,389	[-0.334, 1.111]	12.6%
Gatterer et al. [37]	0.500	[-0.759, 1.759]	7.9%
Faiss et al. [39]	0.293	[-0.664, 1.250]	10.3%
Brocherie et al. [35]	0.456	[-0.536, 1.449]	10.0%
Kasai et al. [38]	2.222	[1.341, 3.103]	11.0%
Goods et al. [32]	-0.651	[-1.563, 0.273]	10.6%
Brocherie et al. [34]	0.546	[-0.287, 1.379]	11.5%
Montero & Lundby [33]	0.213	[-0.804, 1.230]	12.5%
Combined	**0.455**	**[-0,017, 0.927]**	**100.0%**



Heterogeneity: Tau² = 0.00; df = 8 (P = 0.21); I² = 6.19

Test for overall effect: Z = 1.89 (P = 0.05)