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SYSTEMATIC REVIEW

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 regarding which numerous studies have reported effects on sea-level physical performance outcomes that are debated. No previous study has performed a meta-analysis of the effects of RSH.

Objective We systematically reviewed the literature and meta-analyzed the effects of RSH versus 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 [$\dot{V}O_{2max}$]).

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 and RSN on sea-level performance outcomes.

Results After systematic review, nine 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 to 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 to 0.89; $P = 0.30$) and $\dot{V}O_{2max}$ (SMD = 0.18, 95% CI −0.25 to 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 $\dot{V}O_{2max}$ for RSH versus RSN was not significantly different.

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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 is more efficient than RSN to significantly improve mean repeated-sprint performance, while an additional positive (but non-significant) effect on best repeated-sprint and maximal oxygen uptake ($\dot{V}O_{2max}$) is reported.

RSH requires sport-specific adjustment of the main training variables including the 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, microvascular 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 regularly undergo altitude/hypoxic training via the different strategies available [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 chambers, nitrogen-enriching or oxygen-filtering portable devices, mobile inflatable hypoxic marquees) [7].

Nowadays, 'live low–train high' (LLTH) methods are increasingly popular. In particular, 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 high recruitment of fast-twitch fibers [8–12]. In 2013, when compared with 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 the definition of fatigue criteria and/or repeated-sprint test control [22, 23]. However, the growing interest in 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 [$\dot{V}O_{2max}$]).

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 the 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 versus RSN in improving sea-level physical performance outcomes, the following inclusion criteria were considered: (1) single- or double-blinded and placebo-controlled or crossover design (i.e., with at least an intervention group completing RSN); (2) trained (i.e., regular training load >2 h/week) 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 test from which $\dot{V}O_{2max}$ could be determined) performed under normoxic conditions. Exclusion criteria were as follows: (1) prior acclimatization/acclimation to hypoxia; (2) absence of a physical performance measurement; (3) lack of an RSN group in the experimental design; and/or (3) animal subjects.

2.3 Data Extraction

A search of electronic databases and a scan of the reference lists of articles retrieved revealed 125 relevant studies (Fig. 1). Based on the removal of duplicates and screening of the title or abstract, 103 articles were dismissed. We evaluated 22 full-text articles and nine were included in the meta-analysis. Each study was read and coded for the following descriptive variables: sex, training status, altitude level, intervention duration and frequency, and 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-intervention 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, Braunschweig, 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

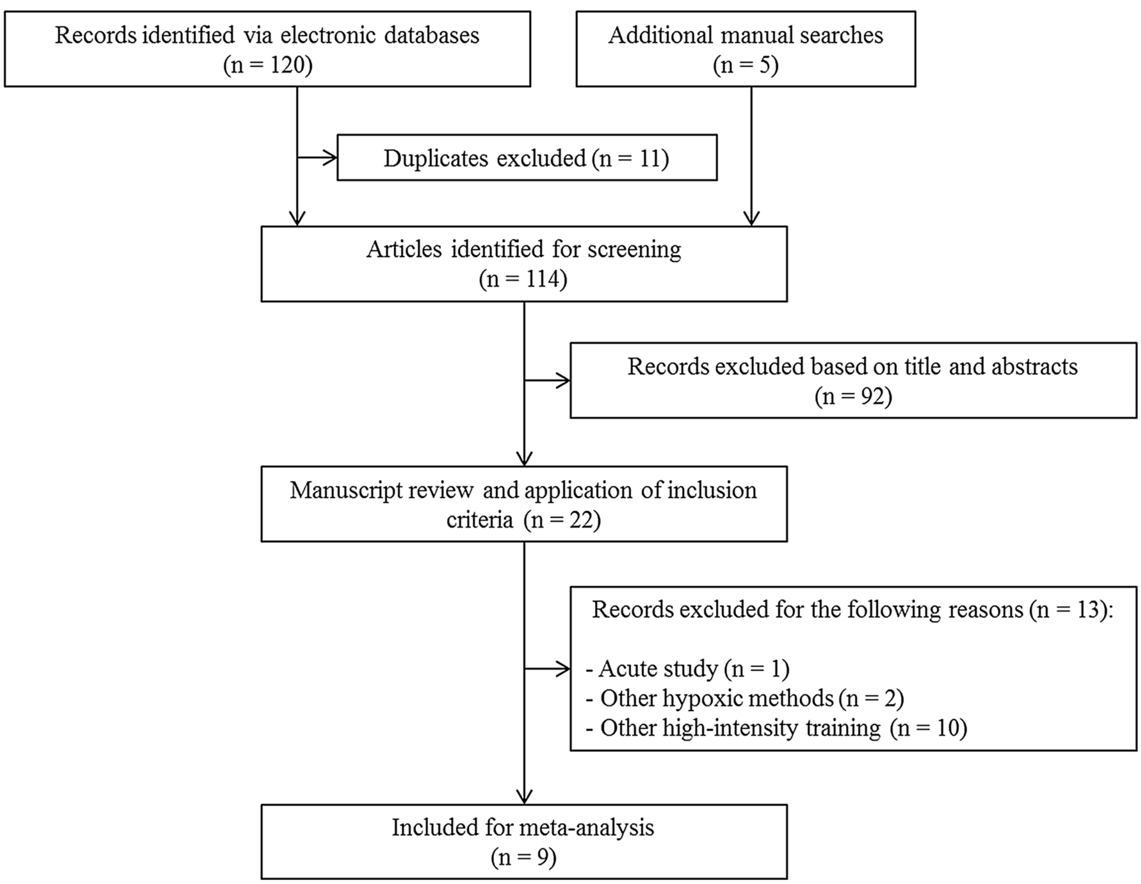

Fig. 1 Flow chart of study selection

considered using direct (i.e., $\dot{V}O_{2max}$ or peak oxygen uptake [$\dot{V}O_{2peak}$]) or estimated (data were calculated from field test, e.g., distance covered during Yo–Yo intermittent recovery test level 1/2 or velocity at $\dot{V}O_{2max}$) measurements of $\dot{V}O_{2max}$.

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 and 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

A summary of the participants and training characteristics of the meta-analyzed studies are displayed in Table 1. A total of seven studies comprised only male participants [9, 32–37], one study included only females [38], and another study 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]. The average duration of the training intervention was 3.7 ± 1.3 weeks with 2.6 ± 0.6 sessions per week. Exercise protocols consisted of a mean 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 the number of sprint repetitions (i.e., from six to ten repetitions for closed-loop design), duration/length of effort, (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 $\dot{V}O_{2max}$ during field incremental protocols) measurements of $\dot{V}O_{2max}$.

Visual examination of the funnel plots (not shown), 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 $\dot{V}O_{2max}$ in the studies included in the meta-analysis.

3.2 Meta-Analysis

The forest plots depicting the individual SMDs and associated 95% confidence intervals (CIs) and random-effects models for RSA best performance, mean RSA performance, and $\dot{V}O_{2max}$ 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 to 0.93), providing a significant small to moderate effect ($P = 0.05$) in favor of RSH versus RSN, as shown in Fig. 3. Likewise, the effect on best RSA performance was higher with RSH than with RSN (SMD = 0.31, 95% CI −0.27 to 0.89; small to moderate effect; $P = 0.30$) (Fig. 2). In addition, there was a trivial non-significant effect of RSH versus RSN on $\dot{V}O_{2max}$ improvement (SMD = 0.18, 95% CI −0.25 to 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 $\dot{V}O_{2max}$ ($I^2 = 0.00\%$).

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 $\dot{V}O_{2max}$ (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 conclusions of the majority of both best and mean RSA studies (six of nine studies for best RSA performance; eight of nine studies for mean RSA performance), which were that RSH has a small to moderately greater beneficial effect than RSN on RSA outcomes

Table 1 Summary of the participants and training characteristics of the studies included in the meta-analysis (in chronological order)

Study	Design	Participants [M or F (RSH, RSN)]	Training status	Altitude level (m)[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	3000	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. [36]	Parallel, single-blind	M (15, 15)	Academy rugby union and rugby league players	3500	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. [37]	Parallel, single-blind	M (5, 5)	Adolescent footballers	3000	5 × 1.5	3 × 5 × 10 s, 20 s overground shuttle runs, 5 min	6 × 40 m shuttle-run sprints[d]; 20 s passive recovery	YYIR2
Faiss et al. [39]	Parallel, double-blind	M (n = 11), F (n = 6); (9, 8)	Elite cross-country skiers	3000	2 × 3	4 × 5 × 10 s, 20 s 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. [35]	Parallel, double-blind	M (8, 8)	Adolescent footballers	2900	5 × 2	5 × 4 × 5 s, 45 s treadmill and overground shuttles, 5 min	10 × 30 m running sprints; 30 s passive recovery	VAMEVAL
Kasai et al. [38]	Parallel, single-blind	F (16, 16)	College lacrosse players	3000	4 × 2	2 × 10 × 7 s, 30 s cycling, 10–20 min	10 × 7 s ergocycle sprints; 30 s passive recovery	Graded ergocycle power
Goods et al. [32]	Parallel, single-blind	M (9, 10)	Semi-elite AFL players	3000	5 × 3	3 × 7 × 5 s, 15–35 s 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	2 × 3	4 × 5 × 5 s, 25 s overground, 5 min	8 × 20 m sprints, 20 s passive recovery	YYIR2
Montero and Lundby [33]	Crossover, double-blind	M (15)	Moderately trained endurance athletes	3000	4 × 3	4 × 5 × 10 s, 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, *F* females, *M* males, *Reps* repetitions, *RSA* repeated-sprint ability, *RSH* repeated-sprint training in hypoxia, *RSN* repeated-sprint training in normoxia, *VAMEVAL* maximal incremental running test, modified version of the University of Montreal Track Test, *YYIR1* and *YYIR2* Yo–Yo intermittent recovery tests level 1 and 2

[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 tests was considered

(Figs. 2, 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 used their results to recalculate 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., ninth sprint in Faiss et al. [9] and eleventh 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 and mean power outputs or best time; mean or total time; sprint decrement and/or fatigue index) were used in the different RSH studies, this meta-analysis reinforces these findings as we carefully reported the best and mean RSA performance across an equivalent number of sprints performed for both RSH and RSN groups from all included studies.

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. Solid evidence suggests that RSH mechanisms likely differ from those associated with 'intermittent hypoxic training' [16–18]. With maximal intensity efforts performed in hypoxia, enhanced oxygen utilization (via improved blood perfusion level) and 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, compensatory vasodilatation with an induced nitric oxide-dependent increase in muscle blood flow aimed at matching the increased oxygen demand at the muscular level when exercising in hypoxia [40, 41]; secondly, greater microvascular oxygen delivery to fast-twitch fibers [42], mainly due to their higher fractional oxygen extraction [43]; and thirdly, specific molecular adaptations arising from the oxygen-sensing pathway [15–18]. In support of this, 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 and Lundby [33] demonstrated a marked RSH-induced increase in the 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 [44], 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 [45, 46]. 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 [47] 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 [48], improved

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: Tau² = 0.00; df = 8 (P = 0.53); I² = 11.14

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

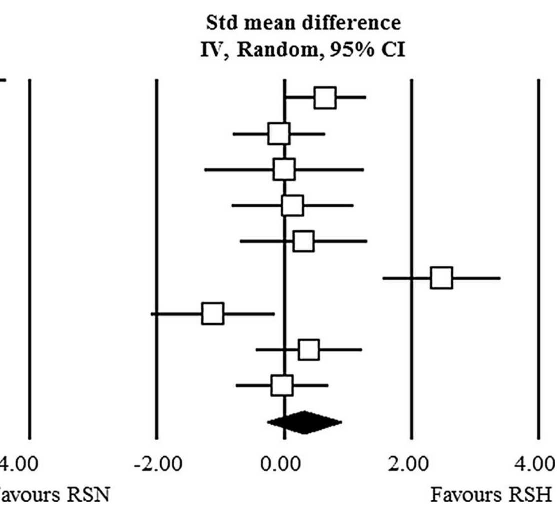

Fig. 2 Forest plot of the standardized mean difference (SMD) between the effect of repeated-sprint training performed in hypoxia (RSH) vs. normoxia (RSN) on best repeated-sprint ability performance. *Squares* represent the SMD for each study. The *diamond* represents the pooled SMD for all studies. *CI*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

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)

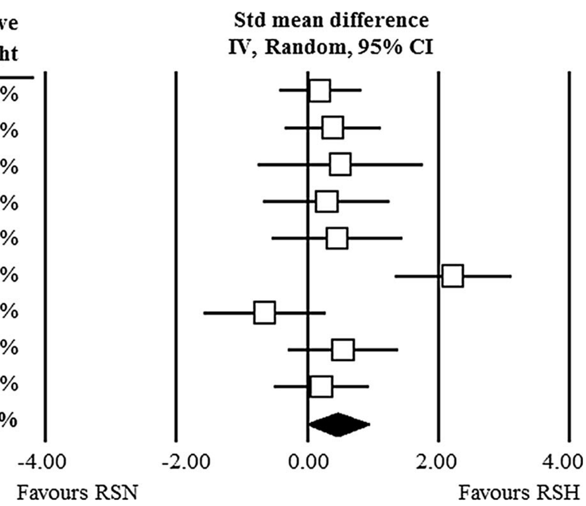

Fig. 3 Forest plot of the standardized mean difference (SMD) between the effect of repeated-sprint training performed in hypoxia (RSH) vs. normoxia (RSN) on mean repeated-sprint ability performance. *Squares* represent the SMD for each study. The *diamond* represents the pooled SMD for all studies. *CI*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

Study	SMD	[95% CI]	Relative weight
Faiss et al. [9]	-0.500	[-1.129, 0.129]	15.8%
Galvin et al. [36]	0.441	[-0.283, 1.166]	14.2%
Gatterer et al. [37]	-0.338	[-1.586, 0.911]	7.9%
Faiss et al. [39]	0.401	[-0.561, 1.363]	10.8%
Brocherie et al. [35]	0.083	[-0.898, 1.063]	10.6%
Kasai et al. [38]	1.330	[0.565, 2.096]	13.6%
Brocherie et al. [34]	-0.078	[-0.896 , 0.741]	12.8%
Montero & Lundby [33]	0.011	[-1.003, 1.026]	14.3%
Combined	**0.181**	**[-0.247, 0.610]**	**100.0%**

Heterogeneity: Tau² = 0.00; df = 7 (P = 0.86); I² = 0.00

Test for overall effect: Z = 0.83 (P = 0.41)

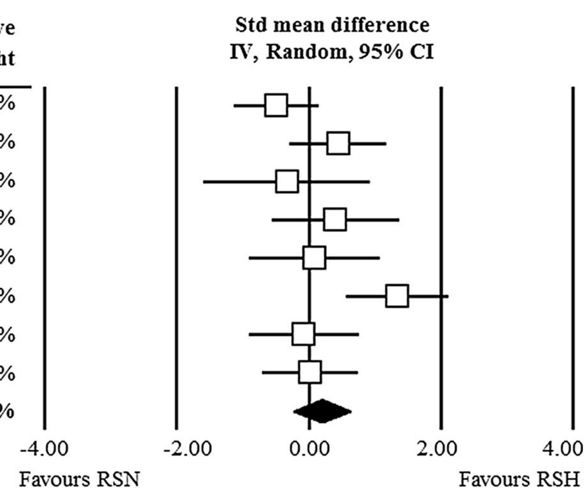

Fig. 4 Forest plot of the standardized mean difference (SMD) between the effect of repeated-sprint training performed in hypoxia (RSH) vs. normoxia (RSN) on maximal oxygen uptake ($\dot{V}O_{2max}$). *Squares* represent the SMD for each study. The *diamond* represents the pooled SMD for all studies. *CI* confidence interval, *df* degrees of freedom, *IV* inverse variance, *Std* standardized

removal of waste metabolites when blood flow is raised [49] (as reported post-RSH [9]) might delay fatigue during an RSA test.

A trivial beneficial effect of RSH on aerobic capacity (Fig. 4) compared with RSN was noted (five of eight studies in RSH vs. RSN). Although calculations were based on the results of different field-based tests and not systematically from directly measured $\dot{V}O_{2max}$ 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 $\dot{V}O_{2max}$ using a modified version of the University of Montreal Track Test (i.e., the VAMEVAL maximal incremental running test) [50], sport-specific aerobic tests such as Yo–Yo intermittent recovery tests [51] may be more appropriate. Reportedly, 4 weeks of treadmill RSH induced a +33% improvement in the 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 $\dot{V}O_{2max}$ (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].

Table 2 Protocol recommendations for repeated-sprint training in hypoxia

Variable	Recommendations
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

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 between 2 and 5 weeks with two to three sessions per week. Furthermore, training protocols considerably differed with one to five sets, four to ten 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. [52] demonstrated that RSH appears to be 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 the 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 a different number of sets and repetitions) being potentially more appropriate for specific physiological (e.g., oxidative vs. glycolytic component) and physical development (e.g., $\dot{V}O_{2max}$). Regarding recovery type, applying active recovery (i.e., at low to moderate intensity) under hypoxic conditions may not be the most efficient method. Hence, it may alter performance of subsequent sprint efforts, in particular via a slowing down of the muscle re-oxygenation rate [9], and could lead to premature fatigue. In support of this, a previous study [53] conducted in normoxia indicated that active recovery (i.e., 50% of velocity at $\dot{V}O_{2max}$) induced a lower replenishment of oxygen in myoglobin and hemoglobin and a reduced rate of phosphocreatine re-synthesis 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 the risk of injury and discomfort [28]. On the other hand, neuromuscular fatigue is higher in cycling- than in running-RSA modes [54]. Taking these factors into consideration, well-designed protocols using sport-specific conditions and/or ecological settings [34, 55, 56] 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 $\dot{V}O_{2max}$ was trivially higher for RSH than for RSN.

Compliance with Ethical Standards

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Conflict 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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