Routledge
Taylor & Francis Group

Journal of Sports Sciences

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/rjsp20

Repeated-sprint training in hypoxia: A review with 10 years of perspective

Raphaël Faiss, Antoine Raberin, Franck Brocherie & Grégoire P. Millet

To cite this article: Raphaël Faiss, Antoine Raberin, Franck Brocherie & Grégoire P. Millet (24 Oct 2024): Repeated-sprint training in hypoxia: A review with 10 years of perspective, Journal of Sports Sciences, DOI: 10.1080/02640414.2024.2416821

To link to this article: https://doi.org/10.1080/02640414.2024.2416821

Published online: 24 Oct 2024.

JOURNAL OF SPORTS SCIENCES
https://doi.org/10.1080/02640414.2024.2416821

Routledge
Taylor & Francis Group

Repeated-sprint training in hypoxia: A review with 10 years of perspective

Raphaël Faiss[a], Antoine Raberin[a], Franck Brocherie[b] and Grégoire P. Millet[a]

[a]Institute of Sports Sciences, Department of Physiology, Faculty of Biology and Medicine, University of Lausanne, Lausanne, Switzerland; [b]Laboratory Sport, Expertise and Performance, French Institute of Sport, Paris, France

ABSTRACT

Over the past decade, numerous studies have investigated an innovative "live low-train high" approach based on the repetition of short (<30 s) "all-out" sprints with incomplete recoveries in hypoxia; the so-called Repeated-Sprint training in Hypoxia (RSH). The aims of the present review are therefore threefold. First, this study summarizes the available evidence on putative additional performance enhancement after RSH comparing to the same training in normoxia (RSN). Second, a critical analysis of underpinning mechanisms discusses how advantages can be obtained through RSH for sea-level performance enhancement. An enhanced microcirculatory vasodilation leading to improved muscle perfusion and/or oxygenation and an increase in muscular phosphocreatine content may help explain the superiority of RSH vs. RSN. Third, the present review aims to provide guidelines for coaches, athletes and scientists to apply RSH interventions with regard to the interval duration, exercise-to-rest ratio and training volume. In conclusion, this review supports repeated-sprint training in hypoxia as an efficient (but not magic) training intervention with 77% of the controlled studies reporting an additional benefit with added hypoxia, mainly for team-, combat- and racket-sports athletes but also for all other sports (e.g. endurance) that require repeated accelerations with lesser fatigue.

Summary box

- This review critically analyzes the results of the studies involving repeated-sprint training in hypoxia (RSH) since 2013.
- 10 years ago, RSH was proposed as a promising training strategy shown to delay muscle and metabolic fatigue, particularly during repeated-sprint exercises with incomplete recoveries.
- In the past decade, RSH has gained great popularity among athletes, coaches and scientists as an effective training reproduced in various sports with a large majority of studies reporting beneficial outcomes.
- RSH may improve performance in a fibre-type-selective and intensity-dependent manner, with mechanisms presumably different than those associated with other (less intense) hypoxic training methods.

ARTICLE HISTORY
Received 25 June 2024
Accepted 8 October 2024

KEYWORDS
Altitude training; hypoxia; team sports; repeated sprints

1. Introduction

Towards achieving sea-level peak performance, for long, endurance athletes and coaches have felt compelled to include an additional hypoxic stimulus in their training regimen expecting further gains through physiological adaptations mainly through haematological adaptations (e.g., increase in haemoglobin mass), improved oxygen delivery, or peripheral adaptations at the muscle level. In the past decade, an innovative method (Repeated-Sprint training in Hypoxia, RSH) based mainly on peripheral adaptations was thoroughly investigated as an efficient sport-specific training strategy including hypoxia since the first interventional study was published in 2013 (Faiss, Léger, et al., 2013). Conceptually, RSH is defined as the repetition of several short (≤30 s) "all-out" exercise bouts in hypoxia interspersed with incomplete recoveries (exercise-to-rest ratio < 1:6). The application of maximal-intensity bouts in hypoxia (i.e., "all-out" sprints) contrasts with more traditional intermittent hypoxic training (IHT) regimens encompassing longer submaximal intervals where hypoxia supposedly augments the physical strain during exercise bouts (Huang et al., 2023).

Interestingly, IHT was investigated thoroughly in the past three decades with many unfulfilled promises (Levine, 2002; Roels et al., 2005) related to skeletal muscle tissue adaptations arising through the oxygen-sensing pathway (i.e. capillary-to-fibre ratio, fibre cross-section area, myoglobin content and oxidative enzyme activity such as citrate synthase) that supposedly would only occur in hypoxic conditions. Most of these expected muscle tissue adaptations are negligible for resting exposure to hypoxia (Lundby et al., 2009) and require high-intensity exercise (Hoppeler & Vogt, 2001; Vogt et al., 2001; Zoll et al., 2006).

Nevertheless, when adding hypoxia during interval/intermittent training, additional performance benefits after intervention were initially reported only in approximately 50% of the studies (Millet et al., 2010); a proportion recently confirmed in a systematic review of "Live Low-Train High" (LLTH) studies (Seitz et al., 2020). After two decades of research on IHT, one

CONTACT Raphaël Faiss raphael.faiss@unil.ch Institute of Sports Sciences, University of Lausanne, Synathlon 2316, Quartier Centre, Lausanne 1015, Switzerland

may assume that "*IHT does not increase exercise performance at sea level in endurance athletes any more than simply training at sea level*" (Lundby et al., 2012). Eventually, performance gains after LLTH interventions seemed to be dependent on the intensity of the exercise intervals in hypoxia (Faiss, Girard, et al., 2013). In other words, the harder the intervals when training in hypoxia, the larger the performance gains possibly associated with the additional hypoxic stress.

To further this reasoning, RSH was conceived with a maximal-intensity training stimulus (i.e., "all-out" sprints) allowing to maintain a high fast-twitch (FT) fibre recruitment. When prior studies with high intensity training or repeated-sprint intervals were considered (Bishop et al., 2011; Laursen & Jenkins, 2002), adding a hypoxic stimulus to a repeated-sprint regimen was thought as an attractive strategy to enhance the repeated-sprint ability in team sports. RSH is particularly interesting since single sprint performance of short duration (<10 s) is generally preserved under hypoxic conditions (up to a simulated altitude of 5000 m, beyond 3000 m), whereas fatigue resistance during repeated-sprint ability (RSA) tests is reduced with earlier and larger decrements in mechanical work (Balsom et al., 1994; Brocherie et al., 2023; Girard et al., 2017; Smith & Billaut, 2010). The combination of maximal-intensity exercise bouts interspersed with incomplete recoveries through RSH was therefore hypothesized to overcome some inherent limitations of submaximal exercise intensities where hypoxia induces hypoxaemia and a lower oxygen delivery that limits work capacity during IHT intervals (Levine, 2002).

RSH was consequently reported to delay muscle fatigue during a repeated sprint test to exhaustion in the first study testing the latter hypothesis (Faiss, Léger, et al., 2013). In that seminal study with a robust sample size ($n = 50$), the power output during 10-s sprints (by 6–7%) and a 30-s Wingate test (by 3–5%) were similarly improved after 4 weeks of RSH (at a simulated altitude of 3000 m, $F_IO_2 = 14.5\%$) when compared to the same training in normoxia (repeated-sprint training in normoxia, RSN) (at 485 m, $F_IO_2 = 20.9\%$).

Several previous studies (Balsom et al., 1994; Brosnan et al., 2000; Smith & Billaut, 2010) on the acute responses of high-intensity intermittent exercise in hypoxia were available prior to 2013 and showed that both the sprint duration and the exercise-to-rest ratio were important for both the cerebral and muscle acute deoxygenation. However, the study by Hoppeler et al. first pointed out that high-intensity exercise in hypoxia led to specific muscle tissue adaptation (i.e., larger mitochondrial volume or capillary densities) not observed either in normoxia or at lower-intensity (Hoppeler & Vogt, 2001). This interventional study was not based on sprint exercises and the so-called high-intensity was quite modest (lactate 4–5 mmol.l^{-1}), but it opened the way for a field-based investigation performed in 2008 by Prof. Millet – but published only in 2015 (Brocherie, Girard, et al., 2015) – with young Qatari football players, where RSA was further improved after 10 sessions of RSH than RSN.

RSH was hence shown to improve single sprint power output after training 10-s sprints interspersed with 20-s recoveries with the ability to perform more sprints after RSH but not after RSN (Faiss, Léger, et al., 2013). Interestingly, performance gains were supported by insightful explanatory mechanisms supported by mRNA regulation of genes involved in the glycolytic pathway at the muscle level, and muscle oxygenation data indicating larger oxygen de-/re-oxygenation and perfusion inducing an improved behaviour of FT fibres. It was suggested that RSH would stimulate positive adaptations in terms of muscle phosphocreatine [PCr] resynthesis and oxygen utilization at the muscle level (Faiss, Girard, et al., 2013) because of the challenge on the functional reserve in muscle oxygen-diffusing capacity likely utilized in hypoxia (Calbet & Lundby, 2009) and confirmed in a recent study (Kasai et al., 2017). In parallel, the oxygen demand at the muscular level for a given intensity is partly fulfilled during exercise in hypoxia by compensatory vasodilatation mechanisms that were shown to be intensity-dependent in increasing local blood flow (Casey & Joyner, 2012).

A fertile ground was set to further investigate benefits of RSH across different disciplines from endurance athletes to team, combat or racket sports with a large interest for such hypoxic training reflected by the growing number of cross-sectional or interventional studies and reviews on RSH since 2013 (Figure 1).

Beyond shortcomings in theories and methodologies of the various altitude training strategies, the aim of this narrative review is therefore to provide evidence-based best practices from state-of-the-art knowledge on RSH for athletes, coaches and sports medicine professionals.

2. Methods – selection of relevant scientific publications on RSH for a narrative review

Peer-reviewed scientific publications in English language on RSH were identified by searching "repeated-sprint training in hypoxia" in the most relevant electronic databases (i.e., PubMed® and Web of Science™). Editorial articles, comments, letters to the editor and conference proceedings were excluded. This allowed to cross-reference, in electronically available journals, 109 publications related to repeated-sprint exercises where an additional systemic hypoxic stimulus was included between the first publication specifically on RSH in February 2013 (Faiss, Léger, et al., 2013) and the last to date in May 2024 (Lanfranchi et al., 2024). Focus was primarily set on studies including systemic hypoxia, therefore excluding studies relying only on local hypoxia at the muscle level (e.g., vascular occlusion induced by blood flow restriction or ischaemic preconditioning) or those that involve inducing intermittent hypoxaemia through apnoeas or voluntary changes in the ventilatory pattern (e.g., hypoventilation at low lung volume, VHL). The studies reviewed here were then categorized as training interventions ($n = 52$), cross-sectional studies (i.e., investigating hypoxia and repeated sprints acutely at a single time point) ($n = 49$) or reviews ($n = 8$). Selection criteria were then refined among the training intervention studies to include only (single- or double-blinded) studies comparing a RSH intervention with either a comparable group training in normoxia (i.e., vs. RSN) or a cross-over design. The training interventions included were limited to RSH as defined earlier (i.e., ≤30 s sprints with an exercise-to-rest ratio of ≤1:6). In addition, a measure of physical performance (e.g., repeated-sprint ability, peak oxygen consumption (VO_2 peak) or average/peak power

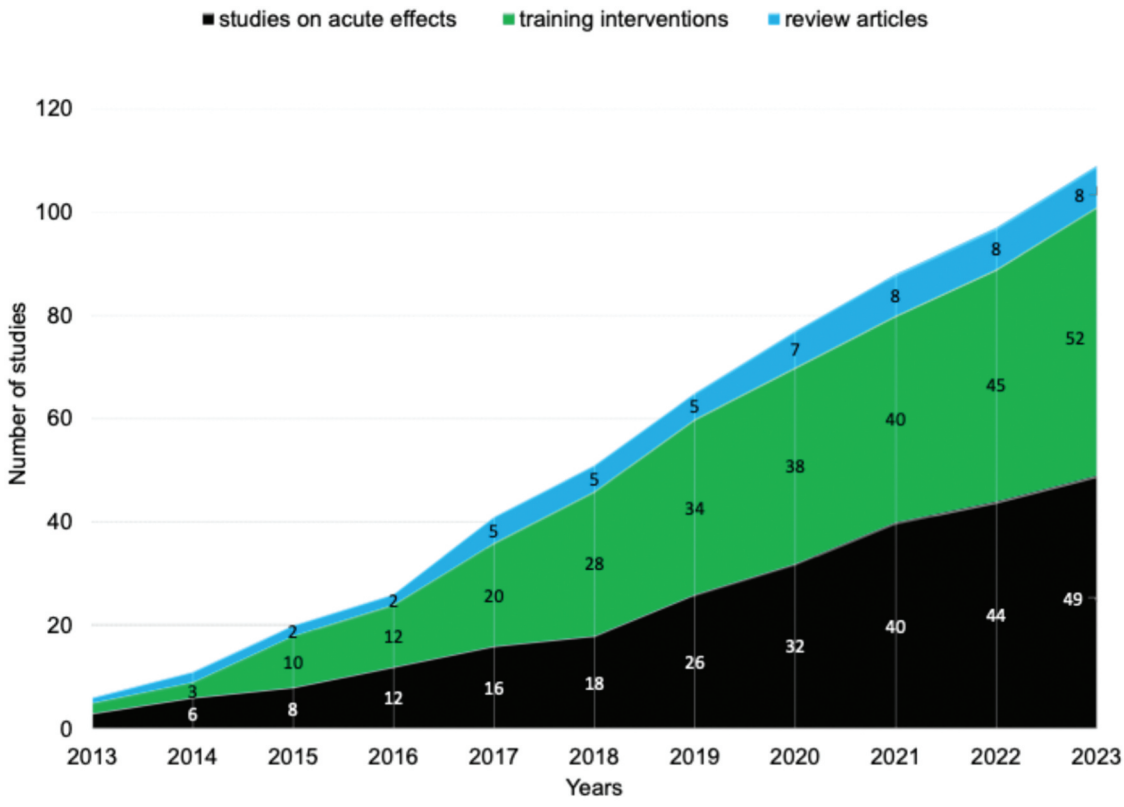

Figure 1. Indexed scientific publications on repeated-sprint training in hypoxia (RSH) from 2013 to 2023 identified by searching "repeated-sprint training in hypoxia" in the PubMed® and Web of Science™ databases.

output during (single or repeated) sprints) was required. Among the large number of studies where RSH was investigated as a training intervention, 22 studies fulfilled the latter criteria for inclusion in this review (Table 1). Search of the literature, identification, review of the relevant studies and quality assessment were conducted independently by all co-authors before data extraction by the first author.

Due to the multiple sporting disciplines investigated resulting in multiple exercise training protocols or intervals, it was decided to prefer a narrative review format allowing to concatenate existing findings from systematic reviews, meta-analyses, and cross-sectional studies. We herewith acknowledge that any putative performance gains associated specifically with RSH may at first only be evaluated with a systematic review of studies with robust designs (i.e., blinded and well-controlled). Second, a narrative approach may additionally allow incorporating perspectives from case reports or studies including elite athletes with useful practical expertise on the implementation of RSH despite the possible lack of a control group. Finally, studies on acute response to single RSH sessions may allow better outline underpinning mechanisms of performance alterations reported initially.

3. Evidence on performance gains after RSH from systematic reviews and meta-analyses

RSH has attracted a large number of investigations (Figure 1) with 77% of the controlled studies reporting an additional benefit of hypoxia (Table 1) and no study reporting any mechanism affecting performance negatively. This contrasts with the 28% of studies reporting negative mechanisms after prolonged hypoxic exposures (i.e., "live high-train high" or "live high-train low") studies (Millet et al., 2010).

After being suggested as a promising method to improve hypoxic training outcomes in team sports (Faiss, Girard, et al., 2013), RSH was first mentioned in a systematic review in 2014 despite evidence being reported from only three studies at the time (McLean et al., 2014). The latter review concluded that "*improvements are more likely following high-intensity short-term and intermittent training*" like RSH. This confirms the mechanisms proposed initially with the importance of maximal efforts with added hypoxia to trigger systemic performance response (Faiss, Girard, et al., 2013; Faiss, Léger, et al., 2013).

Performance improvements following RSH were consequently reviewed in a first meta-analysis of nine studies reporting that RSH is more effective than RSN to significantly improve the mean repeated-sprint performance (+2%) (Brocherie et al., 2017). This analysis underlined the fact that additional performance gains are not tremendous but may represent a significant benefit in world class athletes (McKay et al., 2022) especially considering that most RSH studies have included cohorts of elite athletes. In other words, RSH may provide practical benefits in "real word" elite sport.

A review including several types of LLTH interventions confirmed RSH as a potent and well-tolerated training model with underlying mechanisms requiring further research (Millet et al., 2019). A more recent systematic review on the performance outcomes after RSH summarized findings from 13 well-

Table 1. Summary of research findings relative to the use of repeated sprint training in hypoxia (RSH) in controlled blinded studies with performance measurement in normoxia.

#	Author (year)	Subjects	Design (number of training sessions, altitude, training content)	Groups	Additional benefit from hypoxia	Negative mechanism?	Statistically significant results ($p < 0.05$)
1	Faiss, Girard, et al. (2013)	Moderately trained	8 sessions over 4 wks, 3000 m, cycling, 3 × 5 all-out 10-s sprints interspersed	RSH, $n = 20$			+6% PO & +38% sprints in RSA to exhaustion
		male cyclists	with 20 s recovery at 120 W	RSN, $n = 20$	Yes	No	+7% PO, NS in sprint number in RSA to exh.
				CON, $n = 10$			NS changes
2	Galvin et al. (2013)	Trained male rugby	12 sessions over 4 wks, 3500 m, running, all-out sprint on a non-motorized	RSH, $n = 15$	Yes	No	+33% distance Yo-Yo IR1
		players	treadmill, 10 × 6 s sprints interspersed with 30 s passive recovery	RSN, $n = 15$			+14% distance Yo-Yo IR1
3	Gatterer et al. (2014)	Young male football	10 sessions over 5 wks, 3300 m, running, 3 sets of 5 all-out shuttle runs	RSH, $n = 5$	Yes	No	+20% distance Yo-Yo IR1, −16% fatigue slope
		players	inside a 4.75 m long hypoxic chamber interspersed with 20 s passive recovery	RSN, $n = 5$			+21% distance Yo-Yo IR1, +9% fatigue slope
4	Kasai et al. (2015)	Trained female team	8 sessions over 4 wks, 3000 m, 2 sets of 10 × 7 s sprints interspersed	RSH, $n = 16$	Yes	No	+5% peak & +10% mean PO during RSA
		sport athletes	with 30 s passive rest	RSN, $n = 16$			+1.5% peak & +6% mean PO during RSA
5	Gatterer et al. (2015)	Trained football male	8 sessions over 12 days, 3300 m, running, 3 sets of 5 all-out shuttle runs	RSH, $n = 7$	No	No	+30% distance Yo-Yo IR1, −30% RSA fatigue slope
		players	inside a 4.75 m long hypoxic chamber interspersed with 20 s passive recovery	RSN, $n = 7$			+27% distance Yo-Yo IR1, −33% RSA fatigue slope
6	Faiss et al. (2015)	Highly trained male	6 sessions over 2 wks, 3000 m, double-poling, 4 sets of 5 × 10 s all-out	RSH, $n = 9$	Yes	No	+29% peak RSA PO, +57% sprints in RSA
		& female XC skiers	interspersed with 20 s active recovery	RSN, $n = 8$			+26% peak RSA PO, NS change in sprint number
7	Brocherie, Girard, et al. (2015)	Youth male football	10 sessions over 5 wks, 2900 m, running, 2-3 sets of 5-6 × 15 s sprints (15 s passive	RSH, $n = 8$	Yes	No	+4% first sprint perf, −4% cumulated RSA time
		players	recovery) on a motorized treadmill & 20 explosive strength/agility drills	RSN, $n = 8$			+2% first sprint perf, −2% cumulated RSA time
8	Goods et al. (2015)	Team sport male	15 "top-up" sessions over 5 wks, 3000 m, cycling, 3 sets of 7 × 5 s all-out sprint	RSH, $n = 9$	No	No	+5% peak & +10% mean PO during RSA
		athletes	with variable 15-35 s recovery between sprints, 3 min between sets	RSN, $n = 10$			+9% peak & +14% mean PO during RSA
				CON, $n = 9$			NS changes
9	Montero and Lundby (2017)	Endurance trained	12 sessions over 4 wks, 3000 m, cycling, 3 × 5 all-out 10-s sprints interspersed	RSH, $n = 8$	No	No	+7% peak & +12% mean PO during RSA
		males	with 20 s at recovery at 20 W	RSN, $n = 7$			+7% peak & +10% mean PO during RSA
10	Kasai et al. (2017)	Male sprint	10 sessions over 5 days, 3000 m, cycling, morning: sprints 1 × 10 s + 5 × 6 s −24 s rest	RSH, $n = 10$	Yes	No	+3% peak & mean PO during RSA
		runners	+4× 20 s (5-15 min rest), afternoon: sprints 5 × 6 s −36 s rest + 4 × 20 s (40 s rest)	RSN, $n = 9$			NS increase in peak & mean PO during RSA
11	Hamlin et al. (2017)	Well-trained male	6 sessions over 3 weeks, 3000 m, cycling, 4 sets of 5 s all-out cycling sprints	RSH, $n = 8$	Yes	No	+27% distance Yo-Yo IR1, −1.9% RSA fatigue
		rugby players	interspersed with 25 s active recovery (20-50 W). 5 post-tests from 2 days to 5 wks	RSN, $n = 10$			+22% distance Yo-Yo IR1, −0.7% RSA fatigue
12	Brechbuhl, Brocherie, et al. (2018)	Male & female	5 sessions over 12 days, 3000 m, running, 4 sets of 5 × 6 s all-out shuttle run sprints	RSH, $n = 10$	Yes	No	+15% TTE tennis test, +14% ball accuracy
		tennis players	inside a 15 m long hypoxic chamber interspersed with 24 s passive recoveries	RSN, $n = 10$			+8% TTE tennis test, −5% ball accuracy
13	Kasai et al. (2019)	Male sprint	6 sessions over 6 days, 3000 m, cycling 4 × 15 s sprint (5 min rest) + 3 × 30 s sprint	RSH, $n = 9$	Yes	No	−4% 10 m running time

(*Continued*)

Table 1. (Continued).

#	Author (year)	Subjects	Design (number of training sessions, altitude, training content)	Groups	Additional benefit from hypoxia	Negative mechanism?	Statistically significant results ($p < 0.05$)
		runners	(10 min rest) + 1-3 sets of 5 × 6 s sprints (30 s rest, 10 min between sets)	RSN, $n = 9$			−2% 10 m running time
14	Beard, Ashby, Kilgallon, et al. (2019)	Professional male	4 sessions over 2 wks, 3000 m, cycling, 3 sets of 8 × 10 s all-out sprint	RSH, $n = 10$	Yes	No	+6% peak & +6% mean PO during RSA
		rugby players	interspersed with 20 s passive recovery	RSN, $n = 9$			NS changes in peak & mean PO during RSA
15	Beard, Ashby, Chambers, et al. (2019)	Professional male	4 sessions over 2 wks, 3000 m, double-poling, 3 sets of 8 × 10 s all-out sprints	RSH, $n = 18$	Yes	No	+10% peak & +11% mean PO during RSA
		rugby players	interspersed with 20 s passive recovery	RSN, $n = 18$			NS changes in peak & mean PO during RSA
16	Wang et al. (2019)	Recreationally active	8 sessions over 4 wks, 2900 m, cycling, 3 sets of 5 × 10 s all-out sprint	RSH, $n = 9$	Yes	No	+13% mean & +21% last sprint PO during RSA
		males	interspersed with 20 s active recovery. ß-alanine supplementation, pooled data.	RSN, $n = 8$			+12% mean & + 20% last sprint PO during RSA
17	Brechbuhl et al. (2020)	Competitive male	5 sessions over 12 days, 3000 m, shuttle-runs, 4 sets of 5 × 8 s all-out sprints	RSH, $n = 11$	Yes	No	+17% TTE tennis test, +39% ball accuracy
		& female tennis	Interspersed with 22 s passive recovery. 5 min interest recovery.	RSN, $n = 11$			NS +4% TTE tennis test, NS change ball accuracy
		Players		CON, $n = 8$			NS changes
18	Kong et al. (2022)	Young sedentary	12 sessions over 4 weeks, 2500-3400 m, cycling, 80 × 6 s all-out sprints	RSH, $n = 30$	Yes	No	+10% peak oxygen consumption
		females	interspersed with 9 s rest (max. resistance 5% of body mass)	RSN, $n = 15$			+4% (NS) in peak oxygen consumption
				CON, $n = 15$			NS changes
19	Shi et al. (2023)	Male handball &	6 over 2 wks (RSH_2), or 15 over 5 wks (RSH_5), 3500 m, running, 3 sets of	RSH_2, $n = 10$	Yes	No	+18% distance Yo-Yo IR1, +14% RSA PO
		football players	5 × 5 s all-out sprints interspersed with 25 s passive recovery	RSH_5, $n = 10$			+22% distance Yo-Y1, +16% RSA PO
				RSN, $n = 12$			+4% (NS) Yo-Yo IR1, +6% RSA PO
19	Brocherie et al. (2023)	Professional	4 over 9 days, 5000 m, cycling, 4 sets of 5 all-out sprints	RSH, $n = 12$	No	No	+2% RSA distance
		female rugby players	interspersed with 25 s recovery	RSN, $n = 11$			+2% RSA distance
20	Piperi et al. (2024)	Active male and	14 sessions over 7 wks, 3000 m, cycling, 3 × 5 all-out 10-s sprints	RSH, $n = 22$	Yes	No	+83% sprints in RSA to exhaustion
		females	interspersed with 20 s recovery	RSN, $n = 19$			+38% (NS) sprint in RSA to exhaustion
21	Birol et al. (2024)	Trained team-sport	3 sessions over 5 days, 3500 m, cycling, 5 sets of 5 × 5 s all-out sprints	RSH, $n = 9$	No	No	+13% peak & +22% mean PO during RSA
		male players	Interspersed with 25 s recovery	RSN, $n = 9$			+7% peak & +4% mean PO during RSA
				CON, $n = 9$			NS changes
22	Lanfranchi et al. (2024)	Physically active	9 sessions over 3 wks, 3800 m, cycling, 6 × 6 all-out sprints	RSH, $n = 9$	Yes	No	+4% PO Wingate test, −13% RSA PO decrement
		males	interspersed with 24 s recovery 1.5 W per kg body weight	RSN, $n = 7$			+1% PO Wingate test, −40% RSA PO decrement

This table is limited to investigations with repeated sprint training in hypoxia (RSH) or repeated sprint in normoxia (RSN) with blinded conditions. Five studies included a non-training control (CON) group. Hypoxia was obtained by simulation through normobaric hypoxia (NH) using either a hypoxic chamber or a mask. Significant difference between groups is shown in bold.
NS, non-significant ($p > 0.05$); PO, power output; Yo-Yo IR1, Yo-Yo Intermittent Recovery level 1 test; TTE, time to exhaustion ; RSA, repeated sprint ability test.

controlled (and blinded) studies in addition to one repeated-sprint study where local hypoxia was induced by VHL (Zelenovic et al., 2021). That review confirms that additional benefits from RSH are consistent across studies for repeated-sprint ability performances (i.e., peak and mean power during RSA), but the mechanisms of supporting performance gains were not proposed.

Lately, various LLTH strategies were reviewed in a network meta-analysis comparing different modalities and confirmed that RSH can effectively improve performance with importance set for sufficient duration and work intensity (Feng & Jin, 2016). To date, reviews outlined systematically the need to better investigate mechanistic responses to RSH in order to better delineate which physiological adaptations are paramount when implementing RSH according to the participants' profiles (from untrained to elite athletes). The present review is hence timely to provide the most recent update on concurrent knowledge, allowing to provide best practice approaches for RSH. Study designs and significant performance outcomes are summarized in Table 1.

3.1. Studies with no reported additional benefit from RSH vs. RSN

As a starting point, 17 of the 22 well-controlled studies reported additional performance improvement when hypoxia was added to a repeated-sprints training regimen.

In other words, only four studies did not find an additional benefit on performance after RSH vs. RSN. This may first be due to the type of performance assessed or the timing/frequency of the tests before and after the training intervention. For instance, similar improvements after RSH vs. RSN were found after eight training sessions in 12 days in improving the endurance capacity (Yo-Yo intermittent recovery level 1 test) and reducing the fatigue during a RSA test in young football players (Gatterer et al., 2015). Such a short-time intervention may not have allowed to induce specific peripheral adaptations due to a very high training load eliciting fatigue, in particular, in young players, as suggested in a case-report of a young tennis player (Brechbuhl, Brocherie, et al., 2018). Interestingly, the same research group found additional benefits of RSH over RSN with a reduced slope of fatigue with the same training load but over 5 weeks (Gatterer et al., 2014). Furthermore, the peak and mean power output during RSA was largely improved (+5-14%) after 15 sessions of sprinting on a cycle ergometer in highly trained team-sport athletes, while no gains were observed during a treadmill RSA test (Goods et al., 2015). The lack of additional benefit of adding hypoxia in that context may be due either to the addition of the repeated-sprint training as a "top-up" while maintaining an already intense team-sport training regimen or to the lack of training specificity, i.e., on a cycle ergometer for athletes requiring running-based abilities.

Finally, in a study including 4 weeks of repeated-sprint training (12 sessions, 3 sets of 5 × 10-s sprints interspersed with 20 s of recovery) in a cross-over design (6 weeks "wash-out" between either RSN or RSH), the peak and mean power output were improved similarly (+7-12%) during a RSA test with no additional benefit in the hypoxic training group (Montero & Lundby, 2017). Performance was assessed with 12 sets of repeated sprints tests in various conditions (e.g., in normoxia or hypoxia and with or without prior exhausting exercises) over only 3 days, which may have induced persistent fatigue for the RSA efforts, hence blunting any difference between conditions.

No performance change was also observed in a single sprint after four RSH sessions at 5000 m in female world-class rugby players (Brocherie et al., 2023). The lack of improvement may in that case be due to the very high simulated altitude (blunting adaptations following a very short-term training phase with a concomitant lack of specific RSA measurement). This is in accordance with the negative effect of a strong hypoxic stress found in swimmers performing repeated sprint training at a simulated altitude of >4000 m (Camacho-Cardenosa et al., 2020). The latter study was notably not included in the review due to the lack of an adequate blinding for the hypoxic condition.

In one of the latest studies to date, RSA performance was improved after repeated sprint-training (peak and mean power output) with larger gains on average for RSH vs. RSN while statistical significance was not met ($p = 0.05$) for the differences between groups (Birol et al., 2024).

In all the above-cited studies, RSN and RSH were however systematically favourable in enhancing exercise performance (e.g., for repeated-sprint ability). Despite no differences when hypoxia was added, adaptations in the training process (i.e., quality and organization of the exercises (i.e., repeated sprints)) definitely require to be considered in the context of an ecological and well-thought implementation to result in performance improvements (Impellizzeri et al., 2005). Furthermore, an important point is that none of the studies reported lesser gains after RSH compared to RSN, nor negative mechanisms when hypoxia was added to a repeated-sprint training regimen.

3.2. Studies with additional benefits from RSH vs. RSN

The pioneer RSH-based study included 4 weeks of training encompassing 120 repeated sprints of 10 s interspersed with 20 s of active recovery in eight training sessions at 3000 m (Faiss, Léger, et al., 2013). The sprint duration was set with the hypothesis that the addition of a hypoxic challenge would induce transcriptional adaptations in the skeletal muscle through a hypoxia inducible-factor (HIF-1a) upregulation (Zoll et al., 2006). At the time, IHT was linked to muscular adaptations through mitochondrial density, capillary-to-fibre ratio, and fibre cross-sectional area as well as mitochondrial metabolism, oxidative stress defence, and pH regulation (Dufour et al., 2006; Hoppeler & Vogt, 2001). However, one may question the functional significance of these physiological adaptations (e.g., larger increase in citrate synthase activity after hypoxic training) since the effects of IHT on endurance performance measured in normoxia are "*minimal and inconclusive in trained athletes*" (Lundby et al., 2012). Nevertheless, the amplitude of the positive peripheral adaptations was suggested to be intensity-dependent (Hoppeler & Vogt, 2001). Designing a training intervention in hypoxia with maximal intensity bouts, like repeated sprints, proposed an evident rationale for team-sport athletes if such training elicits improved RSA or decreases fatigue in

crucial situations (e.g., to avoid decreased technical and tactical behaviour and wrong cognitive choices) (Garvican et al., 2013; Mohr et al., 2005).

Delayed fatigue (i.e., more sprints repeated before exhaustion) initially represented a major benefit from RSH vs. RSN in addition to other performance factors (e.g., peak or mean power output during sprints) often being similarly improved regardless of the presence of an additional hypoxic challenge (Table 1).

In an early RSH study in trained rugby players (Galvin et al., 2013), RSH elicited a two-fold greater improvement in the Yo-Yo intermittent recovery level 1 test as an indicator of the individual's ability to repeatedly perform intense exercises (Bangsbo et al., 2008). An "*ameliorated cerebral deoxygenation after hypoxic training*" was suggested to allow "*maintained central drive*" to explain the improved work capacity after RSH (Galvin et al., 2013). Additional benefits on the cerebral function (e.g., improved cerebral oxygenation) in addition to tennis-specific performance gains were also reported in male and female tennis players in two RSH studies due to lesser technical alteration (stroke accuracy) under fatigue (Brechbuhl et al., 2020; Brechbuhl, Brocherie, et al., 2018). Similar improvements were recently reproduced in male team-sport players after 2 or 5 weeks of RSH (Shi et al., 2023). Yo-Yo intermittent recovery level 1 test gains were similar after RSH or RSN (+27-30% distance) in young football players training "all-out" shuttle runs in a hypoxic chamber for 5 weeks, while the fatigue slope during a fixed-number RSA test was clearly lowered (−16%) only after RSH and not RSN (Gatterer et al., 2014). In parallel, a Japanese group investigated RSH thoroughly with three consecutive studies in female team-sport athletes with eight sessions over 4 weeks (Kasai et al., 2015) and in male sprint runners tested after either 10 sessions over 5 days or six sessions over 6 days (Kasai et al., 2017, 2019). Despite the very short training intervention, RSH was systematically superior to RSN in improving the sprint running time and average and peak sprint power outputs.

Potential flaws linked to ineffective blinding of the hypoxic vs. normoxic conditions were then ruled out in two double-blinded studies including either highly trained cross-country skiers (Faiss et al., 2015) or male football players (Brocherie, Girard, et al., 2015) where RSA was improved more after RSH (+54% more sprints before task failure in the cross-country skiers and 2-fold improvement in the cumulated RSA time for the football players).

Lesser fatigue during the RSA test was also found in well-trained rugby players after six RSH sessions over 3 weeks (Hamlin et al., 2017).

In 2019, 8 RSH sessions in recreationally active males were shown to improve more total work and the final sprint power during a RSA test than after RSN in a study combined with ß-alanine supplementation (Wang et al., 2019). The latter study outlined large gains in power output in participants less trained to sprinting, yet with additional gains when training was done in hypoxia vs. normoxia.

Performance benefits were also reported in professional rugby players (larger increase in RSA power output) (Beard, Ashby, Chambers, et al., 2019), indicating that performance gains may not be related to an initial (low) performance level of the participants.

More recently, RSH was also reported as a potent strategy to improve performance also when implemented in young sedentary females (Kong et al., 2022) or less trained males and females (Piperi et al., 2024). In the latter study, no differences were reported between sexes.

Finally, the last RSH study to date found 3% larger gains in power output during a 30-s Wingate test after RSH vs. RSN together with a 27% lesser decrement of the power output during a RSA test in physically active males (Lanfranchi et al., 2024).

4. Mechanisms underlying positive responses to RSH

Overall, supplementary benefits of adding a hypoxic stimulus when performing repeated-sprint training are consistent in the existing body of literature. It is however paramount to outline some underpinning mechanisms that may support such positive systemic performance adaptations despite most of the studies applying a descriptive design where mostly only performance is assessed.

Of importance is that the effectiveness of RSH may depend on many factors (see Chapter 5: specificity of the training stimuli; sprint duration and exercise-to-rest ratio; severity of the hypoxic stimuli) but does not rely on the "hypoxic dose" (i.e., the combination of the exposure duration and the hypoxia severity) (Wilber et al., 2007). Even short exposure to hypoxia may induce the expected vascular and muscle molecular adaptations. It is an important point to understand and a fundamental difference to the LHTH or LHTL methods (Garvican-Lewis et al., 2016; Wehrlin et al., 2016)

Existing and purported mechanisms of peripheral adaptations at the muscle level to support improved RSA performance after RSH are illustrated in Figure 2.

4.1. Fiber-type specific responses and intensity-dependent vasodilatory compensation in hypoxia

By definition, RSH requires the production of repeated maximal-intensity exercises interspersed with incomplete recovery periods. During sprinting, glycolytic FT muscle fibres are preferentially recruited with an intensity-dependent increase (Laughlin & Armstrong, 1982), in contrast to lower intensity (prolonged) intervals where both oxidative slow (ST) and FT muscle fibres are recruited.

Then, a higher blood perfusion may positively affect more FT than ST fibres because FT fibres have a greater fractional oxygen extraction if highly perfused (McDonough et al., 2005). When oxygen availability is limited but the blood flow increased (e.g., when sprinting in hypoxia), FT fibres exhibit an enhanced micro-vascular oxygen delivery to the muscle (Cleland et al., 2012). It was speculated that "*the improved responsiveness of the vascular bed and the improved blood perfusion through vasodilatation mechanisms* (Casey & Joyner, 2012) *could be paramount in RSH*" (Faiss, Girard, et al., 2013). Such intensity-dependent compensatory vasodilation during exercise in hypoxia is mediated through a nitric oxide (NO) pathway. The combination of hypoxia and high shear stress due to increased intensity-dependant blood flow and

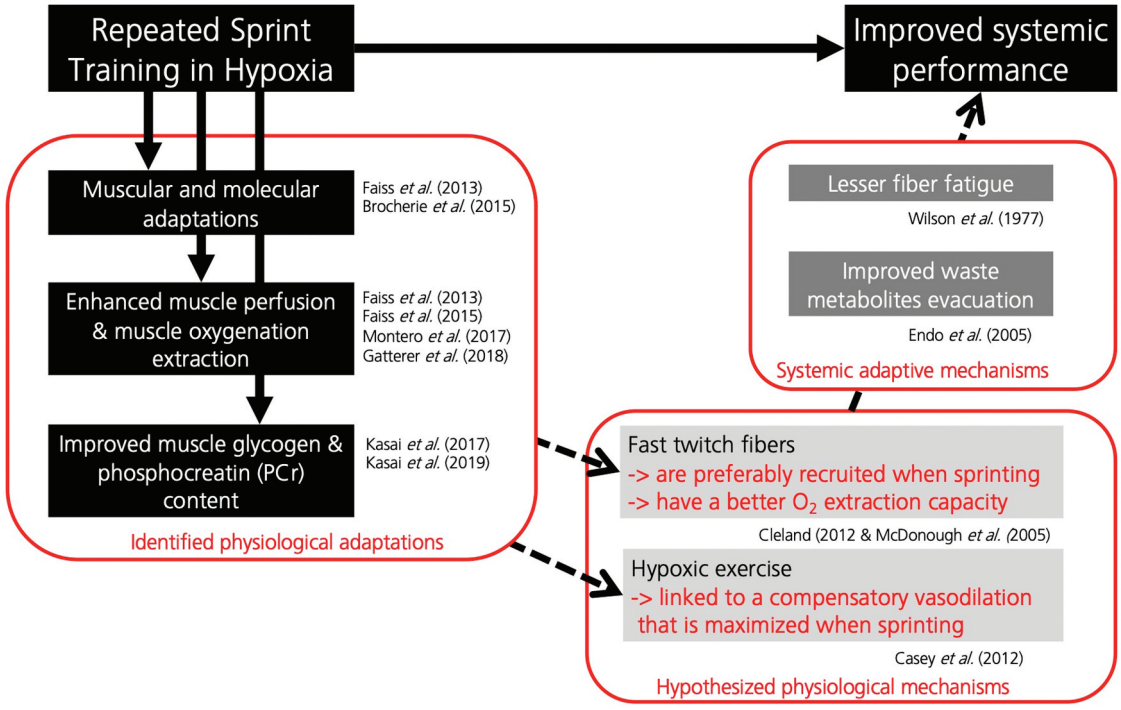

Figure 2. Identified and proposed physiological mechanisms for performance enhancement after RSH.

of the hypoxia has synergistic effects on the endothelial responses, leading to improved capacity in both vascular vasoconstriction and vasodilation, as shown in rodents (Lavier et al., 2021).

Moreover, peripheral vascular effects of nNOS-derived NO were reported during high-speed treadmill with an intensity-dependent mechanism (i.e., no effect at slower speeds) (Copp et al., 2013). Furthermore, when NO bioavailability was increased through nitrate supplementation, blood flow was also enhanced in a fibre-type dependent manner with vascular control and blood flow augmented primarily in FT (but not ST) muscle fibres (Copp et al., 2013) and lower micro-vascular oxygen pressure in contracting FT muscle fibres (Ferguson et al., 2013; McDonough et al., 2005). However, the latter studies were conducted in rodents. Nevertheless, in moderately trained males, a shift in muscle fibre type (towards more FT (type IIa) fibres) was outlined after sprint-interval training in the group who had received a nitrate supplementation only (De Smet et al., 2016). Nitrate therefore seems to exert its action in FT muscle fibres by increasing blood flow when considering supplementation studies in rodents (Hernández et al., 2012) and humans (Coggan et al., 2015). Similarly, there is evidence that muscle oxygenation is improved after nitrate supplementation with an enhanced exercise tolerance only at high but not low pedalling rates in healthy males (Bailey et al., 2015). Furthermore, a limited oxygen supply was reported to "*affect cellular metabolism while the respiratory rate remained relatively unchanged due to compensatory changes*" linked in turn to lesser muscle fibre fatigue (Wilson et al., 1977). A NO-dependent compensatory vasodilation occurring during RSH would hence represent an elegant explanation for the improved oxygen extraction and restoration of oxygen levels observed repeatedly in RSH studies (Faiss et al., 2015; Faiss, Girard, et al., 2013; Gatterer et al., 2018; Montero & Lundby, 2017). The increased muscle perfusion represents a direct indication of an enhanced muscle blood flow that "*may be beneficial (and necessary) in removing metabolic waste products following exercise*" (Endo et al., 2005) (Figure 2).

Interestingly, even if – as explained above – nitrate supplementation and hypoxia exposure may have similar microvascular vasodilatory effects, the combination of these two factors does not induce a larger performance improvement in trained athletes (Sousa et al., 2021, 2022)

4.2. Improved phosphocreatine resynthesis

Besides, the elevated micro-vascular PO_2 related to RSH may in turn allow reducing [PCr] breakdown (Haseler et al., 1999) and potentially speeding up [PCr] recovery kinetics. Faster reoxygenation rates (as illustrated by high amplitude in muscle oxygenation shifts during recoveries between sprints) may help a faster phosphocreatine ([PCr]) resynthesis (McMahon & Jenkins, 2002) and therefore delay muscle fatigue throughout a repeated-sprint exercise.

This hypothesis was investigated with measurements of muscle glycogen and PCr contents were evaluated by carbon magnetic resonance spectroscopy (^{13}C-MRS) and phosphorus magnetic resonance spectroscopy (31P-MRS), respectively, before and after RSH in both male and female athletes (Kasai

et al., 2017, 2019). After only 5 days of repeated-sprint training, muscle glycogen and PCr contents were significantly augmented (Kasai et al., 2017). Hypoxia *per se* had previously been reported to modulate [PCr] resynthesis during exercise (faster [PCr] recovery during a single-leg high-intensity exercise only in hypoxia) (Holliss et al., 2013). Furthermore, intramuscular PCr content was increased specifically after RSH by 21% to support a high power output production in sprint-runners (Kasai et al., 2019). Overall, a faster PCr resynthesis resulting from RSH would manifest as a better maintenance of power production (better recovery between efforts) during intermittent, high-intensity exercises (Endo et al., 2005).

Nevertheless, large shifts in [PCr] can be expected during repeated sprints with a concomitant evident impact on H^+ production (and hence pH). The muscle energy supply (e.g., [PCr] resynthesis) however seems to be the principal effector in power output maintenance during repeated sprints rather than the control of muscle pH (Mendez-Villanueva et al., 2012).

4.3. Transcription factors supporting adaptations towards an improved glycolytic activity

The upregulation of genes (from the messenger RNA (mRNA)) involved in pH regulation was however also reported after RSH (Faiss, Girard, et al., 2013) and sprint-interval training in hypoxia (Puype et al., 2013), leading towards an improved muscle buffer capacity.

mRNA may act as the translator in the protein synthesis machinery in response to a given training stimulus. To avoid flawed analyses, any upregulation of mRNA targets needs to be interpreted carefully. Nevertheless, hypoxia-inducible factors (namely, HIF1-α) are known to be upregulated in response to exercise in hypoxia (Faiss, Léger, et al., 2013; Zoll et al., 2006) and, in particular, in the regulation of genes involved in glycolysis and pH regulation (De Smet et al., 2016). For instance, mRNA expressions for monocarboxylate transporters 1 and 4 (MCT-1 and MCT-4) were inversely regulated after RSH vs. RSN (Faiss, Léger, et al., 2013), suggesting a different adaptive response in the working muscle when repeating sprints in hypoxia. For instance, MCT-4 increased by 20% only after RSH, whereas MCT-1 was decreased after RSH (−36%) but increased after RSN (+26%). During heavy exercise, lactate is transported across the plasma membrane by monocarboxylate transporters where MCT-4 (predominantly expressed in FT anaerobic fibres) has a higher capacity to transport lactate for the extrusion of lactic acid out of the muscle cell (Kobayashi, 2004). Conversely, MCT-1 has a lesser transport capacity (despite higher affinity) of lactate into the skeletal muscle from the circulation. More interestingly, MCT-4 was reported to maintain the functional motor unit by facilitating the lactate efflux, whereas action potential conduction was impaired when downregulated in mice (Bisetto et al., 2019).

Furthermore, hypoxia *per se* alters MCT-4 (but not MCT-1), which was upregulated through a HIF-1α-dependent pathway (Ullah et al., 2006).

Overall, an increase in MCT-4 may allow to delay fatigue after RSH by maintaining the exercise capacity because its upregulation combines hypoxia and intense exercise. If MCT-4 expression is not improved after RSN, it may conversely explain a disruption in the lactate shuttle, leading to earlier muscle fibres' fatigue during RSA (Ullah et al., 2006). Fatigue resistance in FT muscle fibres may also be positively influenced by an increase in carbonic anhydrase III (CA3) (Feng & Jin, 2016) observed only after RSH (Faiss, Léger, et al., 2013).

By extension, RSH likely positively impacts glycolytic performance and skeletal muscle adaptations that could arguably contribute to the improved RSA performance observed in normoxia after RSH (Faiss, Léger, et al., 2013). Finally, adaptive responses specific to RSH were recently highlighted at the muscle level (namely, an S100A/Akt pathway) to mediate downstream targets regulating protein synthesis for skeletal muscle adaptations (Lanfranchi et al., 2024). Specific adaptations for genes and protein expression involved in mitochondrial biogenesis (e.g., peroxisome proliferator-activated receptor coactivator 1α (PGC-1α) and angiogenesis (e.g., vascular endothelial growth factor (VEGF)) in the presence of a stabilization of HIF-1α were hence reported through exercise alone (RSN) or in combination with hypoxia (RSH) (Lanfranchi et al., 2024). Conversely, reduced oxidative phosphorylation protein levels in response to RSN and RSH training were observed. From the latter study, it is still unclear if RSH differently alters muscle glycolytic or oxidative adaptations as compared to RSN while the involvement of the S100A13/Akt pathway in the increase in muscle mass and glycolytic fate in response to RSH is suggested.

4.4. Minimal adaptations to improve aerobic capacity

Conversely, gains in the aerobic capacity seem less likely to occur after RSH (Brocherie et al., 2017). For instance, in a rare study assessing mitochondrial respiration of peripheral blood mononuclear cells (high-resolution respirometry), RSH was speculated to have a negative impact on mitochondrial function due to excess reactive oxygen species (ROS) production (Gatterer et al., 2018), in accordance with the downregulation of mRNA expression of genes implicated in mitochondrial biogenesis after RSH (Faiss, Léger, et al., 2013). In contrast, several studies have however reported additional benefits after RSH for high-intensity endurance capacity (i.e., Yo-Yo intermittent recovery level 1 test) (Galvin et al., 2013; Gatterer et al., 2014, 2015; Hamlin et al., 2017; Shi et al., 2023), suggesting that RSH may ad minima not exert a negative effect on the endurance capacity while not being adequate for specifically improving it.

5. Additional perspectives on the implementation of RSH in athletes

Overall, RSH may improve performance in a fibre-type selective and intensity-dependent manner, with mechanisms presumably different than those associated with other (less intense) hypoxic training strategies.

Further studies are however requested to clarify if RSH may be used as an effective pre-acclimatization strategy prior exposure and/or competition at high altitude.

Nevertheless, both vascular and muscle molecular mechanisms seem to combine in a specific manner that is neither observed in normoxia nor at low intensity.

Despite contentious underpinning physiological mechanisms needing further research, RSH may definitely be implemented safely, in lack of any reported negative mechanism with benefits for team sports like football, rugby union or Australian football, where the ability to repeat high speed runs during an entire game is essential for overall performance (Gray & Jenkins, 2010; Hills et al., 2024).

Besides, like any other training strategy, RSH "*requires sport-specific adjustment in length/duration of sprint and recovery intervals, exercise:recovery ratio, and session frequency*"(Brocherie et al., 2017).

This was thoroughly investigated in several cross-sectional studies reporting the acute effects of RSH with varying sprint durations and exercise-to-rest ratios (Raberin, Elmer, et al., 2023; Raberin, Willis, et al., 2023; Tong et al., 2021) or different hypoxia severity levels (Goods et al., 2014; Gutknecht et al., 2022; Warnier et al., 2020).

5.1. Sport-specific RSH

One may question the interest in rugby players to pedal on a cycle ergometer or perform double-poling sprints at 3000 m for performance improvements on the pitch. In contrast, cycling sprints in heavy athletes may allow to avoid the heavy mechanical strain at the musculo-skeletal level during running acceleration, deceleration or changes of direction. In international-level professional players, RSH "*appears of practical relevance since only a short preparation window is available prior to international games, although the improvement from RSA to game behaviour remains unclear*" (Beard, Ashby, Chambers, et al., 2019; Beard, Ashby, Kilgallon, et al., 2019). The practicality of such short blocks (i.e., only few sessions) of RSH has been emphasized by several experts in team sports (Brocherie, Millet, et al., 2015) with valid transfer of cycling sprints for on-field performance (Brocherie et al., 2023)

Similar results were reported after RSH on a cycle ergometer with 19 rugby players, with reduced fatigue during RSA but also gains during an intermittent aerobic test (Yo-Yo intermittent recovery level 1) (Hamlin et al., 2017). Sprint runners also benefited from cycling RSH to improve the explosive running power (i.e., faster 0–10 m running time) (Kasai et al., 2019).

The extent to which a given form of RSH transfers into team-sport or any other sport-specific performance certainly remains to be elucidated. Nevertheless, the amplitude of performance gains after RHS appeared to be largest when sport-specific (e.g., with double-poling for XC skiers or shuttle-runs for tennis players) training (and testing) was possible (Brechbuhl et al., 2020; Faiss et al., 2015). The training load associated with RSH also needs to be considered since it may represent a very intense (and unusual) strategy for some athletes. To that extent, when RSH is added in addition to an existing training programme (i.e., as "top-up" training sessions), overall effects may be blunted due to cumulated fatigue (Hamlin et al., 2017).

5.2. Initial sporting level and sex for positive adaptations

There are numerous studies reporting benefits for a given training method when including initially untrained subjects. Interestingly, benefits from RSH are reported indifferently from sedentary (Kong et al., 2022) or untrained subjects (Piperi et al., 2024) to professional athletes (Beard, Ashby, Chambers, et al., 2019; Beard, Ashby, Kilgallon, et al., 2019; Brechbuhl, Schmitt, et al., 2018; Brocherie et al., 2024; Brocherie, Millet, et al., 2015).

Highly trained athletes may for instance have better physiological capacities to potentiate muscular adaptive mechanisms resulting from maximal efforts disrupting muscle metabolism (Gatterer et al., 2018).

Beyond any particular physiological adaptations, RSH may have initially represented a cutting-edge strategy unknown or not implemented by competitors, thus providing some psychological advantage. RSH may definitely allow for an interesting and novel training challenge in highly trained professional athletes who seem to cope very well with the requirements of repeated maximal efforts (Brechbuhl, Schmitt, et al., 2018; Faiss & Rapillard, 2020).

Furthermore, positive outcomes were found independently of the sex of the participants in several studies including female athletes with no sex differences when both male and females were included in the same study (Brechbuhl et al., 2020; Brocherie et al., 2023; Kasai et al., 2015; Kong et al., 2022; Piperi et al., 2024). In that context, repeated sprint ability and the Yo-Yo intermittent recovery level 1 test were recently shown not to be affected by the menstrual cycle in high-level female football players (Tounsi et al., 2018). Taken together, these results support the use of RSH independently of the sex of the athletes, keeping in mind the need to individually assess the response to the training load and hypoxic stimulus.

5.3. Optimal sprint duration and exercise-to-rest ratio during RSH

Recent studies investigated the acute performance and psychophysiological responses of repeated cycling sprints to exhaustion with different sprint durations and different exercise-to-rest ratios (1:6) between different effort durations and inspired oxygen fractions (Raberin, Elmer, et al., 2023; Raberin, Willis, et al., 2023). Sprint duration represented the primary factor eliciting differences in performance and muscle oxygenation. When considering the factors contributing to fatigue during RSA, sprints lasting between 5 and 12 s seem adequate to balance power maintenance and factors limiting performance (Girard et al., 2011). During a given timeframe, shorter sprints may then allow to produce a higher number of repetitions with more frequent transitions between sprints and recoveries triggering a related reoxygenation and PCR resynthesis. For example, sets of 6-s sprints interspersed with 14-s recoveries were successfully implemented in a professional cyclists, allowing to perform 150 sprints in only five training sessions (Faiss & Rapillard 2020). Besides, "*hypoxia did not modify repeated-sprint exercise performance with a short exercise-to-rest ratio*" (Raberin, Willis, et al., 2023), while the outcome was different with a higher ratio (1:2) (Raberin, Elmer, et al., 2023). Conversely, some studies investigated sprint-interval training (i.e., with 30 s sprints and 270 s recovery phases, exercise-to-rest ratio = 1:9) with performance outcomes differing largely from RSH studies (De Smet et al., 2017; Puype et al., 2013). Positive mechanisms after RSH are likely suggested

in the studies presented in this review (Table 1) that all used exercise-to-rest ratios varying from 1:1 to 1:7. A recent study combining a prolonged hypoxic exposure with RSH reported that higher exercise-to-rest ratios (i.e., 1:5 vs. 1:2) appeared to be more effective for performance improvements (Bouten et al., 2023). From the latter mechanisms presented earlier, the aims for RSH are hence twofold: first, to maintain maximal power output during sprinting in hypoxia and, second, to trigger adaptations due to incomplete recovery phases. Conclusively and based on the above, the nature of the recovery between repetitions and sets (e.g., passive rest or active recovery) needs to be practically considered to repeatedly allow for a maximal recruitment of fast twitch fibres during sprints and for a rapid increase in muscle perfusion during recoveries (Figure 2). Practical considerations on the type of equipment used (cycle ergometer, motorized or non-motorized treadmill, and double-poling ergometer) also need to be considered when designing session by the setup of an adequate resistance and evaluating the time required to reach peak power.

5.4. Optimal hypoxic stimulus – hypoxia severity level

Hypoxia *per se* is known to affect cerebral oxygenation and may impair RSA (Smith & Billaut, 2010). A comprehensive review concluded that "*larger alterations in RSA (i.e., with earlier and larger performance decrements) occur at altitudes above ~3000 m or inspired fraction of oxygen < 14.4% than at lower elevations*" (Girard et al., 2017). When RSA performance was compared across three different altitudes (i.e., 2000 m, 3000 m, and 4000 m), the absolute training quality was reported to be potentially blunted at the highest altitude (Goods et al., 2014). In accordance, a study comparing RSH with or without additional local blood flow restriction outlined a larger impairment when O_2 availability was too low (Solsona et al., 2024). The absence of additional gain after RSH at a simulated altitude of 5000 m (Brocherie et al., 2024) definitely suggests that "*higher may not necessarily be better*". It is therefore safe to conclude that a moderate simulated altitude (~3000–4000 m) shall be employed, targeting arterial O_2 desaturation levels between 70 and 85% as found in the current RSH studies with positive outcomes. Monitoring arterial O_2 saturation (i.e., SpO_2) may represent a useful yet simple tool to assess the magnitude of individual responses to the hypoxic challenge (Soo et al., 2020), allowing to determine an optimal altitude level (starting from 1500 m) (Gutknecht et al., 2022). Hypoxic conditions and exercise-to-rest ratios are nevertheless paramount when designing an optimal RSH training intervention (Millet & Faiss, 2012).

5.5. Technology and practical considerations for RSH protocols

RSH requires a hypoxic environment allowing to reduce O_2 convection towards the working muscle. There is therefore no limitation in implementing RSH in hypobaric hypoxia (e.g., terrestrial altitude) beyond practical consideration on the logistical and time constraints to reach an adequate altitude. Then, evidence exists for differences between hypobaric and normobaric hypoxia (NH) (Millet et al., 2013), while most of the studies on RSH have been conducted (successfully) in NH (i.e., simulated altitude). The use of hypoxic chambers allows several athletes to train in hypoxia at the same time while maintaining (or adjusting) a stable hypoxic environment. The use of masks connected to smaller hypoxic generators (normally used for hypoxic tents) is possible while a large buffer bag shall be used with a three-way valve (to avoid CO_2 rebreathing) as long as they can cope with the large amount of hypoxic air required during sprinting blocks due to the high minute ventilation observed at maximal intensity in elite athletes. A large arterial O_2 desaturation level can be used as an indicator of the hypoxic stimulus.

Besides, arterial desaturation may also be induced by specific breathing techniques (namely, voluntary hypoventilation at low lung volume (VHL)). However, unlike RSH, VHL also leads to hypercapnia and elevated blood bicarbonate concentration possibly leading to other physiological adaptations (e.g., buffering capacity). Studies on VHL with repeated sprints were therefore not included in the present review, while the potential of VHL in conjunction with RSH for performance improvement shall be of interest in future research.

6. Conclusion

RSH was proposed 10 years ago as a promising training strategy in intermittent sports to eventually positively influence physical qualities for match-related performance. Delaying fatigue with an improved ability to repeat sprints therefore represents a key component of team-sport performance characterized by intense exercise bouts repeated throughout a game. To date, there is more ample evidence for additional benefits of RSH compared to RSN on subsequent RSA performance. Some pertinent mechanisms (intensity-dependent vasodilation in hypoxia and potential fibre-selective effects) underpinning RSH-induced performance gains were suggested but investigated only scarcely. Despite a lack of systematic mechanistic evidence for improvements after RSH due to peripheral adaptations at the muscle level, the mechanisms proposed in this review support the efficiency of RSH to improve systemic athletic performance. Since 2013, benefits linked to RSH could be confirmed as likely fibre-type selective, with positive adaptations probably dependent on specific microvascular effects in FT fibres' behaviour.

Controversial results with no added benefits for RSH vs. RSN were reported in 5 out of 22 studies warranting further research focusing on adequate hypoxic stimulus, optimal exercise-to-rest ratio and pertinent periodization to confirm the true usefulness of RSH. None of the studies in this review however reported either lesser gains after RSH compared to RSN or negative mechanisms when hypoxia was added to a repeated-sprint training regimen.

Overall, a growing body of evidence in the field supports the efficacy of RSH when implemented in ecological sport-specific situations with a high exercise-to-rest ratio at a moderate (~3000 m) simulated (or real) altitude.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

The author(s) reported that there is no funding associated with the work featured in this article.

ORCID

Raphaël Faiss http://orcid.org/0000-0001-6029-9516
Antoine Raberin http://orcid.org/0000-0001-5032-8301
Franck Brocherie http://orcid.org/0000-0002-0808-7986
Grégoire P. Millet http://orcid.org/0000-0001-8081-4423

Author contributions

RF, AR, FB and GPM conceptualized and designed the study. RF drafted the first version of the manuscript. All authors then contributed to the interpretation of the data, critically revising the manuscript for its intellectual content. All authors gave approval for the final version of this work to be published, being accountable for all aspects of the work.

References

Bailey, S. J., Varnham, R. L., DiMenna, F. J., Breese, B. C., Wylie, L. J., & Jones, A. M. (2015). Inorganic nitrate supplementation improves muscle oxygenation, O 2 uptake kinetics, and exercise tolerance at high but not low pedal rates. *Journal of Applied Physiology*, *118*(11), 1396–1405. https://doi.org/10.1152/japplphysiol.01141.2014

Balsom, P. D., Gaitanos, G. C., Ekblom, B., & Sjodin, B. (1994). Reduced oxygen availability during high intensity intermittent exercise impairs performance. [research support, non-U.S. Gov't]. *Acta Physiologica Scandinavica*, *152*(3), 279–285. https://doi.org/10.1111/j.1748-1716.1994.tb09807.x

Bangsbo, J., Iaia, F. M., & Krustrup, P. (2008). The Yo-Yo intermittent recovery test: A useful tool for evaluation of physical performance in intermittent sports. *Sports Medicine*, *38*(1), 37–51. https://doi.org/10.2165/00007256-200838010-00004

Beard, A., Ashby, J., Chambers, R., Brocherie, F., & Millet, G. P. (2019). Repeated-sprint training in hypoxia in international rugby union players. *International Journal of Sports Physiology & Performance*, *14*(6), 850–854. https://doi.org/10.1123/ijspp.2018-0170

Beard, A., Ashby, J., Kilgallon, M., Brocherie, F., & Millet, G. P. (2019). Upper-body repeated-sprint training in hypoxia in international rugby union players. *European Journal of Sport Science*, *19*(9), 1175–1183. https://doi.org/10.1080/17461391.2019.1587521

Birol, A., Aras, D., Akalan, C., Aldhahi, M. I., & Gülü, M. (2024). Three sessions of repeated sprint training in normobaric hypoxia improves sprinting performance. *Heliyon*, *10*(6), e27607. https://doi.org/10.1016/j.heliyon.2024.e27607

Bisetto, S., Wright, M. C., Nowak, R. A., Lepore, A. C., Khurana, T. S., Loro, E., & Philp, N. J. (2019). New insights into the lactate shuttle: Role of MCT4 in the modulation of the exercise capacity. *iScience*, *22*, 507–518. https://doi.org/10.1016/j.isci.2019.11.041

Bishop, D., Girard, O., & Mendez-Villanueva, A. (2011). Repeated-sprint ability – part II. *Sports Medicine*, *41*(9), 741–756. https://doi.org/10.2165/11590560-000000000-00000

Bouten, J., Brick, M., Saboua, A., Hadjadj, J. L., Piscione, J., Margot, C., & Brocherie, F. (2023). Effects of 2 different protocols of repeated-sprint training in hypoxia in elite female rugby sevens players during an altitude training camp. *International Journal of Sports Physiology & Performance*, *18*(9), 953–959. https://doi.org/10.1123/ijspp.2023-0121

Brechbuhl, C., Brocherie, F., Millet, G. P., & Schmitt, L. (2018). Effects of repeated-sprint training in hypoxia on tennis-specific performance in well-trained players. *Sports Medicine International Open*, *2*(5), E123–e132. https://doi.org/10.1055/a-0719-4797

Brechbuhl, C., Brocherie, F., Willis, S. J., Blokker, T., Montalvan, B., Girard, O., & Schmitt, L. (2020). On the use of the repeated-sprint training in hypoxia in tennis. *Frontiers in Physiology*, *11*, 13. https://doi.org/10.3389/fphys.2020.588821

Brechbuhl, C., Schmitt, L., Millet, G. P., & Brocherie, F. (2018). Shock microcycle of repeated-sprint training in hypoxia and tennis performance: Case study in a rookie professional player. *International Journal of Sports Science & Coaching*, *13*(5), 723–728. https://doi.org/10.1177/1747954118783586

Brocherie, F., Girard, O., Faiss, R., & Millet, G. P. (2015). High-intensity intermittent training in hypoxia: A double-blinded, placebo-controlled field study in youth football players. *The Journal of Strength & Conditioning Research*, *29*(1), 226–237. https://doi.org/10.1519/jsc.0000000000000590

Brocherie, F., Girard, O., Faiss, R., & Millet, G. P. (2017). Effects of repeated-sprint training in hypoxia on sea-level performance: A meta-analysis. *Sports Medicine*, *47*(8), 1651–1660. https://doi.org/10.1007/s40279-017-0685-3

Brocherie, F., Millet, G. P., Hauser, A., Steiner, T., Rysman, J., Wehrlin, J. P., & Girard, O. (2015). "Live High-train Low and High" hypoxic training improves team-sport performance. *Medicine & Science in Sports and Exercise*, *47*(10), 2140–2149. https://doi.org/10.1249/mss.0000000000000630

Brocherie, F., Racinais, S., Cocking, S., Townsend, N., Couderc, A., Piscione, J., & Girard, O. (2023). Repeated-sprint training at 5000-m simulated altitude in preparation for the world Rugby Women's sevens series: Too high? *Medicine & Science in Sports and Exercise*, *55*(10), 1923–1932. https://doi.org/10.1249/mss.0000000000003226

Brocherie, F., Racinais, S., Couderc, A., Piscione, J., & Girard, O. (2024). Four sessions of repeated-sprint cycling training with or without severe hypoxia do not modify overground running sprint force-velocity profile. *International Journal of Sports Physiology & Performance*, *19*(1), 80–83. https://doi.org/10.1123/ijspp.2023-0112

Brosnan, M. J., Martin, D. T., Hahn, A. G., Gore, C. J., & Hawley, J. A. (2000). Impaired interval exercise responses in elite female cyclists at moderate simulated altitude. *Journal of Applied Physiology*, *89*(5), 1819–1824. https://doi.org/10.1152/jappl.2000.89.5.1819

Calbet, J. A. L., & Lundby, C. (2009). Air to muscle O(2) delivery during exercise at altitude. *High Altitude Medicine & Biology*, *10*(2), 123–134. https://doi.org/10.1089/Ham.2008.1099

Camacho-Cardenosa, M., Camacho-Cardenosa, A., González-Custodio, A., Zapata, V., & Olcina, G. (2020). Effects of swimming-specific repeated-sprint training in Hypoxia training in swimmers. *Frontiers in Sports and Active Living*, *2*, 7. https://doi.org/10.3389/fspor.2020.00100

Casey, D. P., & Joyner, M. J. (2012). Compensatory vasodilatation during hypoxic exercise: Mechanisms responsible for matching oxygen supply to demand. *Journal of Physiology, Paris*, *590*(24), 6321–6326. https://doi.org/10.1113/jphysiol.2012.242396

Cleland, S. M., Murias, J. M., Kowalchuk, J. M., & Paterson, D. H. (2012). Effects of prior heavy-intensity exercise on oxygen uptake and muscle deoxygenation kinetics of a subsequent heavy-intensity cycling and knee-extension exercise. *Applied Physiology, Nutrition, and Metabolism*, *37*(1), 138–148. https://doi.org/10.1139/h11-143

Coggan, A. R., Leibowitz, J. L., Kadkhodayan, A., Thomas, D. P., Ramamurthy, S., Spearie, C. A., & Peterson, L. R. (2015). Effect of acute dietary nitrate intake on maximal knee extensor speed and power in healthy men and women. *Nitric Oxide: Biology & Chemistry / Official Journal of the Nitric Oxide Society*, *48*, 16–21. https://doi.org/10.1016/j.niox.2014.08.014

Copp, S. W., Holdsworth, C. T., Ferguson, S. K., Hirai, D. M., Poole, D. C., & Musch, T. I. (2013). Muscle fibre-type dependence of neuronal nitric oxide synthase-mediated vascular control in the rat during high speed treadmill running. *Journal of Physiology, Paris*, *591*(11), 2885–2896. https://doi.org/10.1113/jphysiol.2013.251082

De Smet, S., van Herpt, P., D'Hulst, G., Van Thienen, R., Van Leemputte, M., & Hespel, P. (2017). Physiological adaptations to hypoxic vs. Normoxic training during intermittent living high. *Frontiers in Physiology*, *8*, 347. https://doi.org/10.3389/fphys.2017.00347

De Smet, S., Van Thienen, R., Deldicque, L., James, R., Sale, C., Bishop, D. J., & Hespel, P. (2016). Nitrate intake promotes shift in muscle fiber type composition during sprint interval training in hypoxia. *Frontiers in Physiology*, *7*, 233. https://doi.org/10.3389/fphys.2016.00233

Dufour, S. P., Ponsot, E., Zoll, J., Doutreleau, S., Lonsdorfer-Wolf, E., Geny, B., & Lonsdorfer, J. (2006). Exercise training in normobaric hypoxia in endurance runners. I. Improvement in aerobic performance capacity. *Journal of Applied Physiology*, *100*(4), 1238–1248. https://doi.org/10.1152/japplphysiol.00742.2005

Endo, M., Okada, Y., Rossiter, H. B., Ooue, A., Miura, A., Koga, S., & Fukuba, Y. (2005). Kinetics of pulmonary $\dot{v} \hbox{O}_{2}$ and femoral artery blood flow and their relationship during repeated bouts of heavy exercise. *European Journal of Applied Physiology*, *95*(5–6), 418–430. https://doi.org/10.1007/s00421-005-0051-2

Faiss, R., Girard, O., & Millet, G. P. (2013). Advancing hypoxic training in team sports: From intermittent hypoxic training to repeated sprint training in hypoxia. *British Journal of Sports Medicine*, *47*(Suppl 1), i45–i50. https://doi.org/10.1136/bjsports-2013-092741

Faiss, R., Léger, B., Vesin, J. M., Fournier, P. E., Eggel, Y., Dériaz, O., Millet, G. P., & Vinciguerra, M. (2013). Significant molecular and systemic adaptations after repeated sprint training in hypoxia. *PLOS ONE*, *8*(2), 13. https://doi.org/10.1371/journal.pone.0056522

Faiss, R., & Rapillard, A. (2020). Repeated sprint training in Hypoxia: Case report of performance benefits in a professional Cyclist. *Frontiers in Sports and Active Living*, *2*, 7. https://doi.org/10.3389/fspor.2020.00035

Faiss, R., & Rapillard, A. (2020). Repeated sprint training in hypoxia: Case report of performance benefits in a professional cyclists. *Frontiers in Sports and Active Living*, *2*(7).

Faiss, R., Willis, S., Born, D. P., Sperlich, B., Vesin, J. M., Holmberg, H. C., & Millet, G. P. (2015). Repeated double-poling sprint training in hypoxia by competitive cross-country skiers. *Medicine & Science in Sports and Exercise*, *47*(4), 809–817. https://doi.org/10.1249/mss.0000000000000464

Feng, & Jin, J. P. (2016). Carbonic anhydrase III is expressed in mouse skeletal muscles independent of fiber type-specific myofilament protein isoforms and plays a role in fatigue resistance. *Frontiers in Physiology*, *7*, 597. https://doi.org/10.3389/fphys.2016.00597

Ferguson, S. K., Hirai, D. M., Copp, S. W., Holdsworth, C. T., Allen, J. D., Jones, A. M., & Poole, D. C. (2013). Impact of dietary nitrate supplementation via beetroot juice on exercising muscle vascular control in rats. *Journal of Physiology, Paris*, *591*(2), 547–557. https://doi.org/10.1113/jphysiol.2012.243121

Galvin, H. M., Cooke, K., Sumners, D. P., Mileva, K. N., & Bowtell, J. L. (2013). Repeated sprint training in normobaric hypoxia. *British Journal of Sports Medicine*, *47*(Suppl 1), 74–79. https://doi.org/10.1136/bjsports-2013-092826

Garvican, L. A., Hammond, K., Varley, M. C., Gore, C. J., Billaut, F., & Aughey, R. J. (2013). Lower running performance and exacerbated fatigue in soccer played at 1600 m. *International Journal of Sports Physiology & Performance*, *9*(3), 397–404. https://doi.org/10.1123/ijspp.2012-0375

Garvican-Lewis, L. A., Sharpe, K., & Gore, C. J. (2016). Time for a new metric for hypoxic dose? *Journal of Applied Physiology: Respiratory, Environmental and Exercise Physiology*, (1985), 00579 02015. https://doi.org/10.1152/japplphysiol.00579.2015

Gatterer, H., Klarod, K., Heinrich, D., Schlemmer, P., Dilitz, S., & Burtscher, M. (2015). Effects of a 12-day maximal shuttle-run shock microcycle in hypoxia on soccer specific performance and oxidative stress. *Applied Physiology, Nutrition, and Metabolism*, *40*(8), 842–845. https://doi.org/10.1139/apnm-2014-0479

Gatterer, H., Menz, V., Salazar-Martinez, E., Sumbalova, Z., Garcia-Souza, L. F., Velika, B., & Burtscher, M. (2018). Exercise performance, muscle oxygen extraction and blood cell mitochondrial respiration after repeated-sprint and sprint interval training in Hypoxia: A Pilot study. *Journal of Sports Science & Medicine*, *17*(3), 339–347.

Gatterer, H., Philippe, M., Menz, V., Mosbach, F., Faulhaber, M., & Burtscher, M. (2014). Shuttle-Run sprint Training in hypoxia for youth elite soccer players: A Pilot study. *Journal of Sports Science & Medicine*, *13*(4), 731–735.

Girard, O., Brocherie, F., & Millet, G. P. (2017). Effects of Altitude/Hypoxia on single- and multiple-sprint performance: A comprehensive review. *Sports Medicine*, *47*(10), 1931–1949. https://doi.org/10.1007/s40279-017-0733-z

Girard, O., Mendez-Villanueva, A., & Bishop, D. (2011). Repeated-sprint ability - part I factors contributing to fatigue. *Sports Medicine*, *41*(8), 673–694. https://doi.org/10.2165/11590550-000000000-00000

Goods, P. S. R., Dawson, B., Landers, G. J., Gore, C. J., & Peeling, P. (2015). No additional benefit of Repeat-Sprint training in hypoxia than in Normoxia on sea-level repeat-Sprint ability. *Journal of Sports Science & Medicine*, *14*(3), 681–688.

Goods, P. S. R., Dawson, B. T., Landers, G. J., Gore, C. J., & Peeling, P. (2014). Effect of different simulated altitudes on repeat-sprint performance in team-sport athletes. *International Journal of Sports Physiology & Performance*, *9*(5), 857–862. https://doi.org/10.1123/ijspp.2013-0423

Gray, A. J., & Jenkins, D. G. (2010). Match analysis and the physiological demands of Australian football. *Sports Medicine*, *40*(4), 347–360. https://doi.org/10.2165/11531400-000000000-00000

Gutknecht, A. P., Gonzalez-Figueres, M., Brioche, T., Maurelli, O., Perrey, S., & Favier, F. B. (2022). Maximizing anaerobic performance with repeated-sprint training in hypoxia: In search of an optimal altitude based on pulse oxygen saturation monitoring. *Frontiers in Physiology*, *13*, 12. https://doi.org/10.3389/fphys.2022.1010086

Hamlin, M. J., Olsen, P. D., Marshall, H. C., Lizamore, C. A., & Elliot, C. A. (2017). Hypoxic repeat sprint training improves Rugby player's repeated sprint but not endurance performance. *Frontiers in Physiology*, *8*, 10. https://doi.org/10.3389/fphys.2017.00024

Haseler, L. J., Hogan, M. C., & Richardson, R. S. (1999). Skeletal muscle phosphocreatine recovery in exercise-trained humans is dependent on O2 availability. *Journal of Applied Physiology*, *86*(6), 2013–2018. https://doi.org/10.1152/jappl.1999.86.6.2013

Hernández, A., Schiffer, T. A., Ivarsson, N., Cheng, A. J., Bruton, J. D., Lundberg, J. O., & Westerblad, H. (2012). Dietary nitrate increases tetanic [Ca2+]i and contractile force in mouse fast-twitch muscle. *Journal of Physiology, Paris*, *590*(15), 3575–3583. https://doi.org/10.1113/jphysiol.2012.232777

Hills, S. P., Izri, E., Howells, D., Lonergan, B., Kilduff, L. P., Waldron, M., & Arslan, E. (2024). Assessing the locomotor demands of international men's and women's rugby sevens match-play according to passage of play. *PLOS ONE*, *19*(6), e0304186. https://doi.org/10.1371/journal.pone.0304186

Holliss, B. A., Fulford, J., Vanhatalo, A., Pedlar, C. R., & Jones, A. M. (2013). Influence of intermittent hypoxic training on muscle energetics and exercise tolerance. *Journal of Applied Physiology: Respiratory, Environmental and Exercise Physiology*, *114*(5), 611–619. https://doi.org/10.1152/japplphysiol.01331.2012

Hoppeler, H., & Vogt, M. (2001). Muscle tissue adaptations to hypoxia. *Journal of Experimental Biology*, *204*(18), 3133–3139. https://doi.org/10.1242/jeb.204.18.3133

Huang, Z., Yang, S., Li, C., Xie, X., & Wang, Y. (2023). The effects of intermittent hypoxic training on the aerobic capacity of exercisers: A systemic review and meta-analysis. *BMC Sports Science, Medicine and Rehabilitation*, *15*(1), 174. https://doi.org/10.1186/s13102-023-00784-3

Impellizzeri, F. M., Rampinini, E., & Marcora, S. M. (2005). Physiological assessment of aerobic training in soccer. *Journal of Sports Sciences*, *23*(6), 583–592. https://doi.org/10.1080/02640410400021278

Kasai, N., Kojima, C., Sumi, D., Takahashi, H., Goto, K., & Suzuki, Y. (2017). Impact of 5 days of sprint training in hypoxia on performance and muscle energy substances. *International Journal of Sports Medicine*, *38*(13), 983–991. https://doi.org/10.1055/s-0043-117413

Kasai, N., Mizuno, S., Ishimoto, S., Sakamoto, E., Maruta, M., & Goto, K. (2015). Effect of training in hypoxia on repeated sprint performance in female athletes. *Springer Plus*, *4*(1), 7. https://doi.org/10.1186/s40064-015-1041-4

Kasai, N., Mizuno, S., Ishimoto, S., Sakamoto, E., Maruta, M., Kurihara, T., & Goto, K. (2019). Impact of six consecutive days of sprint training in hypoxia on performance in competitive sprint runners. *The Journal of Strength & Conditioning Research*, *33*(1), 36–43. https://doi.org/10.1519/jsc.0000000000001954

Kobayashi, M. (2004). Fiber type-specific localization of monocarboxylate transporters MCT1 and MCT4 in rat skeletal muscle. *The Kurume Medical Journal*, *51*(3/4), 253–261. https://doi.org/10.2739/kurumemedj.51.253

Kong, Z. W., Lei, O. K., Sun, S. Y., Li, L., Shi, Q. D., Zhang, H. F., & Nie, J. L. (2022). Hypoxic repeated sprint interval training improves cardiorespiratory fitness in sedentary young women. *Journal of Exercise Science & Fitness*, *20*(2), 100–107. https://doi.org/10.1016/j.jesf.2022.01.005

Lanfranchi, C., Willis, S. J., Laramée, L., Alonso, S. C., Pialoux, V., Kayser, B., & Zanou, N. (2024). Repeated sprint training in hypoxia induces specific skeletal muscle adaptations through S100A protein signaling. *FASEB Journal*, *38*(8), 16. https://doi.org/10.1096/fj.202302084RR

Laughlin, M. H., & Armstrong, R. B. (1982). Muscular blood flow distribution patterns as a function of running speed in rats. *The American Journal of Physiology*, *243*(2), H296–306. https://doi.org/10.1152/ajpheart.1982.243.2.H296

Laursen, P. B., & Jenkins, D. G. (2002). The scientific basis for high-intensity interval training: Optimising training programmes and maximising performance in highly trained endurance athletes. *Sports Medicine*, *32*(1), 53–73. https://doi.org/10.2165/00007256-200232010-00003

Lavier, J., Beaumann, M., Menetrey, S., Bouzourene, K., Rosenblatt-Velin, N., Pialoux, V., & Millet, G. P. (2021). High-intensity exercise in hypoxia improves endothelial function via increased nitric oxide bioavailability in C57BL/6 mice. *Acta Physiologica*, *233*(2), e13700. https://doi.org/10.1111/apha.13700

Levine, B. D. (2002). Intermittent hypoxic training: Fact and fancy. *High Altitude Medicine & Biology*, *3*(2), 177–193. https://doi.org/10.1089/15270290260131911

Lundby, C., Calbet, J. A., & Robach, P. (2009). The response of human skeletal muscle tissue to hypoxia. *Cellular and Molecular Life Sciences*, *66*(22), 3615–3623. https://doi.org/10.1007/s00018-009-0146-8

Lundby, C., Millet, G. P., Calbet, J. A., Bartsch, P., & Subudhi, A. W. (2012). Does 'altitude training' increase exercise performance in elite athletes? *British Journal of Sports Medicine*, *46*(11), 792–795. https://doi.org/10.1136/bjsports-2012-091231

McDonough, P., Behnke, B. J., Padilla, D. J., Musch, T. I., & Poole, D. C. (2005). Control of microvascular oxygen pressures in rat muscles comprised of different fibre types. *Journal of Physiology, Paris*, *563*(3), 903–913. https://doi.org/10.1113/jphysiol.2004.079533

McKay, A. K. A., Stellingwerff, T., Smith, E. S., Martin, D. T., Mujika, I., Gooseyy-Tolfrey, V. L., & Burke, L. M. (2022). Defining training and performance caliber: A participant classification framework. *International Journal of Sports Physiology & Performance*, *17*(2), 317–331. https://doi.org/10.1123/ijspp.2021-0451

McLean, B. D., Gore, C. J., & Kemp, J. (2014). Application of 'live low-train high' for enhancing normoxic exercise performance in team sport athletes. *Sports Medicine*, *44*(9), 1275–1287. https://doi.org/10.1007/s40279-014-0204-8

McMahon, S., & Jenkins, D. (2002). Factors affecting the rate of phosphocreatine resynthesis following intense exercise. *Sports Medicine*, *32*(12), 761–784. https://doi.org/10.2165/00007256-200232120-00002

Mendez-Villanueva, A., Edge, J., Suriano, R., Hamer, P., Bishop, D., & Earnest, C. P. (2012). The recovery of repeated-sprint exercise is associated with PCr resynthesis, while muscle pH and EMG amplitude remain depressed. [research support, non-U.S. Gov't]. *PLOS ONE*, *7*(12), e51977. https://doi.org/10.1371/journal.pone.0051977

Millet, G. P., & Faiss, R. (2012). Hypoxic conditions and exercise-to-rest ratio are likely paramount. *Sports Medicine*, *42*(12), 1081–1083. https://doi.org/10.1007/bf03262313

Millet, G. P., Faiss, R., & Pialoux, V. (2013). Evidence for differences between hypobaric and normobaric hypoxia is conclusive. *Exercise and Sport Sciences Reviews*, *41*(2), 133. https://doi.org/10.1097/JES.0b013e318271a5e1

Millet, G. P., Girard, O., Beard, A., & Brocherie, F. (2019). Repeated sprint training in Hypoxia? An innovative method. *Deutsche Zeitschrift f¸r Sportmedizin*, *70*(5), 115–122. https://doi.org/10.5960/dzsm.2019.374

Millet, G. P., Roels, B., Schmitt, L., Woorons, X., & Richalet, J. P. (2010). Combining hypoxic methods for peak performance. *Sports Medicine*, *40*(1), 1–25. https://doi.org/10.2165/11317920-000000000-00000

Mohr, M., Krustrup, P., & Bangsbo, J. (2005). Fatigue in soccer: A brief review. *Journal of Sports Sciences*, *23*(6), 593–599. https://doi.org/10.1080/02640410400021286

Montero, D., & Lundby, C. (2017). No improved performance with repeated-sprint training in hypoxia versus Normoxia: A double-blind and crossover study. *International Journal of Sports Physiology & Performance*, *12*(2), 161–167. https://doi.org/10.1123/ijspp.2015-0691

Piperi, A., Warnier, G., de Ten Ryen, S. V. D., Benoit, N., Antoine, N., Copine, S., & Deldicque, L. (2024). Repeated sprint training in hypoxia improves repeated sprint ability to exhaustion similarly in active males and females. *Medicine & Science in Sports and Exercise*, *56*(10), 1988–1999. https://doi.org/10.1249/MSS.0000000000003485

Puype, J., Van Proeyen, K., Raymackers, J. M., Deldicque, L., & Hespel, P. (2013). Sprint interval training in hypoxia stimulates glycolytic enzyme activity. *Medicine & Science in Sports and Exercise*, *45*(11), 2166–2174. https://doi.org/10.1249/MSS.0b013e31829734ae

Raberin, A., Elmer, J., Willis, S. J., Richard, T., Vernillo, G., Iaia, F. M., & Millet, G. P. (2023). The oxidative–glycolytic balance influenced by sprint duration is key during repeated sprint in hypoxia. *Medicine & Science in Sports and Exercise*, *55*(2), 245–254. https://doi.org/10.1249/mss.0000000000003042

Raberin, A., Willis, S. J., Richard, T., Elmer, J., Vernillo, G., Iaia, F. M., & Millet, G. P. (2023). Hypoxia does not change performance and psychophysiological responses during repeated cycling sprints to exhaustion with short exercise-to-rest ratio. *International Journal of Sports Physiology & Performance*, *18*(2), 213–217. https://doi.org/10.1123/ijspp.2022-0234

Roels, B., Millet, G. P., Marcoux, C. J., Coste, O., Bentley, D. J., & Candau, R. B. (2005). Effects of hypoxic interval training on cycling performance. *Medicine & Science in Sports and Exercise*, *37*(1), 138–146. https://doi.org/10.1249/01.MSS.0000150077.30672.88 pii.

Seitz, H., Preissler, E., Catal-‐Lehnen, P., & Weitl, M. (2020). Effects of the 'live low-train high' method on variables of endurance capacity. A systematic review. *Deutsche Zeitschrift für Sportmedizin*, *71*(2), 43–50. https://doi.org/10.5960/dzsm.2019.413

Shi, Q. D., Tong, T. K., Nie, J. L., Tao, D., Zhang, H. F., Tan, X. Y., & Kong, Z. W. (2023). Repeated-sprint training in hypoxia boosts up team-sport-specific repeated-sprint ability: 2-week vs 5-week training regimen. *European Journal of Applied Physiology*, *123*(12), 2699–2710. https://doi.org/10.1007/s00421-023-05252-x

Smith, K. J., & Billaut, F. (2010). Influence of cerebral and muscle oxygenation on repeated-sprint ability. *European Journal of Applied Physiology*, *109*(5), 989–999. https://doi.org/10.1007/s00421-010-1444-4

Solsona, R., Dériaz, R., Albert, S., Chamoux, M., Lloria-Varella, J., Borrani, F., & Sanchez, A. M. J. (2024). Impact of systemic hypoxia and blood flow restriction on mechanical, cardiorespiratory, and neuromuscular responses to a multiple-set repeated sprint exercise. *Frontiers in Physiology*, *15*, 12. https://doi.org/10.3389/fphys.2024.1339284

Soo, J., Girard, O., Ihsan, M., & Fairchild, T. (2020). The use of the SpO(2) to FiO(2) ratio to individualize the hypoxic dose in sport science, exercise, and health settings. *Frontiers in Physiology*, *11*, 570472. https://doi.org/10.3389/fphys.2020.570472

Sousa, A., Viana, J. L., Milheiro, J., Reis, V. M., & Millet, G. P. (2021). Effect of hypoxia and nitrate supplementation on different high-intensity interval-training sessions. *European Journal of Applied Physiology*, *121*(9), 2585–2594. https://doi.org/10.1007/s00421-021-04726-0

Sousa, A., Viana, J. L., Milheiro, J., Reis, V. M., & Millet, G. P. (2022). Dietary nitrate supplementation is not helpful for endurance performance at simulated altitude even when combined with intermittent normobaric hypoxic training. *Frontiers in Physiology*, *13*, 839996. https://doi.org/10.3389/fphys.2022.839996

Tong, T. K., Tao, E. D., Chow, B. C., Baker, J. S., & Jiao, J. J. (2021). Acute performance responses to repeated treadmill sprints in hypoxia with varying inspired oxygen fractions, exercise-to-recovery ratios and

recovery modalities. *European Journal of Applied Physiology*, *121*(7), 1933–1942. https://doi.org/10.1007/s00421-021-04628-1

Tounsi, M., Jaafar, H., Aloui, A., & Souissi, N. (2018). Soccer-related performance in eumenorrheic Tunisian high-level soccer players: Effects of menstrual cycle phase and moment of day. *The Journal of Sports Medicine and Physical Fitness*, *58*(4), 497–502. https://doi.org/10.23736/s0022-4707.17.06958-4

Ullah, M. S., Davies, A. J., & Halestrap, A. P. (2006). The plasma membrane lactate transporter MCT4, but not MCT1, is up-regulated by hypoxia through a HIF-1α-dependent mechanism. *Journal of Biological Chemistry*, *281*(14), 9030–9037. https://doi.org/10.1074/jbc.M511397200

Vogt, M., Puntschart, A., Geiser, J., Zuleger, C., Billeter, R., & Hoppeler, H. (2001). Molecular adaptations in human skeletal muscle to endurance training under simulated hypoxic conditions. *Journal of Applied Physiology*, *91*(1), 173–182. https://doi.org/10.1152/jappl.2001.91.1.173

Wang, R., Fukuda, D. H., Hoffman, J. R., La Monica, M. B., Starling, T. M., Stout, J. R., & Hu, Y. (2019). Distinct effects of repeated-sprint training in Normobaric Hypoxia and β-alanine supplementation. *Journal of the American College of Nutrition*, *38*(2), 149–161. https://doi.org/10.1080/07315724.2018.1475269

Warnier, G., Benoit, N., Naslain, D., Lambrecht, S., Francaux, M., & Deldicque, L. (2020). Effects of sprint interval training at different altitudes on cycling performance at sea-level. *Sports*, *8*(11), 13. https://doi.org/10.3390/sports8110148

Wehrlin, J. P., Marti, B., & Hallen, J. (2016). Hemoglobin mass and aerobic performance at moderate altitude in elite athletes. *Advances in Experimental Medicine and Biology*, *903*, 357–374. https://doi.org/10.1007/978-1-4899-7678-9_24

Wilber, R. L., Stray-Gundersen, J., & Levine, B. D. (2007). Effect of hypoxic "dose" on physiological responses and sea-level performance. *Medicine & Science in Sports and Exercise*, *39*(9), 1590–1599. https://doi.org/10.1249/mss.0b013e3180de49bd

Wilson, D. F., Erecińska, M., Drown, C., & Silver, I. A. (1977). Effect of oxygen tension on cellular energetics. *American Journal of Physiology-Cell Physiology*, *233*(5), C135–C140. https://doi.org/10.1152/ajpcell.1977.233.5.C135

Zelenovic, M., Kontro, T., Stojanovic, T., Alexe, D. I., Bozic, D., Aksovic, N., & Adrian, S. M. (2021). Effects of repeated sprint training in hypoxia on physical performance among athletes: A systematic review. *International Journal of Morphology*, *39*(6), 1625–1634. https://doi.org/10.4067/S0717-95022021000601625

Zoll, J., Ponsot, E., Dufour, S., Doutreleau, S., Ventura-Clapier, R., Vogt, M., Flück, M., Richard, R., & Flück, M. (2006). Exercise training in normobaric hypoxia in endurance runners. III. Muscular adjustments of selected gene transcripts. *Journal of Applied Physiology*, *100*(4), 1258–1266. https://doi.org/10.1152/japplphysiol.00359.2005