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SYSTEMATIC REVIEW

The Effect of Natural or Simulated Altitude Training on High-Intensity Intermittent Running Performance in Team-Sport Athletes: A Meta-Analysis

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Abstract

Background While adaptation to hypoxia at natural or simulated altitude has long been used with endurance athletes, it has only recently gained popularity for team-sport athletes.

Objective To analyse the effect of hypoxic interventions on high-intensity intermittent running performance in team-sport athletes.

Methods A systematic literature search of five journal databases was performed. Percent change in performance (distance covered) in the Yo-Yo intermittent recovery test (level 1 and level 2 were used without differentiation) in hypoxic (natural or simulated altitude) and control (sea level or normoxic placebo) groups was meta-analyzed with a mixed model. The modifying effects of study characteristics (type and dose of hypoxic exposure, training duration, post-altitude duration) were estimated with fixed effects, random effects allowed for repeated measurement within studies and residual real differences between studies, and the standard-error weighting factors were derived or imputed via standard deviations of change scores. Effects and their uncertainty were assessed with magnitude-based inference, with a smallest important improvement of 4% estimated via between-athlete standard deviations of performance at baseline.

Results Ten studies qualified for inclusion, but two were excluded owing to small sample size and risk of publication bias. Hypoxic interventions occurred over a period of 7–28 days, and the range of total hypoxic exposure (in effective altitude-hours) was 4.5–33 km h in the intermittent-hypoxia studies and 180–710 km h in the live-high studies. There were 11 control and 15 experimental study-estimates in the final meta-analysis. Training effects were moderate and very likely beneficial in the control groups at 1 week (20 ± 14%, percent estimate, ± 90% confidence limits) and 4-week post-intervention (25 ± 23%). The intermittent and live-high hypoxic groups experienced additional likely beneficial gains at 1 week (13 ± 16%; 13 ± 15%) and 4-week post-intervention (19 ± 20%; 18 ± 19%). The difference in performance between intermittent and live-high interventions was unclear, as were the dose of hypoxia and inclusion of training in hypoxia.

Conclusions Hypoxic intervention appears to be a worthwhile training strategy for improvement in high-intensity running performance in team-sport athletes, with enhanced performance over control groups persisting for at least 4 weeks post-intervention. Pending further research on the type of hypoxia, dose of hypoxia and training in hypoxia, coaches have considerable scope for customising hypoxic training methods to best suit their team's training schedule.

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Key Points

While altitude training or hypoxic interventions have long been used with endurance athletes, the role of various hypoxic interventions for team-sport athletes has only relatively recently gained interest from the academic and coaching communities. This meta-analysis is the first to examine the effects of natural or simulated altitude training in team-sport athletes on Yo-Yo intermittent recovery (YYIR) performance (i.e. distance covered).

Results indicated improved high-intensity intermittent running performance following hypoxic interventions, regardless of the altitude training method (intermittent vs. live-high protocols, and whether studies included a 'training high' component).

Improvements in YYIR performance compared to the control group persisted 4 weeks post-intervention.

1 Introduction

The physiological demands of a team-sport competition typically include repeated bouts of short but intense bursts of activity, followed by longer periods of relative inactivity or light-to-moderate exercise [1]. For example, field hockey [2], rugby [3], soccer/football [4] and Australian Rules football [5] team-sport athletes typically complete between 22–30 sprints per game, interspersed by periods of low-to-moderate-intensity activity in invariant sequences. While the periods of high-intensity exercise are far less frequent than the periods of low-intensity activity, they usually precede essential match manoeuvres such as the lead-up to a goal [6] (or defence thereof), or contest for possession of the ball, the consequence of which may substantially affect the outcome of the game. It is therefore essential that a team-sport athlete not only has well-developed anaerobic power, but also a well-functioning aerobic capacity for the quick recovery from such repeated anaerobic bursts [7, 8].

These discontinuous bouts of activity in team-sport athletes have meant that many of the continuous-styled ramp protocols for the assessment of maximal oxygen uptake may not accurately reflect the team-sport athlete's ability to perform repeated bouts of high-intensity exercise [9]. To this end, the Yo-Yo intermittent recovery test (YYIR) was developed wherein the athlete completes 2 × 20 m back-to-back shuttles (paced by an audible beep) interspersed by 10 s of active recovery. As the test progresses, these beeps get closer together, requiring a higher intensity of exercise. The test is concluded when the athlete can no longer keep up with the audible beeps. There are two versions of this test: level 1, which has a lower starting speed and slower progression between beeps and focusses on endurance capacity, while the more intense level 2 test is somewhat shorter (5–15 min, compared to 10–20 min for level 1), and has a larger focus on the athlete's anaerobic capacity [9]. However, level 1 will also test anaerobic capacity in less fit participants [9]. The athlete's performance is judged by the distance covered (m) during the test [9]. YYIR performance has been used in a number of team sports [10–14], and is sensitive enough to differentiate between playing positions [13], match performance [12] and level of competitiveness [14], reflecting an efficient and effective team-sport performance test.

To achieve well in the YYIR tests, and in gameplay, team-sport athletes must have highly advanced anaerobic and aerobic energy systems [9] to maximise the power output required in acceleration, speed work, and repeated sprint or high-intensity manoeuvres, all the while resisting fatigue (including optimising metabolic recovery and maintaining neuromuscular integrity) [15]. As altitude training has been associated with improved muscle strength and endurance [16], fatigue resistance during repeated sprints [17] as well as the more typically associated aerobic performance improvement [1, 15, 18, 19], the application of altitude training for team-sport athletes has received considerable attention [1, 15, 20]. For example, in 2013 a conference centred on the relevance of altitude training was hosted in Doha, Qatar where experts in the field met to discuss research and future research directions relating to the role of altitude training in team-sport athletes [20].

Athletes considering altitude training might employ several different methods, including both simulated and natural altitude techniques. Indeed, with the convenience of simulated altitude devices it is now more feasible for team-sport athletes to engage in such training without having to leave their places of residence or training grounds. There are several different approaches to simulated altitude training, of which the most common include: traditional extended exposure to either natural or artificial altitude (hypoxic tents or chambers) which have become known as 'live high–train high' (LHTH; where athletes both live and train at high altitude) or 'live high–train low' (LHTL; where athletes live in a hypoxic environment but train at sea level). When using simulated altitude devices, participants using the LHTH or LHTL techniques typically spend more than 10 h/day in an altitude tent or room. When athletes using the 'live-high' approach include both hypoxic and normoxic training in their programme, it is termed ‘live high–train low and high’ (LHTLH). Given the time commitment of LHTH, LHTL and LHTLH, shorter but more intense hypoxic training protocols have been developed which typically use oxygen filters or nitrogen dilution to create hypoxic air, which is then delivered to the participant either via an altitude tent or room, or through a face-mask. Short-duration hypoxic intervention can be administered while the participants rest and is termed ‘intermittent hypoxic exposure’ (IHE). During IHE, participants receive a few minutes of severe hypoxia alternated with a few minutes of normoxic exposure to recover, repeated several times (usually for between 40–90 min). Varying forms of exercise conducted under short-term hypoxia are collectively known as ‘live low–train high’ (LLTH) techniques, and can include repeated sprints (RSH), aerobic and/or high-intensity exercise training (intermittent hypoxic training, IHT) or resistance training (RTH) under hypoxic environments. For more information on these techniques and their effectiveness on repeated-sprint performance, readers are referred to Girard et al. [21].

The combination of the increase in awareness of the potential for performance benefit from altitude training in team-sport athletes and the relative convenience of simulated altitude devices has resulted in an increase in literature published on the effect of altitude training on team-sport athletes. While much of the research indicates a positive performance benefit with altitude training [15, 21–24], controversy remains, with some researchers suggesting altitude training does little to increase performance and should not be recommended to elite athletes [25] (see also Millet et al. [26] and Lundby and Robach [27] for further debate). With these debates in mind, and the call for more research and information on the effects of altitude training for improved sea level performance rather than altitude acclimatization [20, 21, 24], the aim of this meta-analysis was to determine whether using altitude training (simulated or natural) enhances the high-intensity, intermittent running performance (estimated by YYIR) of team-sport athletes at sea-level more than similar normoxic training.

While the completion of such a meta-analysis is not without limitation and controversy, particularly given the range of hypoxic protocols and the diversity of the sport-specific athletes in each of the studies, the findings of such a meta-analysis would: (a) be a necessary start in quantitatively assessing the effectiveness of altitude training for team-sport athletes, and (b) provide an indication of the types of altitude-related studies into which team-sport athletes are currently being recruited.

2 Methods

A systematic search of the research literature was conducted and analysed according to the Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) guidelines [28]. Search databases included the electronic catalogues of PubMed, Medline, Web of Science, SPORTDiscus and the local University’s Library database. Additional publications were included following a review of the reference lists of selected journal articles, previously selected articles from former EndNote libraries and the recommendations from reviewing colleagues.

2.1 Search Criteria

Search terms and outcomes are shown in Fig. 1. Given the small field of study (i.e. team sports and hypoxic interventions), racquet sports were included in the search criteria so as to cast as wide a net as possible when trying to find relevant studies. The intermittent nature of racquet sports such as tennis, badminton and squash, and in particular the doubles versions of these games, share many similarities with team sports such as basketball, volleyball or handball. However, no racquet sport studies were identified by the literature search.

2.1.1 Inclusion Criteria

Studies were required to be intervention-styled with the purpose of examining the effect of altitude or low-oxygen training on sea-level performance. Any form of low-oxygen training was accepted, including natural or simulated altitude, and any protocol, including LHTH, LHTL, LHTLH, IHT, IHE, RTH and RSH, or any other techniques. Both normobaric and hypobaric conditions were accepted; studies were required to use team-sport athletes as their participants and report at least one performance variable (for preliminary acceptance), with measurement of either the YYIR level 1 or level 2 test required for final acceptance (these results were reported as a percent change from baseline, and then used interchangeably). As such, caution is urged when interpreting these results. All studies published (or accepted for publication) in English in an academic, peer-reviewed format including masters and doctoral theses published prior to 1 September 2016 were accepted.

2.1.2 Exclusion Criteria

Studies involving animals (simulated), altitude exposure not for the purpose of enhancing sea-level performance (such as clinical applications [29–35] or acute responses to

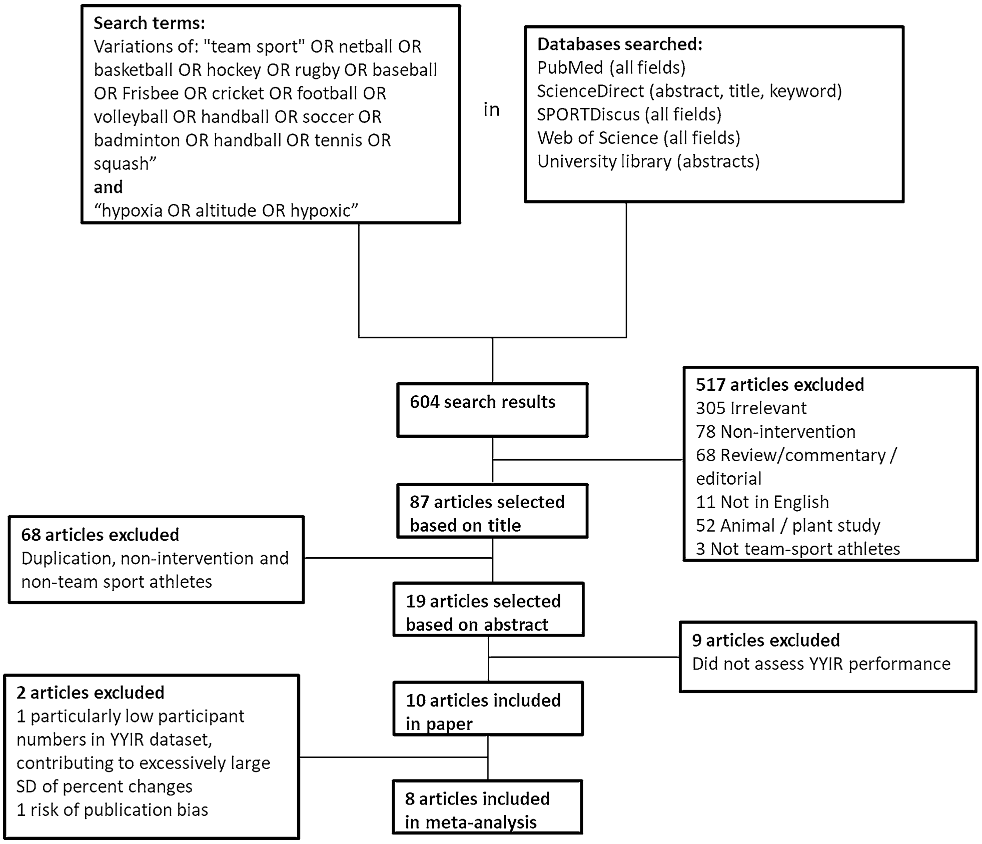

Fig. 1 Search terms and outcomes. *SD* standard deviation, *YYIR* Yo-Yo intermittent recovery test

altitude), not available in English, acclimatization studies (i.e. only performance at altitude reported), individual sports or studies focussing on high altitude natives were excluded.

2.2 Study Records

All search results were systematically reviewed, one database search at a time, by one key researcher. Where the potential inclusion of a study was less obvious, the article was discussed with a second researcher. The final selection of all short-listed articles was examined for suitability by all three authors prior to inclusion in the study.

To analyse the data, selected papers [17, 36–43] were scrutinized and the percent change and SD of the percent change of the pre-post change score were recorded. Where this information was not available from the publications, the relevant authors were contacted for further information. All percent changes and the SD of the percent changes for selected studies reporting YYIR were made available (no imputation was necessary).

One study [39] was removed from the analysis due to particularly small sample size, which contributed to excessively high SD of the change scores.

2.3 Data Outcomes and Prioritization

The YYIR (distance covered) was used as the main outcome to assess change in team-sport athlete performance following altitude training. To create a similar platform from which studies varying in their (simulated) altitude training approaches could be compared, a total hypoxic dose in kilometre-hours (km h = height above sea level in metres/1000 × total hours of exposure) was determined [44] for all studies, regardless of the training style or whether exercise was used in addition to the hypoxic exposure.

2.4 Meta-Analysis: Data Synthesis and Risk of Bias Analysis

The general linear mixed-model procedure (Proc Mixed) in the Statistical Analysis System (Version 9.4, SAS Institute, Cary, NC, USA) was used to perform the meta-analysis. The dependent variable was log-transformed factor mean change from baseline in the given group at the given time point. The time point defined three predictor variables: duration of exposure to altitude in km h that had accrued by that point (or by the end of the exposure to altitude, in the case of time points after the altitude exposure); the time since the exposure to altitude; and the time since baseline, representing training time in the study. The duration of exposure to altitude and the time since exposure were included as simple linear fixed effects for the altitude group only, while the training time was included as a simple linear fixed effect without regard to the group. The other fixed effects in the model were a dummy variable representing the altitude group and a dummy variable representing training at altitude.

Random effects in the model were specified to capture the repeated-measures nature of the observations and to quantify between- and within-study variation not explained by the fixed effects. To estimate the shared and unique between-study variance for the hypoxic intervention and control groups, a study identity random effect, plus this effect interacted with dummy variables for hypoxic intervention and control treatments, was used. Then, to estimate the shared and unique within-study variance for the hypoxic-intervention and control groups, a 'pair-identity' random effect, with a unique nominal value for each time point for each study, again plus this effect interacted with dummy variables for hypoxic intervention and control treatments, was used. The random effects were specified with two random statements and independent (variance-components) structure. The residual was set to unity to properly weight the estimates by the inverse of the square or their standard errors [45]. The variances were combined appropriately to provide estimates of the standard deviation representing variation between study-estimates in the hypoxic intervention and in the control groups not explained by the fixed effects. The values from the solution for the random effects and their standard errors were also combined appropriately to derive a t statistic for each study-estimate. Scatter plots of the t statistic versus the log transformation of the factor standard error of estimate for the hypoxic interventions and control groups were then inspected for evidence of outliers and publication bias. This kind of plot is superior to the usual funnel plot, because the t value is effectively adjusted for uncertainty in the study estimates and for the contribution of study covariates [46]. There were no outliers (absolute value of t statistic > 3.5), but the five estimates in the hypoxic exposure groups of Inness et al. [40] all had higher standard errors and larger positive t values (range 2.0–2.4) than those of any other studies, indicating the potential for publication bias. The meta-analysis was therefore repeated with this study deleted.

Outcomes of the meta-analysis were determined by predicting the mean change in the hypoxic intervention groups minus the mean change in the control groups immediately post (1–3 days) and at 1 week and 4 weeks after the hypoxic intervention for the median value of maximum altitude exposure across the eight studies (33 km h). The outcomes were expressed as percent effects on YYIR performance distance by back-transformation. Magnitudes of effects were evaluated via standardization. For this purpose, a between-subject SD representing the typical variation in YYIR performance was derived from the square root of the weighted mean of the variances of the log-transformed factor SD at baseline (where the weighting factor was the degrees of freedom of the SD in each study). The effects in log-transformed units were divided by this standard deviation and their magnitudes interpreted with the following scale: < 0.2, trivial; 0.2–0.6, small; 0.6–1.2, moderate; > 1.2, large [46]. The thresholds in this scale were halved for interpreting the magnitude of the standardized standard deviations derived from the random effects [47]. Uncertainty in the effects was expressed as 90% confidence limits (CLs) and as probabilities that the true value of the effect was beneficial, trivial or harmful (for the predicted mean effects of altitude exposure) or substantially increased, trivial, or substantially decreased (for the individual fixed effects and for the standard deviations representing variation between study estimates). These probabilities are not presented quantitatively but were used to make qualitative probabilistic clinical inferences and non-clinical inferences respectively [46]. For a clinical inference the effect was deemed unclear when the chance of benefit was sufficiently high to warrant use of the treatment but the risk of harm was unacceptable. Such unclear effects were identified as those with an odds ratio of benefit to harm of < 66, a ratio that corresponds to an effect that is borderline possibly beneficial (25% chance of benefit) and borderline most unlikely harmful (0.5% risk of harm). Effects were otherwise deemed clinically clear and expressed as the chance of the true effect being trivial, beneficial or harmful with the following scale: 25–75%, possibly; 75–95%, likely; 95–99.5%, very likely; $> 99.5\%$, most likely. For a non-clinical inference the effect was deemed unclear if the 90% confidence interval (CI) overlapped thresholds for substantial increases and decreases; effects were otherwise deemed clear and were evaluated probabilistically as described above.

3 Results

3.1 Study Description

Most studies used the LLTH approach ($n = 5$) and of those, all used high ($n = 2$) to maximal ($n = 3$) exercise intensities. Participants ranged from amateur to elite team sport players. While most studies continued their interventions for about 4 weeks, the overall hypoxic dose was low (ranging from 4.5–18.3 km h). The LHTLH strategy was the next most common for team sport athletes ($n = 3$). In this category two studies used repeated sprint training for 2 weeks in elite athletes, while one used moderate-intensity aerobic training over a 4-week period in social soccer players. The overall hypoxic dose in these studies was considerably higher than in the LLTH studies, with hypoxic doses ranging from 539 to 700 km h. Finally, three studies used passive hypoxic exposure (LHTL, $n = 2$; and IHE, $n = 1$). All three studies added passive hypoxic exposure to regular team training sessions (which included some high-intensity training) and were conducted in sub-elite to elite players over a 2- to 3.5-week period. The hypoxic dose for the LHTL groups was similar to that for the LHTLH groups (384–539 km h) while the dose for the IHE group was similar to that for the LLTH studies (32.5 km h). Tables 1, 2 and 3 provide description of individual studies (including type of blinding used, sample size and date of publication), participant descriptions (primary sporting context and age) and the interventions (including any exercise training, type of altitude training used and the hypoxic dose).

There appeared to be no apparent benefit of higher hypoxic doses on YYIR test performance (see Fig. 2, which displays similar performance changes with higher and lower hypoxic doses).

Figure 3 displays the between-group (i.e. hypoxic test group change versus normoxic control group change) performance difference in YYIR test performance over time. These results suggest that performance improvements following hypoxic interventions relative to normoxic control groups at 28 days post-intervention and 1 week post-intervention are similar. There is little information regarding the performance change between 5 and 28 days post-intervention.

3.2 Meta-Analytic Outcomes

While there were beneficial training effects in both the control and hypoxic groups immediately post-intervention, there were enhanced performance effects in the groups receiving hypoxic treatments. At 1 and 4 weeks post-intervention, the control groups continued to improve their YYIR test performance; however, the hypoxic groups displayed an additional 'likely beneficial' improvement over and above the changes witnessed in the control group. There were no further performance improvements associated with additional hypoxic training or height above sea-level. Table 4 shows the percent and standardized estimates (± 90% CL) and the qualitative outcomes for the predictors.

3.3 Synthesis of the Results

The random effects model properly allowed for real differences in study estimates between and within studies. The effects for both the control [14 ± 15; effect estimate (%), ± 90% CL] and the experimental (10 ± 15) groups were unclear. The magnitudes of the observed effect in the between-study estimate standard deviations in both the control and experimental groups were moderate. These data indicate that after the fixed effects (altitude duration, time since exposure to altitude and whether the group received hypoxic treatments or participated in exercise at altitude) were accounted for, there was still a moderate level of variation between the groups. This within- and between-study variability suggests that individual responses to altitude training almost certainly exist in individual settings, but data were not sufficient to address this question in this analysis.

4 Discussion

This is the first article attempting to meta-analyse the effect of all forms of natural and simulated altitude training on high-intensity intermittent running performance (as assessed using YYIR test) in team-sport athletes. Overall, the meta-analysis revealed clear improvements in YYIR performance in both the control groups (likely positive) and the hypoxic groups (very likely positive) immediately post-intervention. Each class of hypoxic intervention demonstrated clear (likely beneficial) improvements in performance over the control group persisting up to 4 weeks post-intervention with an unclear difference in the training effect between the shorter-duration intermittent protocols, and the longer-duration 'live-high' protocols immediately post-intervention. Interestingly, the magnitude of the performance improvement at 4 weeks was possibly greater than it was at 1 week post-intervention (i.e. the difference between hypoxic and control groups was greater, with hypoxic groups outperforming the control groups more so at 4 weeks than they did at 1 week post-intervention).

The greater magnitude of performance improvement at 4-weeks post-intervention compared to the first week post-intervention appears to support Millet et al. LHTH training adaptation model [48]. These authors have identified three phases following altitude training: a positive phase immediately post-training owing to haemodilution and ventilatory changes from altitude (but performance improvements are quite variable and not found in all athletes, resulting in potentially beneficial but also unreliable performance outcome for athletes); a second phase characterised by re-acclimatization and a reduction in performance potentially due to the loss of any acute altitude-related neuromuscular adaptation; and finally a third phase, characterised by a plateau in altitude-adjusted fitness, during which performance is enhanced. While the data from this meta-analysis do not support a decrease in performance associated with

Table 1 Team-sport athletes undertaking live low–train high protocols

Study	Blinding	Participants	Age, years (mean ± SD)	Groups/ hypoxic protocol	Data included	Hypoxic training dosage	Training mode	Other training	Hypoxic dose		
									Height (m above SL)	Total hypoxic exposure (h)	km h
Galvin et al. [38]	SB	Sub-elite rugby players	18.4 ± 1.5	RSH RSN	YYIR, RSA (running: Sprint decr and total sprint time)	6 min/day, 4 days/ week, 4 weeks	Non-motorised treadmill	Preseason training (RS replaced field-based speed sessions.)	3750	1.2	4.5
Gatterer et al. [39][a]	SB	Elite male soccer players	15.3 ± 0.5	5 RSH 5 RSN	YYIR, RSA (running: Sprint decr and mean sprint time)	40 min/day, 1–2 days/week, 5 weeks	Shuttle sprints (4.5 m shuttles)	Preseason (preparation) phase; normal field team training	3300	5.3	17.6
Gatterer et al. [64]	DB	Amateur male soccer players	23.9 ± 2.1	7 RSH 7 RSN	YYIR, RSA (running: Sprint decr and mean sprint time)	25 min/day, 4 days/week, 2 weeks	Shuttle sprints (4.5 m)	Off-season; usual training habits	3300	3.3	11.0
Inness et al. [40][a]	C	Sub-elite male Australian football players		10 IHT 11 INT	Hb and YYIR	40 min/day, 3 days/week, (C 2 days/week), 1 week	HIIT cycling	Preseason; normal squad training	2500	2.0	5.0
				10 IHT 11 INT		As above, 2 weeks			2500	4.0	10.0
				10 IHT 11 INT		As above, 4 weeks			2500	7.3	18.3
McLean et al. [41]	DB	Amateur male Australian football players	23.2 ± 2.8	9 IHT 8 INT	MAS, YYIR	30 min/day, 2 days/week, 4 weeks	Treadmill	Preseason training (2 resistance training, and 2 football training sessions/ week)	3000	4.0	12.0

SB single blind, *DB* double blind, *C* Controlled, unblinded, *YYIR* Yo-Yo intermittent recovery test (measured in meters covered), *RSA* repeated-sprint ability, *Sprint decr* sprint decrement (usually measured as either total sprint time/(best sprint time × number of sprints) × 100 or mean sprint time/best sprint time × 100), *Hb* haemoglobin, *MAS* maximal aerobic speed, *RS* repeated sprints, *HIIT* high-intensity interval training, *IHT* intermittent hypoxic training (exercise in hypoxia), *INT* intermittent normoxic training (similar exercise in normoxia), *RSH* repeated-sprint training in hypoxia, *RSN* repeated-sprint training in normoxia, *SL* sea level, *km h* kilometre-hours, the standardised hypoxic dose where km h = (meters above sea level/1000) × total duration of exposure in hours

[a] Study excluded from the meta-analysis but included in the table for the reader's interest

Table 2 Team-sport athletes undertaking live high–train low protocols

Study	Blinding	Participants	Age, years (mean ± SD)	Groups/ hypoxic protocol	Data included	Hypoxic training dosage	Other training	Hypoxic dose		
								Height (m above SL)	Total hypoxic exposure (h)	km h
Brocherie et al. [36]	DB	Elite male hockey players	LHTL: 25.3 ± 4.2 LLTL: 22.3 ± 4.6	12 LHTL, 9 LLTL (also 11 LHTLH)	Hb (mass), YYIR, RSA (total sprint time and sprint decr.), CMJ	14 h/day, 2 weeks	Usual training, RS and explosive strength/ COD/agility training	2900	196	539
Inness et al. [43]	C	Sub-elite male Australian football players	LHTL: 20.1 ± 1.2 LLTL: 20.2 ± 1.4	4 LHTL, 5 LLTL	Hb (mass), YYIR	12 h/day, 5 days	Preseason training	3000	60	180
				7 LHTL, 6 LLTL		12 h/day, 1.5 weeks		3000	120	360
				8 LHTL, 7 LLTL		12 h/day 3.5 weeks		3000	228	384
Kilding et al. [17]	SB	Elite and sub-elite male basketball players	IHE: 23.3 ± 5.6 INE: 21.2 ± 3.3	7 IHE, 7 INE	Hb (g/L), YYIR, RSA (total sprint time)	7 min hypoxia: 3 min rest × 4; i.e. 0.5 h/day, 2 weeks	1–2 competitions, 2–4 team training, and 0–2 weight trainings/ week	4650	7	32.5

IHE intermittent hypoxic exposure (several minutes of hypoxic exposure alternated with several minutes of normoxic exposure, alternated several times), *DB* double blind, *C* controlled, unblinded, *SB* single blind, *Hb* haemoglobin, *YYIR* Yo-Yo intermittent recovery test (measured in meters covered), *RSA* repeated-sprint ability, *Sprint decr* sprint decrement (usually measured as either total sprint time/(best sprint time × number of sprints) × 100 or mean sprint time/best sprint time × 100), *CMJ* counter movement jump, *LHTL* live high train low, *RS* repeated sprints, *COD* change of direction training, *LLTL* live low, train low, *INE* intermittent normoxic exposure (as for IHE, but with normoxic placebo), *LHTLH* live high train low and high, *SL* sea level, *km h* kilometre-hours, the standardised hypoxic dose where km h = (meters above sea level/1000) × total duration of exposure in hours

the ‘second phase’, it is possible that this decline in performance could have occurred between weeks 1 and 4. We would therefore recommend that athletes, coaches and researchers consider the timing of post-altitude competitive performance when planning to use a ‘live-high’ altitude training model.

While there were insufficient studies in this meta-analysis to explore each of the predictors (weeks post treatment, including exercise in hypoxia, and the intervention duration) with hypoxic dose (km h) in each of the intermittent and live high subgroups, we were able to graphically examine possible trends in performance adaptation with hypoxic interventions (see Fig. 2). Meta-analysis results and visual inspection of the effect of hypoxic dose on change in YYIR performance suggest that there is no clear advantage in using longer-term ‘live-high’ protocols compared to the shorter ‘intermittent’ protocols in improving sea level, high-intensity intermittent running performance in team-sport athletes. These findings are in contrast to the recommendations provided to endurance athletes, which state that in order to elicit a change in sea-level performance mediated by an increase in erythropoiesis, an athlete should be exposed to an altitude of 2000–2500 m above sea level for 4 weeks or more, and for at least 22 h per day using natural altitude, or 12–16 h per day at 2500–3000 m using simulated altitude [49]. This recommendation is equivalent to 1232–1540 km h for natural altitude, or 840–1344 km h for simulated altitude [44]. Of the selected studies in the current meta-analysis, the highest hypoxic dose was only 700 km h. This suggests

Table 3 Team-sport athletes using live high - train low and high protocols

Study	Blinding	Participants	Age, years (mean ± SD)	Groups/ hypoxic protocol	Data included	Hypoxic training dosage	Training mode	Other training	Hypoxic dose				
									HT height (m above SL)	Live high dosage and duration	LH height (m above SL)	Total hypoxia (h)	km h
Brocherie et al. [36]	DB	Elite male hockey players	LHTLH: 27.6 ± 4.8 LLTL: 22.3 ± 4.6	11 LHTLH 9 LLTL	Hb mass, YYIR, RSA (total time and sprint decr.), CMJ	50 min/day 3 days/ week 2 weeks	RS: 15 min W/U, 4 sets of 5 × 5 s sprints, 25 s rest, 5 min between sets. 10 min CD	Usual team practice	3000	14 h/day, 7 days/ week, 2 weeks	2750	201	539
Buchheit et al. [52]	SB	Elite male Australian football players	LHTLH: 22 ± 2.2 LLTL: 21.5 ± 1.7	9 LHTLH 8 LLTL	Hb (mass and g/dl), YYIR, CMJ	40 min/day 7 days/ week 1 week	RS: 3–5 sets of 10–15 reps of 15–30 s cycling sprints	Sport specific skills and strength	2800	14 h/day, 7 days/ week, 1 week	2800	103	274
						40 min/day 7 days/ week 2 weeks			2800	14 h/day, 7 days/ week, 2 weeks	2800	205	568
Zhang et al. [42]	C	Social male soccer players	LHTLH: 21.2 ± 0.74 LLTL: 21.2 ± 0.95	8 LHTLH 8 LLTL	Hb (g/L),	30 min/day 2 days/ week 2 weeks	LHTLH: 30 min at 72% VO_{2max}, LLTL: 30 min at 80% VO_{2max}	Soccer training 3/week	2500	10 h/day, 7 days/ week, 2 weeks	2500	142	350
						30 min/day 2 days/ week 3 weeks			2500	10 h/day, 7 days/ week, 3 weeks	2500	213	525
						30 min/day 2 days/ week 4 weeks			2500	10 h/day, 7 days/ week, 4 weeks	2500	284	700

SB single blind, *DB* double blind, *C* Controlled, unblinded, *YYIR* Yo-Yo intermittent recovery test (measured in meters covered), *RSA* repeated-sprint ability, *Sprint decr* sprint decrement (usually measured as either total sprint time/(best sprint time × number of sprints) × 100 or mean sprint time/best sprint time × 100), *Hb* haemoglobin, *MAS* maximal aerobic speed, *RS* repeated sprints, *HIIT* high-intensity interval training, *IHT* intermittent hypoxic training (exercise in hypoxia), *INT* intermittent normoxic training (similar exercise in normoxia), *RSH* repeated-sprint training in hypoxia, *RSN* repeated-sprint training in normoxia, *SL* sea level, *km h* kilometre-hours, the standardised hypoxic dose where km h = (meters above sea level/1000) × total duration of exposure in hours

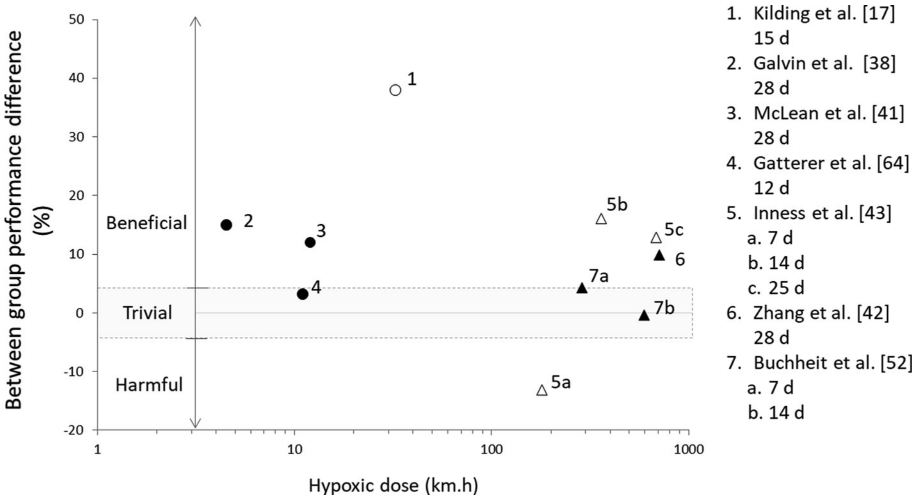

Fig. 2 The effect of hypoxic dose (km h) on change in high-intensity, intermittent running performance (YYIR). Three studies have been excluded from this graph due to absence of a normoxic control group [36], risk of publication bias [40] and a particularly small sample size [39]. *YYIR* Yo-Yo intermittent recovery test, filled circle: hypoxic training, open circle: intermittent hypoxic exposure, filled triangle: live high, train low and high, open triangle: live high, train low, *d* intervention duration (days), *km h* kilometre hours (height above sea level in meters/1000 × total number of hours of exposure)

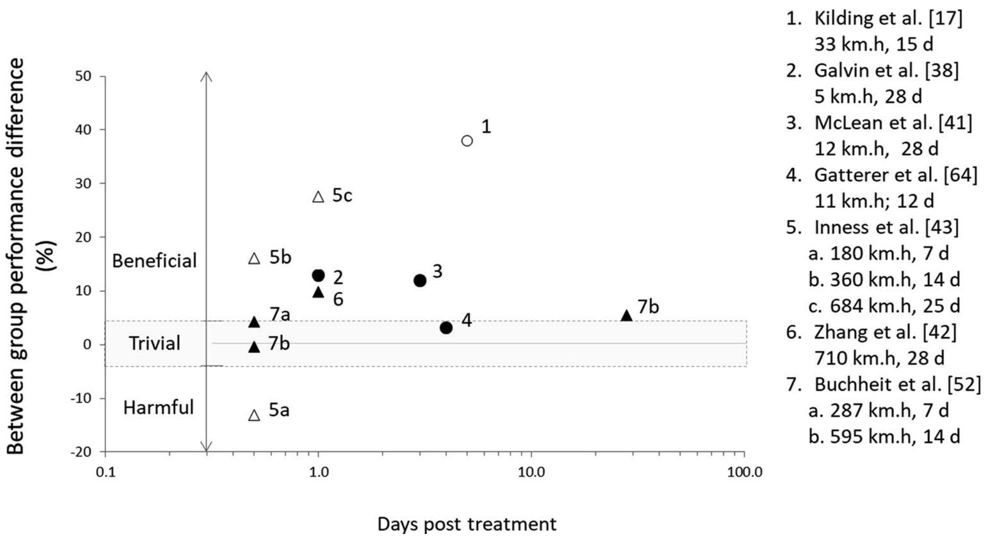

Fig. 3 The post-intervention longevity of the change in high-intensity, intermittent running performance (YYIR) following hypoxic exposure. Three studies have been excluded from this graph due to absence of a normoxic control group [36], risk of publication bias [40], and a particularly small sample size [39]. *YYIR* Yo-Yo intermittent recovery test, filled circle: hypoxic training, open circle: intermittent hypoxic exposure, filled triangle: live high, train low and high, open triangle: live high, train low, *d* intervention duration (days), *km h* kilometre hours (height above sea level in meters/1000 × total number of hours of exposure)

that a lower altitude than originally expected [49, 50] may trigger beneficial performance-related changes [51] in team-sport athletes.

Indeed, there was evidence of aerobic adaptation in the studies meta-analysed. Five of the meta-analysed articles measured haemoglobin mass (Hbmass), and of these articles, two demonstrated a 2.7 and 3.6% improvement compared to the −0.4% and 0.5% improvements in the respective control groups [52, 53], another article which did not have a comparable sea-level control group demonstrated 3–4% increases in their hypoxic groups at the end of their intervention [36], and the remaining two studies did not measure Hbmass in their control groups, but reported an increase of 0.2 and 3.8% after 7 and 14 days of hypoxic exposure, respectively [43], and 2.7% after 28 days [40]. These findings suggest that although far from Wilber et al. [49] recommended hypoxic dose for the improvement of aerobic metabolism, some aerobic

Table 4 Effect of individual and combined effects of the predictors in the meta-analytic model on high-intensity intermittent running performance (Yo-Yo intermittent recovery test)

	Percent estimate, ± 90% CL	Standardized estimate, ± 90% CL	Qualitative outcome[a]
Predictors			
Control groups	13, ± 13	0.55, ± 0.54	Likely positive
Live high groups	19, ± 14	0.82, ± 0.53	Very likely positive
Intermittent hypoxic groups	19, ± 16	0.82, ± 0.62	Very likely positive
Live high–intermittent hypoxia	0, ± 12	0.00, ± 0.55	Unclear
Extra effect of hypoxic exercise	1, ± 12	0.04, ± 0.55	Unclear
Effect of post-exposure duration (4 weeks post–1 week post)	5, ± 6	0.21, ± 0.24	Possibly positive
Predicted effects of control groups at:			
1 week post	20, ± 14	0.84, ± 0.52	Very likely beneficial
4 weeks post	25, ± 23	1.04, ± 0.83	Very likely beneficial
Predicted additional effect of live high protocols (hypoxic-control groups) at:			
1 week post	13, ± 15	0.57, ± 0.62	Likely beneficial
4 weeks post	18, ± 19	0.78, ± 0.74	Likely beneficial
Predicted additional effect of intermittent hypoxia protocols (hypoxic-control groups) at:			
1 week post	13, ± 16	0.57, ± 0.66	Likely beneficial
4 weeks post	19, ± 20	0.78, ± 0.76	Likely beneficial

CL confidence limits

[a] Qualitative outcome, magnitude based inference based on 4.2% smallest worthwhile change

adaptation did occur in the selected team-sport studies. As the YYIR tests do maximally stress the aerobic energy system [9], it is possible that these haematological adaptations facilitated improvement in the YYIR test performance.

The motivation behind Wilber et al. [49] recommendations for a longer hypoxic dose (as compared to shorter intermittent, or hypoxic training only protocols; or less than 4 weeks of altitude training with at least 22 h per day) is to maximise adaptations associated with the mechanisms of the hypoxic-inducible factor-1α (HIF-1α) pathway which functions to reduce oxygen stress by stimulating erythropoiesis, angiogenesis and glucose metabolism [54]. However, HIF-1α is highly sensitive to hypoxia and is rapidly broken down following return to normoxic or sea level conditions, abruptly halting HIF-1α related adaptation such as the increase in erythropoietin. It is possible that the sudden decrease in erythropoietin upon return to sea level [55] may not only halt but actively reverse the formation of any new red blood cells produced by the body in response to the hypoxic or altitude training, in a process known as neocytolysis [49, 56]. Wilber et al. caution that the risk of neocytolysis following shorter, 1- to 3-h hypoxic interventions will undermine any erythropoietic-related adaptation with these protocols.

However, neocytolysis may also play a role in longer-term, traditional LHTH protocols. For example, Garvican et al. attributed the sudden decrease in haemoglobin mass, serum erythropoietin, and reticulocytes and rapid increase in ferritin following a 21-day altitude training camp in elite cyclists to the sudden decrease in erythropoietin and associated neocytolysis following return to sea level [57]. Therefore, in contrast to Wilber et al. [49], Garvican et al. [57] posit that continuous but interspersed returns to a normoxic environment (or sea level) might dampen the sudden drop in erythropoietin, reducing the magnitude of the neocytolysis and preserving some of the erythropoietic changes. Therefore, it is unclear whether a prolonged or intermittent protocol would be more beneficial regarding erythropoietin-focussed adaptation, and begs the question of whether a ‘de-acclimatization period’ or whether brief and/or intermittent returns to hypoxia [50] should take place following natural or simulated altitude training in order to avoid neocytolysis associated with the sudden drop in erythropoietin [55]. While the findings of this meta-analysis cannot confirm whether neocytolysis plays a role in the post-altitude performance change, the theoretical mechanism seems plausible.

It may also be the intermittent exposures to hypoxia (or, in the case of LHTLH, short doses of more extreme hypoxia), rather than the intermittent returns to sea level, that are more, or as, important in preserving HIF-1α-related adaptation [50]. A recent study by Brocherie et al. [58] reported increases in HIF-1α post-intervention, along with upregulation of oxygen signalling, oxygen transport and mitochondrial biogenesis, only in the LHTLH group and not in the LHTL group or sea-level control group, following a 14-day intervention. Furthermore, there was a decrease in citrate synthase protein expression and activity observed in the LHTL group but an increase in both the LHTLH and control groups [58]. These molecular alterations may suggest that neocytolysis played a role in the seemingly reversed aerobic adaptation in the LHTL group, while there was positive training-induced aerobic adaptation in the control group, and combined training and hypoxic-induced aerobic adaptation in the LHTLH group. However, despite earlier findings of maintained Hbmass up to 3 weeks post-intervention [36], most of the molecular changes had returned to normal 3 weeks post-intervention.

Regarding the dichotomy between the molecular and performance-related changes in hypoxic-related adaptation, we agree with Brocherie et al. [58] who suggest that while the absence of the environmental hypoxic exposure may be responsible for the rapid decline in skeletal muscle transcriptional regulation, the performance change over time may be related to the temporal differences in the hypoxic-related adaptations. For example, recently Faiss et al. [59] reported increased expression of genes involved in anaerobic glycolytic activity in muscle immediately after 4 weeks of RSH compared to similar repeated sprints in normoxia (RSN). Similarly, and as mentioned in the paragraph above, Brocherie et al. [58], after adding high-intensity sprints conducted in hypoxia to a LHTL altitude training plan (LHTLH), found immediate (1–2 days post) enhanced molecular responses of factors associated with the signalling and carrying of oxygen (HIF-1α, myoglobin) and mitochondrial biogenesis and metabolism that returned to baseline levels by 3 weeks post-intervention. Other hypoxia-dependent postulated mechanisms that may have an immediate effect post-intervention on YYIR performance include compensatory vasodilation of the active muscle, greater microvascular oxygen delivery, particularly to fast twitch muscle, and increased removal of waste products [24]. Such alterations would improve YYIR performance immediately post hypoxic intervention, but since many of these mechanisms are reliant on regular hypoxic stress to maintain genetic expression, these changes would soon reduce during the post-intervention period. Our results found that YYIR performance was likely to be 5% higher at 4 weeks post-intervention compared to 1 week post-intervention. This maintained performance later into recovery may be associated with the gradual phenotypic change due to the initial adaptation mechanisms postulated earlier in this section, but could also be related to the longer acting aerobic adaptations (such as increased haemoglobin), which tend to take longer to occur [60].

As mentioned in Sect. 1, optimal performance in both team sport and YYIR performance also requires a strong anaerobic capacity. To this end, maximal-intensity exercise training in hypoxia, and RSH in particular, has emerged as a promising training approach. The key advantage of repeated sprint training is the maximal intensity of the repeated efforts, which purportedly maintain high glycolytic muscle fibre recruitment that better enables improved maximal performance in normoxic environments. Indeed, following two repeated sprint training sessions/week for 4 weeks in either normoxia or hypoxia, Faiss et al. [59] noted no difference in maximal power output between the groups (indicating no detriment to maximal power output with repeated sprints in hypoxia), but an increase in the number of sprints prior to fatigue in the hypoxic group, but not in the normoxic group. It is likely that the improved fatigue resistance that Faiss et al. [59] noted in their study probably also played a role in the improved YYIR performance noted in the present analysis.

In addition to monitoring power output, Faiss et al. [59] monitored changes at the cellular level. While these authors noted an increase in HIF-1α, there was little change in oxidative capacity with repeated sprint training in hypoxia. However, the training did evoke changes associated with improved fast twitch muscle activity such as improved capacity for fast twitch muscle fibre lactate removal, pH regulation, and a general shift towards glycolytic energy provision. These adaptations would also likely be useful in meeting the anaerobic demand of the final stages of the YYIR performance. While there have recently been two comprehensive reviews indicating an improvement in repeated sprint ability following RSH (compared to normoxia) [21, 24], whether the improvement in repeated-sprint ability itself would also result in improved YYIR performance is ambivalent [61].

The duality in metabolic demand in team-sport athletes suggests it is also possible that the mechanism for performance improvement in high-intensity intermittent-running performance, and the type of performance evaluated in endurance- and team-sport athletes, is responsible for the conflict in the recommendations between these distinct sporting specializations. That is, the necessity for a team-sport athlete to have highly developed aerobic and anaerobic energy systems to facilitate the high-intensity and intermittent nature of their performance adds to the complexity of formulating an optimal hypoxic dose. In general though, high-intensity exercise in hypoxia is becoming widely regarded as a worthwhile intervention for team-sport athletes. McLean et al. [22] recommend high-intensity hypoxic or normoxic training to overcome the dampened cardiovascular function in hypoxia if beneficial anaerobic performance enhancement is to be achieved. This is a sentiment agreed on by Faiss et al. [62], who have found little benefit of moderate-intensity hypoxic training compared to repeated sprints conducted in hypoxia, which appear to be far more promising regarding improved sea-level performance. McLean et al. [22], in particular, suggest that the associated sea-level training is as important as the concurrent hypoxic training for successful performance enhancement. Indeed because of the exercise-dependent and temporal nature of such adaptations, some researchers have suggested combining hypoxic training types to gain maximal performance advantage, both over the course of a periodised training plan, and during a single intervention as occurs in LHTLH techniques [48]. An example of this would be to use LHTL to improve haematological variables and endurance performance, RSH to improve anaerobic variables and repeated sprint ability, and a combination of the two for team-sports which require both aerobic and anaerobic ability. As another example, in order to develop a good aerobic base, a longer but less intense period of training has been recommended, whereas short, intense bursts of activity are recommended for anaerobic adaptation [48]. It should also be noted that the shorter 'intermittent' altitude protocols (e.g. LLTH), particularly when maximal sprinting exercise is incorporated, also activate HIF-1α pathways and result in non-haematological adaptations such as increased glycolytic activity [59] and/or mitochondrial biogenesis and metabolism [58]. It therefore seems that there are beneficial (but quite mechanistically separate) adaptations that benefit performance with both the longer LHTL and the shorter LLTH protocols.

The unclear results regarding the small effect of the added exercise in hypoxia on overall sea-level high-intensity intermittent running performance may indirectly provide support for Millet et al. [48] proposed combined approach. That is, as all of the participants in the studies selected were engaged in sea-level training in addition to the altitude intervention (either with regular team training, or as part of a LHTLH protocol), at least two of these recommendations (long, passive altitude duration; high-intensity sea-level training; and hypoxic training) were being achieved by all studies. Therefore, it appears that for team-sport athletes even a small hypoxic dose, when combined with regular team-sport training (which would typically include bursts of high-intensity activity), may have beneficial effects on sea-level high-intensity, intermittent running performance.

4.1 Further Research and the Relevance of These Findings for Coaching

What is important to recognise at this point is that the results of the inclusion of hypoxic exercise, and the differences in the intermittent versus live-high protocols, were unclear, and therefore require further investigation before more conclusive recommendations can be made for team sport-athletes.

This paper also did not examine other important physiological changes that may be important to team-sport athletes, such as explosive muscle power, reaction time or overall team performance. Therefore, further research is needed to clarify whether simulated altitude training is appropriate for team-sport athletes in a more holistic sense.

At this time, there is insufficient research available to enable a meta-analysis that can differentiate between the effectiveness of different models of hypoxic delivery. This topic should be revisited when more data from well-controlled team-based studies become available. Speculatively, Fig. 2 indicates unclear performance improvement in high-intensity intermittent running performance between the long-duration hypoxic protocols (LHTLH/LHTH) and the shorter, more intense LLTH protocols such as IHT or RSH, protocols. If the similarity between these protocols is supported by future studies, it would provide coaches with a larger scope for selecting hypoxic training methods that best suit the athlete's current training phase to maximise performance benefit. For example, the longer-duration protocols (such as LHTL) may be more effective early on in the pre-season, while shorter, intermittent (passive or active) protocols might fit better later in the pre-season when exercise intensity is increasing and the anaerobic system is being trained.

Research is also needed to further explore the post-hypoxic intervention adaptation/deadapation period in which a non-linear performance adaptation may exist (see Fig. 3). Understanding the sequence of physiological adaptations and associated change in team-sport performance will better enable coaches to plan hypoxic or altitude training micro-cycles such that their athletes peak in the required competitive period.

As there was an unclear effect of 'training high' on YYIR performance, it is possible that passive hypoxic interventions (such as IHE or LHTL) in addition to regular team-sport training which already contain high-intensity or repeated-sprint training, may be the most convenient means of administering a hypoxic dose if improving YYIR test performance is the primary desired outcome. However, as recent research (published after this meta-analysis was completed) suggests, supplementing LHTL with high-intensity exercise in hypoxia (e.g. LHTLH) produces adaptations that may result in improved YYIR performance [24, 58], and more data and ongoing research are needed regarding the effect of additional exercise in hypoxia on team-sport athlete performance. Further research is also needed to determine whether passive hypoxic intervention is sufficient to influence other drivers of team-sport performance, such as sprint performance, anaerobic performance, and agility.

4.2 Limitations

The authors recognise the extensive limitations inherent in performing a meta-analysis on data that are compounded by various heterogeneities (types of sports, types of hypoxic/altitude interventions, studies with small sample sizes and so on). However, the meta-analysis was conducted none-the-less for the purposes of stimulating discussion and potentially providing an indication of the potential merit or harm in (simulated) altitude training in team-sport athletes.

In addition to the small number of heterogeneous studies in team-sport athletes used for this meta-analysis, the YYIR level 1 and level 2 tests were used indiscriminately, despite slightly different physiological requirements (two studies used level 1, seven studies used level 2, one study did not report which level was used). While both tests are likely to stimulate the aerobic system maximally, the anaerobic energy system is more severely stressed in the YYIR level 2 test [9]. However, as the sample size was already very small, and considering that there is a large correlation [46] between YYIR level 1 and level 2 [63], the outcomes of the tests were not differentiated, and the reader is urged to consider these limitations when interpreting these data.

5 Conclusion

The use of natural or simulated altitude has a beneficial effect on sea-level intermittent, high-intensity running performance (as assessed using the YYIR), with the performance advantage improving up to 4 weeks post-intervention. However, the possibility of a return-to-sea-level re-adjustment period following natural or simulated altitude training warrants further investigation into the optimal timing, dosage, and protocol of hypoxic or altitude training programmes prior to competitive events. The unclear differences in performance associated with the inclusion of exercise training in hypoxia, or the type of natural or simulated altitude training being administered, also warrant further investigation. Outcomes of this meta-analysis suggest that some hypoxic training or exposure is better than none, but the effects of more intensive doses (i.e. exercise training at high altitude, or longer-duration live high protocols) are still unclear. It is postulated that intermittent hypoxic exposure may be beneficial in reducing the effect of neocytolysis on hypoxic-mediated adaptation, as might high- or maximal-intensity exercise both during and after the hypoxic exposure; however more research is needed in these areas. The small number of studies included in this meta-analysis, along with the heterogeneity of protocols and participants, limit the confidence with which we can present these findings. However, such research presents a starting point for the direction of further research and provides some rationale for coaches who wish to implement natural or simulated altitude training with their team-sport athletes.

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Compliance with Ethical Standards

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Conflict of interest Michael Hamlin, Catherine Lizamore and Will Hopkins declare that they have no conflicts of interest relevant to the content of this analysis.

Ethical approval This article was a meta-analysis and therefore did not require separate human ethics approval.

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