REVIEW ARTICLE

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Enhancing Team-Sport Athlete Performance

Is Altitude Training Relevant?

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Abstract

Field-based team sport matches are composed of short, high-intensity efforts, interspersed with intervals of rest or submaximal exercise, repeated over a period of 60–120 minutes. Matches may also be played at moderate altitude where the lower oxygen partial pressure exerts a detrimental effect on performance. To enhance run-based performance, team-sport athletes use varied training strategies focusing on different aspects of team-sport physiology, including aerobic, sprint, repeated-sprint and resistance training. Interestingly, 'altitude' training (i.e. living and/or training in O_2-reduced environments) has only been empirically employed by athletes and coaches to improve the basic characteristics of speed and endurance necessary to excel in team sports. Hypoxia, as an additional stimulus to training, is typically used by endurance athletes to enhance performance at sea level and to prepare for competition at altitude. Several approaches have evolved in the last few decades, which are known to enhance aerobic power and, thus, endurance performance. Altitude training can also promote an increased anaerobic fitness, and may enhance sprint capacity. Therefore, altitude training may confer potentially-beneficial adaptations to team-sport athletes, which have been overlooked in contemporary sport physiology research. Here, we review the current knowledge on the established benefits of altitude training on physiological systems relevant to team-sport performance, and conclude that current evidence supports implementation of altitude training modalities to enhance match physical performances at both sea level and altitude. We hope that this will guide the practice of many athletes and stimulate future research to better refine training programmes.

1. Introduction

Successful team-sport athletes are skilful, operate within well designed strategic and tactical confines and have highly developed decision-making abilities.[1] Importantly, these athletes must also have highly developed, specific, physical capacities. The specific capacities required for field-based team sports such as soccer, Australian football, rugby and hockey include peak speed and power,[2,3] acceleration,[4,5] strength,[6,7] repeated-sprint ability[8,9] and aerobic endurance.[4,10,11] Physical training can enhance team-sport athlete run-based performance.[12,13] Although the number of pure sprints performed in competition is relatively low, speed and acceleration qualities are associated with ball possession and, ultimately, scoring. Training that specifically enhances the capacity to repeat high-intensity efforts (HIE) has clear benefits for these athletes,[14,15] with a likely advantageous transfer to the playing field.[16,17] Furthermore, because aerobic metabolism is largely involved in fuelling recovery from HIE, strategies enhancing aerobic power also improve match fitness.[18,19] In this perspective, it is worth noting that living and/or training at low (~500–2000 m) or moderate (2000–3000 m) altitude[20] is extensively used by endurance athletes to enhance aerobic power and endurance performance.[21,22] Furthermore, altitude training can promote increased anaerobic fitness and may enhance HIE capacity.[23-25] Therefore, some evidence points to the likelihood that altitude training may profit some team-sport athletes.

Since the current review examines the potential benefits of altitude training for team-sport athletes, an additional observation needs to be emphasized. Team-sport athletes, who normally reside at sea level, also compete in venues situated at altitudes sufficient to impair performance.[26,27] Altitudes as low as 300–600 m may have a detrimental effect on some measures of physical performance,[28,29] yet sports such as rugby (union) and soccer are commonly played at altitudes as high as 1600 m (Johannesburg, South Africa), 2000 m (Kunming, China), 2300 m (Addis Ababa, Ethiopia), 2400 m (Mexico City, Mexico), 2600 m (Bogota, Colombia), 2800 m (Quito, Ecuador) and even 3600 m (La Paz, Bolivia). Surprisingly, the extent of our understanding of the effects of hypoxia on HIE capacity is still in its infancy. In fact, we were not able to find any published research reporting the effects of altitude on team-sport performance. Nevertheless, recent data collected by our group in preparation for the 2011 Fédération Internationale de Football Association (FIFA) U20 World Cup (Hammond K et al., unpublished observations) indicate that match running performance may be affected by low altitude (see section 2.3). Interestingly, after

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training in O_2-reduced conditions, both endurance and sprint performances may be improved more at altitude than at sea level.[21,30-32] Although little research describes the effects of altitude training *per se* on team-sport athletes, prior, partial or complete, acclimation of footballers to hypoxia (~1–2 weeks) either at rest or during exercise should enable teams from sea level to perform better at altitude.[26] Thus, if short-term preparation for altitude benefits performance at moderate/high altitude (where high altitude is defined as 3000–5500 m),[20] altitude training properly administered over the course of several weeks is also likely to induce positive adaptations in team-sport athlete physical performance at altitude.

The aim of this review, therefore, is to examine the scientific evidence for use of altitude training for enhancing team-sport *running* performance; the review does not specifically address winning or losing matches. To achieve this objective, the databases SPORTDiscus™, PubMed, Web of Science, and MEDLINE were searched, without any time restriction, using combinations of the terms 'repeated-sprint exercise', 'repeated-sprint ability', 'multiple sprint', 'live high-train low', live low-train high', 'hypoxic training', 'acclimatization', and 'altitude'. To facilitate understanding, the article begins with a brief overview of the match activity profile and key physiological determinants of team-sport performance at sea level and at altitude. Then, we summarize the established benefits of altitude training on physiological systems relevant to team-sport performance, and attempt to draw conclusions about the relevance and efficacy of altitude training interventions for team-sport athletes. Such a review will be useful to guide the practice of many athletes around the world in maximizing their training stimulus to achieve peak fitness. Since professional teams are already sending athletes to altitude camps in the belief that it will enhance athletes' ability to compete,[33] this scientific evidence must be collected urgently. Hopefully, this review will also stimulate more investigators to quantify the effects of acute and chronic hypoxia on team-sport athletes' fitness.

2. Physiology of Team Sports

An understanding of the physiological changes during matches is necessary to comprehend the demands on athletes. This section only provides brief synopses of the key determinants of fatigue during repeated-sprint exercises and team sports, and the reader is referred to the following reviews.[8,9,34]

2.1 Match Activity Profiles

Examining player movement during competition with time-motion analysis can provide valuable information regarding the physiological requirements of matches and the activity profile of athletes.[11,35-40] Soccer athletes, for example, regularly repeat short, high-intensity bouts of exercise, interspersed with longer intervals of rest or submaximal exercise over ≥30 min. The typical distance covered by top-class center midfielders is ~10–13 km per match; which is comprised of 70% low-intensity activity and ~150–250 brief intense actions (average sprint distances of ~10–20 m).[11,41-43] Australian footballers cover the highest distances of the field sports;[4] up to 15 km in finals matches,[44] undertake up to 30% of this distance as high-velocity running[42,44] and accelerate maximally up to 150 times per match.[44] In addition to these locomotive activities, athletes must perform other energy-demanding activities (e.g. jumping, dribbling and tackling) during matches.[35,42,43,45] These high-intensity movements often occur in response to cues such as the movement of the ball or actions of the opposition athletes, and increase energy expenditure over a match.[5] This suggests that, in addition to the intermittent high-intensity nature of team sports, a high aerobic power is crucial to success. In fact, while elite team-sport athletes do not exhibit the specific physical/physiological capacities of elite endurance and sprint athletes, they do possess an efficient combination of 'aerobic' and 'anaerobic' potentials.[12]

2.2 Evidence of Fatigue at Sea Level

Several studies have reported that high-intensity activities are reduced towards the end of matches.[36,42,43,46-48] The amount of sprints,

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high-intensity running and distance covered are lower in the second than in the first half of a soccer match.[43] Although this may be interpreted as the presence of fatigue, such findings may also be influenced by technical plays. There is also evidence of athletes becoming fatigued during a match.[43,46] When repeated-sprint ability was assessed (5×30 m sprints interspersed with 25 seconds of rest[47] and 3×40-m shuttle sprints[49]) prior to and after a match, soccer athletes could not reproduce their initial performance, presumably due to fatigue accumulated during the match. Furthermore, mean recovery time between high-intensity running bouts increases markedly over the duration of a soccer match, which is associated with an 18–21% high-intensity running distance deficit in the final 15-minute period of the match.[46] Following the most intense 5-minute periods of a soccer match, the amount of high-intensity running is decreased by half in the subsequent 5-minute period,[46] and this deficit may actually be underestimated based on our recent work using rolling time periods instead of fixed 5-minute periods.[50]

2.3 Evidence of Fatigue at Altitude

Team sports are regularly played at altitudes that hinder performance. Despite this, almost all studies have been conducted at or near sea-level, and the effect of acute hypoxia on athletes' intermittent performances remains largely unknown. Understanding how hypoxia curtails, and if altitude training benefits, the ability to repeat sprints over extended periods of time is therefore critical and is supported by FIFA.[20] To date, laboratory-based research indicates that a reduction in systemic O_2 delivery contributes to curtail repeated-sprint capacity via varied metabolic and neuromuscular mechanisms.[51-53] For example, total mechanical work was reduced (–8%) during ten 10-second cycle sprints (30 seconds of rest) performed in hypoxic (inspired oxygen fraction [F_IO_2] 0.13, ~3600 m) compared with normoxic conditions.[53] This decrement may be partly caused by reduced muscle reoxygenation during recovery periods between sprints[54] (which could affect phosphocreatine [PCr] resynthesis) and/or an attenuation of central motor drive to active locomotor muscles arising from hypoxia-sensitive sources of inhibition.[52,53] These findings highlight the potentially detrimental effect of moderate altitude for HIE performance over an extended period of time, such as in team sports. It is therefore intuitive that competing at moderate altitude is likely to precipitate fatigue in athletes and influence the outcome of matches. In fact, field data demonstrate large inequalities in the probability of a home team win between sea-level teams and opponents from moderate/high altitude when the match is played at sea level.[26] Recent data collected in preparation for the 2011 FIFA under 20 World Cup (Hammond K et al, unpublished observations) indicate that the total running distance and the low- and high-velocity running were reduced by 9.1%, 8.1% and 15.2%, respectively, during matches played in Denver, Colorado, USA (1600 m) compared with sea level matches. Consistent with the reduced air density at 1600 m, maximal accelerations performed during matches were not influenced at this low altitude. While more data at a range of altitudes must be collected to ascertain this acute effect on team-sport run-based performance, these preliminary results are in agreement with the scarce evidence available on *simulated* team-sport athlete performances. For instance, the ability of rugby athletes to perform endurance work during a 20 m shuttle run decreased (~3.5%) along with their ability to produce repetitive explosive power (~16%) at altitudes 1550–1700 m.[55,56]

2.4 Physiological Determinants

Due to the chaotic nature of team sports, it is impossible to precisely and reliably study physiological responses of athletes during matches. Therefore, sport scientists have relied largely on laboratory-based exercise models to mimic the activity patterns and physical demands of these sports. Although such laboratory tests are a crude way of replicating activity patterns in team sports, which raises a validity issue,[57] they at least provide a starting point. More recently, researchers have developed test protocols combining sprinting, jumping, acceleration, rucking/mauling, scrimmaging

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and agility drills that are more specific to team sports.[35,45,58-60] The following sections briefly outline the main muscle and neural determinants of repeated-sprint exercise, with specific emphasis on factors that might be altered via moderate altitude training.

2.4.1 Metabolic Mechanisms

The recovery of power after sprint exercise is associated with repletion of PCr.[61,62] Since PCr concentration in muscle is limited and its resynthesis time (>5 minutes) is longer than the typical recovery periods (≤30 seconds) observed during multiple-sprint work, PCr availability plays a critical role in the decline of mechanical output during repeated sprints.[63,64] As such, accelerating PCr resynthesis during recovery periods enhances fatigue resistance in repeated-sprint exercises.[12] Furthermore, PCr resynthesis is achieved exclusively via aerobic adenosine triphosphate (ATP) resynthesis,[65,66] and the kinetics of PCr resynthesis are sensitive to manipulations of O_2 availability.[65] Accordingly, the rate of muscle reoxygenation measured after submaximal exercise presents similar recovery kinetics to PCr.[67] Thus, it is not surprising to observe that a slower rate of muscle reoxygenation induced during recovery intervals between sprints via breathing low O_2 fraction impairs,[54] whereas a training-induced increase in reoxygenation rate enhances, sprint capacity.[18] That being said, some caution about this association has been highlighted recently, because complete muscle reoxygenation/high level of muscle oxygenation is not necessarily associated with preserved sprint capacity.[68]

The contributions of anaerobic glycogenolysis and glycolysis to total energy supply during repeated-sprint exercise have been investigated on several occasions. There is a progressive acidosis-driven inhibition of both glycogenolysis (~11-fold) and glycolysis (~8-fold), with minimal contributions being observed during the final sprint of a 10 × 6-second sprint cycling protocol (30 seconds of rest between sprints).[64] This dramatic reduction in energy supply is thought to reduce the maximal mechanical work developed during sprints. Thus, acute and chronic interventions designed to increase muscle buffer capacity (β_m) [hence reducing the negative effects of hydrogen ion accumulation] have sometimes resulted in enhanced repeated-sprint capacity.[69,70] However, caution remains as intracellular acidosis may actually be beneficial for muscle performance at physiological levels.[71,72] Therefore, enhancing β_m does not always improve speed or power maintenance during HIE.

In some studies, athletes reach maximal oxygen consumption ($\dot{V}O_{2max}$) after only a few short, consecutive sprints,[58,73,74] which indicates that the oxidative metabolism is critically taxed and contributes significantly to total energy supply when high-intensity efforts are repeated with relatively short recoveries. In fact, increasing aerobic power via training[18,19,75,76] and/or ergogenic aids (e.g. erythropoietin)[77] is well-known to attenuate fatigue during repeated sprints. This is in accordance with the observation that subjects with a higher $\dot{V}O_{2max}$ consume more O_2 and exhibit greater fatigue resistance during HIE than subjects with a poorer aerobic fitness.[52,78-80] Further, using a hypoxic multiple-sprint paradigm, subjects consume less O_2, exhibit slower muscle reoxygenation during recovery intervals between sprints,[18,54] experience lower cerebral cortex oxygenation[53,81] and experience premature fatigue presumably caused by these varied peripheral and neural mechanisms.[82] Thus, the higher the oxygenation status of active tissues, the higher the capacity to perform work over several sprints. When a match is played at moderate altitude, any hypoxia-induced decline in $\dot{V}O_{2max}$[83] is likely to result in poorer performance compared with sea level.[26,27] The reduction in O_2 delivery and utilization causes reductions in $\dot{V}O_{2max}$ of approximately 7% per 1000 m of altitude ascended[28,84] with a concomitant reduction in 5-minutes cycling time-trial power.[84] At an altitude of 3500 m, $\dot{V}O_{2max}$ is reduced by ~25%, which has particular relevance for team-sport athletes, as during top-level football competition, players compete on average at ~70% $\dot{V}O_{2max}$.[85] The endurance performance decrement observed at altitude in several situations (~1.1–1.5% per 100 m)[27] has been mainly attributed to a reduction in aerobic power. This decrement can also be expected in team-sport athletes. In conclusion, it seems likely that

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training interventions designed to enhance systemic delivery and local consumption of O_2 would result in superior sprint endurance at both sea level and at moderate altitude.

2.4.2 Neuromuscular Mechanisms

Investigations of the electromyographical (EMG) signal (serving as a surrogate for muscle recruitment) reveal a concurrent decline in mechanical performances and EMG signal amplitude.[52,53,86-89] For example, changes in quadriceps EMG amplitude explain 86–98% of the variance in mechanical output during consecutive sprints.[52,86,88] Since hypoxia only exerts insignificant to modest additional influences on neuromuscular transmission and muscle membrane properties,[90,91] the decline in EMG amplitude was interpreted as a reduction in muscle activation. These functional EMG changes were supported by studies showing lower motor unit activity (i.e. decrease in recruitment, firing rate or both) via the twitch-interpolated technique performed before and after repeated sprints.[89,92] The drop in EMG amplitude during repeated sprints is strongly correlated ($r = 0.80–0.95$; $p < 0.05$) with a decline in arterial blood O_2 saturation (SaO_2).[52,86] Interestingly, neurons in the mammalian brain are highly sensitive to the availability of O_2.[93] Despite being only 2–3% of total body weight, at rest the brain receives 15% of cardiac output and consumes ~20% of the body's O_2.[94] As such, a reduction in prefrontal cortex oxygenation induced by acute hypoxia (F_IO_2 0.13, ~3500 m) partly explains the changes in EMG amplitude of active muscles during ten 10-second cycle sprints.[53] Those observations are consistent with the findings that systemic hypoxaemia and insufficient brain oxygenation depress motor neuron electrical activity,[90,95-98] although this effect becomes physiologically significant only above a critical altitude of ~3500 m (SaO_2 <82%).[90,99-101] This finding may, therefore, somewhat limit the role of non-peripheral determinants (i.e. CNS hypoxia) in team-sport performance, since most matches are performed below 3500 m. Overall, an athlete's locomotor and neuromuscular profile (defined by their maximal sprinting and aerobic speeds) is likely the strongest determinant of HIE performance.[10,12,68] Since muscle activation is reduced after several sprints, it can be reasoned that conditioning strategies, which limit arterial hypoxaemia and enhance tissue oxygenation as well as acclimatize athletes to O_2-reduced environments, should improve HIE performance at both sea level and moderate altitude.

2.5 Summary

A combination of metabolic and neuromuscular mechanisms contributes to curtail multiple-sprint work,[8,34] which has recently been confirmed by investigating peripheral fatigue and neuromuscular adjustments after a soccer match.[49] Therefore, training strategies that are able to attenuate the influence of these limiting factors should improve fatigue resistance during repeated HIE.[12] Given the importance of acceleration, speed and power for team-sport athletes, if specific modalities of altitude training can enhance the rate of power development and PCr resynthesis, they may help improve important aspects of team-sport performance (e.g. single- and multiple-sprint performance, acceleration, and jump height). In addition, altitude training has been shown to enhance aerobic fitness in some endurance athletes; it could then also be used to try and maximize fitness in team-sport athletes and accelerate recovery during and following matches, thereby providing a new way of increasing chances of success during matches.

3. Effects of Altitude Training on Performance

3.1 Defining Altitude Training

Hypoxia affects availability of O_2 to several critical organs, and is a powerful signalling agent relevant to varied tissue adaptations.[102,103] It has therefore been reasoned that intensifying the training stimulus by living and/or working in hypoxia may be advantageous for athletes. The traditional 'live high-train high' (LHTH) altitude training method emerged and became popular after the 1968 Olympics in Mexico City (2240 m). This method is beneficial in enhancing haemoglobin mass, but due to adverse effects of chronic high-altitude exposure[104,105] and subsequent

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reductions in training intensity at moderate altitude,[106] its impact on performance is still debated.[21,107,108] Nonetheless, since it is perhaps the most practical modality, its effects are included below. Other options are available to athletes seeking to enhance their performance while avoiding the deleterious effects of chronic hypoxia, which include 'live high-train low' (LHTL)[106] and 'live low-train high'.[23] In this latter modality, athletes breathe reduced amounts of O_2 either at rest (intermittent hypoxic exposure [IHE])[109-113] or during individual training sessions (intermittent hypoxic training [IHT]).[32,103,114,115] These intermittent hypoxic methods are often incorporated into an athlete's training schedule in preference to living at natural altitude (i.e. LHTH and LHTL) due to minimal travel, modest expense and relatively minor disruption to training and daily life. Overall, these different modalities provide varied physiological adaptations, such as increased haemoglobin mass, ventilatory adaptations and possibly increased β_m and improved movement economy.[21,22,30,32] The following sections review the currently-available evidence that hypoxic methods may invoke physiological adaptations beneficial to endurance and HIE performances for team-sport athletes.

3.2 Effects of Altitude Training on Physiological Determinants of Team-Sport Performance

3.2.1 Muscle Glycolytic Capacity and Sprint Performance

The LHTL modality induces a worthwhile (0.8 second) improvement in 400 m run time with a significant association between this improvement and the decrease in base excess.[116] Consistent with this finding is the increased maximal accumulated O_2 deficit (~10%) and mean power output (~3.7%) during a 4-minute cycle exercise after 5, 10 and 15 nights (8–10 hours/night) spent at 2650 m and training at 610 m.[117] In fact, positive changes in muscle proteins involved in acid-base control and an increase in the capacity for lactate, bicarbonate and hydrogen ions fluxes from muscle to blood occur after sleeping in moderate to severe hypoxia.[116,118] A study from our group reported a 17% increase in β_m after 23 nights of LHTL at 3000 m.[119] However, improved anaerobic metabolism and performance after LHTL interventions is not a common finding. No change was observed in glycolytic enzyme activity and β_m after 2 consecutive nights per week (8 hours per night) at ~3600 m over 3 weeks.[120] Furthermore, despite a decline in lactate production after LHTL (20 nights at ~2650 m), there was no change in enzyme activity nor monocarboxylate lactate transporter proteins 1 and 4 (MCT1 and MCT4).[121] Large differences in the protocols used and interindividual variability may explain these discrepancies.[21,31,120]

In addition, two studies investigating the LHTH modality have reported an increase in *in vitro* β_m of ~6% following a 2-week stay at 2000–2700 m.[122,123] A more recent study[124] of mountain climbers who spent 75 days at or above 5250 m found a 5–10% increase in β_m in both vastus lateralis and biceps brachialis muscles that was more apparent in more active climbers. So, it appears that being active while staying at altitude favours greater adaptations of the glycolytic pathways.

Some IHT studies have reported an enhancement in muscle glycolytic potential. Messenger RNAs coding for enzymes of the glycolytic pathway (phosphofructokinase), glucose transport, and pH regulation (content of MCT1 and MCT4) are positively influenced by 6 weeks of IHT.[25,125] Another study reported an increase in phosphofructokinase activity after 8 weeks of IHT.[126] Therefore, upregulation of glycolytic potential, which could in turn influence team-sport performance, may be expected with several weeks of IHT. That being said, peak and mean power outputs during a 30-second Wingate anaerobic test increased (~3–5%) after only 10 days of IHT (120 minutes cycling at 60–70% of heart rate reserve) at 2500 m.[127,128] Ten days of IHT combining sprint exercise (90 minutes cycling at 60–70% of heart rate reserve, followed by two 30-second all-out sprints) at simulated altitudes of ~3200–4400 m also improved (3%) mean power output during a 30-second Wingate anaerobic test, compared with the placebo group training at sea level.[23] Unfortunately, no research about performance benefits of IHT for team-sport athletes could be located.

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Athletes and coaches should be aware that the benefit of IHT for anaerobic performance is not a universal finding since some studies have found no performance benefit.[21,115,129]

As far as IHE is concerned, breathing hypoxic gas (F_IO_2 0.15–0.10; ~2800–5600 m) at rest for 60 minutes per day intermittently over 14 days impaired rugby simulation performance (scrum peak power, offensive and tackle sprints) at sea level.[130] Further, acclimatizing rugby athletes to moderate altitude (1500 m) with a similar protocol had no effect on simulated rugby performances (six repeated 70 m sprints, rugby-specific circuit test including straight-line and agility sprints).[55] Without dismissing any effects of IHE on such performance, it is plausible that the protocol used in this study[55] provided insufficient hypoxic stimulus (hypoxia severity and/or exposure duration) to induce measurable, positive adaptations in sprint capacity. However, compared with a placebo group, 2–3 weeks of IHE enhanced (~2%) 3 km time-trial performance,[131] increased mean and peak power by ~6–8% during five 100 m sprints (~22–25 seconds) performed on a kayak ergometer,[132] and repeated 70 m shuttle sprint run times (~15–20 seconds) by 1–7%.[24] In the context of team-sport performance, it is interesting to note that the benefit of IHE for performance appears to increase from the first to the final repetition when sprints are repeated.[24] More studies need to be conducted to clarify the effects of IHE on team-sport running performance by altering the level of hypoxia and the number of days of exposure.

3.2.2 Muscle Oxidative Power and Endurance Performance

Although not a consensus,[133,134] several studies have shown positive effects of IHT on muscle oxidative power. Greater increases in citrate synthase activity and myoglobin content occurred in an IHT group (4 weeks at ~2300 m) than in a sea-level training group.[135] Similar results were obtained for citrate synthase activity after IHT at ~3500 m.[126,136] In other studies, capillary density and mitochondrial content increased after training for 6 weeks at ~3500–3850 m.[109,125,126,137] An IHT of 3 weeks at ~3000 m altered the intrinsic properties of mitochondria (i.e. greater use of glutamate and lower oxidation of fat),[138] which led to improved peak power during a graded exercise test in well trained athletes.[139] These data are well supported by the observation of improved gene expression of vascular endothelial growth factor after training in O_2-reduced conditions,[125] which may indicate that these muscular adaptations are molecularly driven. Finally, it seems that effectiveness of IHT in inducing positive physiological adaptations increases with training intensity,[22,31] in support of the general idea that higher metabolic stress (combined exercise intensity and hypoxia) yields greater adaptations. So, it may be speculated that high-intensity training in hypoxia is likely to enhance O_2 utilization,[22] which may also benefit team-sport athletes. Owing to these peripheral adaptations, it is normal to observe significant improvements in aerobic performance (35% increase in time to exhaustion at the maximal aerobic speed and 2% increase in 3 km time trial performance) in well trained runners at sea level after IHT.[140,141] However, often these improvements are minor compared with the group undertaking the same training at sea level, and there is no clear trend about the effects of IHT on endurance performance.[31,103] Furthermore, when these physiological changes did occur, they were most often observed in untrained subjects, indicating that benefits, if any, may be diminished in trained athletes, hence elite team-sport athletes.

On the other hand, altitude acclimation (via both IHT and LHTL modalities) frequently improved movement economy,[119,141-147] although this view is not ascribed to universally.[148,149] Such findings may be related to a lower cost of ventilation, greater carbohydrate use for phosphorylation or, more likely, to improved mitochondrial efficiency as denoted by an increase in ATP production per mole of O_2 used.[22]

3.2.3 Systemic O_2 Delivery and Performance

Various altitude training regimens enhance haematological factors important for endurance performance. For example, LHTH[150] and each of natural altitude[106,151] and LHTL,[106,145,146,152] but probably not IHE,[110,153] cause an increase in

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haemoglobin mass. Moreover, a recent study from our group has challenged the recommendation that ~2200 m is the minimal altitude required to upregulate haematological parameters; we measured an ~6–9% increase in haemoglobin and haematocrit after 28-days LHTH (low volume and high intensity) at 1860 m in elite sprint cyclists.[154]

In addition, both capillary number and density increased after IHT;[125,155] this adaptation is particularly salient if you ascribe to the viewpoint that $\dot{V}O_{2max}$ limitations are primarily at the level of muscle diffusion capacity.[156] However, although SaO_2 was higher after 10 consecutive days of IHT (~82–88%), compared with the placebo group,[23] this did not positively affect 20 km time-trial performance. Nonetheless, increased arterial O_2 transport could result in greater oxygenation of tissues, which could enhance performance. To date, there has been only one study investigating the impact of altitude training (specifically IHE) on tissue oxygenation, where muscle oxygenation increased, but this did not improve 20 km time-trial performance.[157] Since mechanical performance during repeated HIE is associated with the oxygenation status of active muscles[54,158] and cerebral cortex,[53,81] further studies should explore the impact of modalities such as LHTH, LHTL and IHT on tissue oxygenation in team-sport athletes. This would be particularly relevant in the context of preparation for altitude where hypoxia-induced reductions in tissue oxygenation impact significantly on performance.

3.3 Possible Implementation of Altitude Training for Team-Sport Athletes

When attempting to periodize training, it is important to consider the best predictors of HIE performance. Recent reviews of the repeated-sprint and team-sport literature confirmed that peak sprint speed (PSS) and maximal aerobic speed (MAS) are the main determinants of performance.[12,13] Therefore, in a practical way, athletes and coaches should develop these two key running speeds first when the goal is to develop HIE capacity in team-sport athletes. All additional training strategies targeting specific physiological adaptations (e.g. PCr resynthesis, β_m) are also obviously welcomed. Section 3.2 highlighted that different hypoxic modalities provide different physiological adaptations. Therefore, it is intuitive that using one particular hypoxic regimen to target one particular physiological attribute may be less beneficial for team-sport athletes than combining different modalities throughout the year. Although one must exercise caution with regards to the above-described studies since the protocols employed far from replicate the complex activity profiles of team sports, below we propose an evidence-based ‘classical’ approach that is targeted at enhancing aerobic fitness, and a more ‘detailed’ combination of modalities to enhance team-sport athlete run-based performance for matches played at sea level or at altitude.

3.3.1 Match Play at Sea Level

Developing endurance and MAS is a major goal during the preparation phase in team sports. Thus, it is likely that athletes would benefit from one to two blocks of LHTH or LHTL annually. For instance, training camps at altitudes sufficient to increase the haemoglobin mass and enhance O_2 transport (i.e. >1800 m) would be favourable (as used ‘classically’ by endurance athletes). Such sojourns would have to be of sufficient duration (i.e. 2–4 weeks).[151,154] Although the intensity of the training conducted at altitude may be reduced due to the acute effects of hypoxia, training intensity *per se* is not paramount in this phase; training volume is the targeted parameter. However, intensity might be partially maintained using interval sets with long recovery breaks.[107] Such training at altitude would help enhance running economy. Alternatively, athletes that have access to hypoxic facilities could incorporate the LHTL modality to their weekly routine with similar targeted altitude and duration. Such a design is likely to lead to positive cardiovascular and metabolic adaptations and to be well tolerated by team-sport athletes in the early stage of their season preparation.

Going into the pre-competition phase, more emphasis is put on PSS, fatigue resistance and the capacity to repeat HIE. At this stage, a combination of approaches may be required. Incorporating

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one block of LHTL at ~2000 m and training below ~1000 m to maintain interval- and sprint-training session intensity would help achieve this goal. Before and after this block, athletes may train in more severe hypoxia (IHT; up to simulated altitudes of ~3500–4000 m) to potentially boost muscle oxidative capacity, increase capillary density as well as enhance the muscle glycolytic potential. This modality could be incorporated annually as two blocks of 2–4 weeks each including two 'hard' IHT sessions per week of 1 hour (e.g. interval training at 80–100% maximal heart rate or sprint training).

Finally, during the competition phase, it is crucial to maintain PSS and, thus, training intensity. The IHT modality appears to be the most optimal in that phase in terms of training load and time constraints. Athletes could perform one to two hard training sessions per week (as above) at moderate simulated altitude (~3000 m) for 2–3 weeks.

3.3.2 Match Play at Altitude

In this situation, acclimatization to moderate altitude is the main goal. Preparation for competition at the altitude of the match for several weeks is likely to be the most efficient strategy, particularly if travel across multiple time zones is also required.[26] This can be achieved in different ways. Besides an evident practicality and team-building effect (i.e. all the players of the same team reside and train together at altitude), LHTH in the form of training camps has been, and will remain, largely adopted by teams to improve their players' fitness and achieve acclimatization before matches at altitude. However, the plateau in $\dot{V}O_{2max}$ and/or performance observed after a few weeks at altitude could be related to a decrement in training intensity at altitude, and thereby potentially offsetting the benefits of acclimatization on O_2 transport. Therefore, Levine and Stray-Gundersen[106] suggested the LHTL modality to be the most optimal. This modality may also be relevant where travel to the competition altitude is not possible. In that case, 2–4 weeks of simulated LHTL in-season would lead to improvement in performance at altitude. However, data to directly support this assertion are not available from the literature.

Intermittent hypoxic training also has the potential to assist athletes in preparation for competition at altitude.[31] Training in hypoxia proved superior to training at sea level in enhancing $\dot{V}O_{2max}$ and endurance performance in hypoxia.[109,134,140] Similarly, after 3–4 weeks of training in a hypobaric chamber at 2300 m the performance of cyclists trained in hypoxia was higher than that of a sea-level group, even though there was no change $\dot{V}O_{2max}$ or performance of the cyclists at sea level.[135] In light of the above data, we can reasonably conclude that there is evidence that IHT enhances endurance performance when subsequent exercise is conducted in hypoxia. However, due to the large variety of protocols and relatively low number of studies (none having explored team-sport performance as yet), we acknowledge that providing clear IHT recommendations for team-sport athletes may still be premature. Nonetheless, there is a general consensus that the effectiveness of IHT increases with training intensity.[22,31] Thus, athletes may benefit from an 'aggressive' IHT in the pre-competition phase, which could involve one to three hard interval-training sessions per week (in addition to normal weekly routine) for 4–6 weeks at ~3500–4000 m to increase capillary density and mitochondrial content. This may enhance general aerobic fitness, but especially, the rate of muscle re-oxygenation during recovery and thereby enhance repeated-sprint ability. This could be followed, in the competition phase, by an extended IHT block (2 days/week for 3 weeks at 2500 m) to upregulate anaerobic potential and enhance sprint performance at altitude. The timing of altitude blocks would also need to be carefully managed since the time course of benefits of altitude training are poorly characterized;[21] for instance, it is not clear if there would be any remnant benefits of an IHT block conducted a few months before competition at moderate altitude.

Finally, wherever possible, athletes are strongly encouraged to travel to the altitude where the match will be played at least a week before the match to attenuate the effects of hypoxia on physiological systems and thus performance. Endurance athletes experienced less aerobic function and performance decrement after being exposed to the

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target altitude (~2300 m) at least 14 days prior to the event.[150,159] Some athletes may also experience acute mountain sickness when ascending above ~3000 m, but the symptoms usually resolve within 1–3 days,[160] which indicates a further reason to travel to the competition site beforehand. Less sleep disturbance a few days after ascent to moderate altitude would also be beneficial for athlete recovery and, hence, for performance.

3.3.3 Anticipated Pitfalls to Implementation and Future Directions

It is complicated to plan training in order to achieve peak fitness in an elite athlete at a precise time of year or for multiple events within a year.[161] The addition of hypoxic training to the yearly programme to further boost the athlete's potential certainly adds to this complexity. While it is theoretically attractive to incorporate altitude training into a yearly team-sport athlete plan, the biggest limitation of such strategy is certainly the lack of sound scientific research to confirm and refine the efficacy of the varied altitude training modalities to enhance the capacity to repeat HIE. For example, the idea of combining approaches has only been introduced recently in the scientific literature.[22] The rationale behind this periodized approach is to elicit 'aerobic' and 'anaerobic' benefits to improve several aspects of match run-based performance. However, the scientific evidence to support a periodized approach is not yet available. Currently, sport scientists and coaches don't know how athletes, especially team-sport athletes, would respond to such a periodized approach to hypoxic training. Since it is impossible to examine the isolated effect of altitude training *per se*, sport scientists should place the emphasis on the comparison of changes observed following two additional training programmes implemented concurrently. Comparing the effect of an additional altitude regimen with a 'control' period is not particularly informative, since it is evident that a greater training stimulus would lead to a greater performance improvement.

Whilst evidence from discrete studies could be extrapolated to an annual plan of periodized hypoxic exposure (as attempted above), the actual demands of competition and potential lengthy periods of sustained fatigue in-season, as well as potentially compromised ability to adapt to a training stimulus, must be considered.[162,163] Assessing the impact of fatigue/overtraining on the ability of athletes to respond to a hypoxic stimulus and to respond to multiple doses of hypoxia over the course of a season (i.e. does an athlete benefit the same from a given altitude block in pre-season and in pre-competition?) will provide original data to design more salient training regimens. This research will have to use team-sport athletes and team-sport relevant tests (e.g. single- and repeated-sprint performance, sprint-jump sequences and repeated-sprint agility tests) to provide ecologically valid data. Finally, the relationship between physical capacity and match running performance is complex.[164] From a practical perspective, whether the physiological and performance changes observed after altitude training can be transferred to match situations remains to be examined.

Furthermore, individual variability in response to altitude training may pose an issue when considering performance enhancement,[165,166] and future studies should therefore determine a screening process designed to identify 'responders' and 'non-responders' of hypoxia training and those athletes most susceptible to decreased performance when competing at altitude. Finally, as physiological fitness does not protect against the effects of moderate altitude exposure, better predictors of individual susceptibility to mountain sickness would also facilitate team selection, particularly if the competition was conducted at high altitude such as La Paz.[167,168] Pending the results of this research, coaches can be proactive on at least one aspect; the effects of altitude training on match running performance are likely to depend upon the physical characteristics of the sport (e.g. volleyball vs soccer) and the player's position on the field. It is intuitive that soccer players may benefit more from endurance adaptations than volleyball or handball players who run relatively less during a match. Along the same line, a goalkeeper, a full back, a midfielder and a forward will not exhibit the same adaptations to, or benefit from, a given hypoxia training programme. For some positions, getting fitter does

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not ultimately translate into better running performance, simply because of the game constraints.[164,169,170] Thus, altitude/hypoxia training might not be worthwhile for some team-sport athletes.

Even after the above pitfalls have been addressed, there will remain the typical issues such as logistical and financial constraints that may limit altitude training to just one of the competition phases or even to a few days only. While the optimal duration of exposure to hypoxia with varied modalities is thought to be ~3 weeks for beneficial changes, elite team-sport athletes may not readily be able to integrate such duration in their yearly periodization for practical reasons.

It should also be appreciated that altitude training is only likely to garner performance benefits of a few percent,[21,107] if any,[115,120,149] and the majority of training benefits can be accrued at sea level with relevant attention to consistent training, adequate recovery/nutrition and skill development. Further, the magnitude of individual responsiveness for performance after altitude training (~2%) is similar in magnitude to the performance benefit itself (1–2%),[166] which means that some individuals will have no benefit at all while others might accrue nearly twice the average performance benefit (that is, up to 4% enhancement).

4. Conclusions

The physiological responses to altitude training exhibited by endurance athletes may contribute to improving team-sport athlete run-based performance. However, despite the 2008 special issue on altitude training in the *Scandinavian Journal of Medicine and Science in Sport*[26,27] and a recent review providing some recommendations for 'intermittent' sports,[22] virtually no research has been conducted on team sports. Nonetheless, we conclude that the current scientific evidence is sufficient to support the use of altitude training modalities by team-sport athletes to enhance their match physical performances at both sea level and altitude. In fact, this practice has already been encouraged to acclimatize athletes for competition at altitude.[26,27] Several teams around the world admit using some sort of hypoxia training in the hope of enhancing their athletes' performances.[33] We also acknowledge that despite an appealing physiological rationale, practitioners may be deceived by the practical implications and may question the cost-to-benefit ratio of such training. Admittedly, there are still a number of areas where research is needed to augment our knowledge of how altitude training might benefit team sports and how varied training modalities might be merged into a yearly plan.

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