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Chapter

ALTITUDE AND FOOTBALL: WHAT ARE NEW METHODS AND OPPORTUNITIES TO MAXIMIZE PLAYERS' FITNESS?

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ABSTRACT

Playing football competition at terrestrial altitude is not an isolated phenomenon. For instance, eight of the last 19 football FIFA World Cup tournaments were hosted by countries located at low-to-moderate altitude. While football-required fitness and technical qualities are affected by the development of neuromuscular fatigue at sea level, hypoxia-induced decrease in convective oxygen transport further hinders the aerobic

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capacity but also the ability to perform consecutive sprints, eventually impacting the outcome of a game. This results from the decrease in partial pressure of oxygen which reduces maximal aerobic power. The later, in turn, increases the relative intensity of any given absolute level of work, potentially delaying recovery of high-energy phosphates between high-intensity intermittent efforts. Despite reduction in air resistance (caused by the decrease in air density) could facilitate high-velocity running, it can also alter drag and lift, thereby impairing sensorimotor skills.

Conversely, altitude/hypoxic training could help footballers preparing for competition at altitude, but also at sea level. Traditional altitude training camps involve chronic exposure to low-to-moderate terrestrial or simulated altitudes (<3000 m or inspired fraction of oxygen >14%) for improving oxygen-carrying capacity. While "live high-train high" or "live high-train low" paradigms are actually implemented by many elite club or national team football squads, the benefits they may have on (repeated-) sprint performance are still debated. The development of hypoxic technologies has led to the emergence of "live low-train high" methods, in isolation (i.e., the "repeated-sprint training in hypoxia" and "resistance training in hypoxia") or in combination with hypoxic/altitude residence (i.e., "live high-train low and high"). Today, the panorama of altitude/hypoxic training methods is wider than ever and includes also practices such as "blood flow restriction" or "ischemic preconditioning", which demonstrate encouraging preliminary results. The aims of this chapter are twofold: First, to summarize the effects of acute altitude/hypoxia exposure on football-specific qualities measured in the laboratory and/or during games at terrestrial altitude. Second, to discuss the potential benefits of each altitude/hypoxic training method in respect to sport-specific physiological and fitness development and/or in-game performance.

1. INTRODUCTION

Football (soccer) is an intermittent activity which includes frequent change of locomotor activities (i.e., from low- to high-intensity running and short-duration sprints) as well as other game-related and energy-demanding efforts (i.e., directional changes, duels, dribbling, tackling, jumping, heading). At the highest level of play, the game has considerably accelerated in recent years. Beyond the technical and tactical aspects, the coaches and their conditioning staffs are therefore constantly looking for innovative approaches to improve their players' fitness level. The analysis of the footballer's physiological determinants shows that in addition to a well-developed aerobic capacity, the ability to repeat maximal or near-maximal efforts (e.g., accelerations, sprints, changes of direction and speed) is a key parameter (Bishop and Girard, 2013).

Performing football competition at terrestrial altitude (i.e., hypobaric hypoxia) is not an isolated phenomenon. For instance, since 1930, eight of the last 19 football FIFA World Cup's hosting countries were located at low-to-moderate altitude. Other age group tournaments (e.g., U-17 and U-20) were also organized at elevated venues. The analyzis from games played at terrestrial altitude (Nassis, 2013; Garvican et al., 2014; McSHarry, 2007) suggests that non-acclimatized players may be at a disadvantage when they have to perform at altitude. In this view, altitude/hypoxic training has gained an increasing interest since the 1968 Olympic Games held in Mexico City (2340 m, barometric pressure 580 mmHg), intially with the primary aim of acclimatizing athletes for competing at altitude (e.g., FIFA World Cup finals) and/or further increasing sea-level performance (Table 1).

Table 1. Historical summary of altitude/hypoxic training methods

Methods	Date	Sports	Publications
Live high-train high (LHTH)	1960s	Endurance	(Dill et Adams 1971)
Intermittent hypoxic training (IHT)	1960s	Endurance	(Roskamm et al., 1969)
Live high-train low (LHTL)	1997	Endurance	(Levine et Stray-Gundersen 1997)
Resistance training in hypoxia (RTH)	2000s	Puissance	(Friedmann et al., 2003)
Repeated-sprint in hypoxia (RSH)	2013	Intermittent	(Faiss et al., 2013b)
Live high-train low and high (LHTLH)	2015	Intermittent	(Brocherie et al., 2015b)
Live high-train high and low (LHTHL)	2015	Endurance	(Rodriguez et al., 2015)

Several altitude/hypoxic training methods such as “live high-train high” (LHTH) and “live high-train low” (LHTL) or more recently “live low-train high” (LLTH) have thus been developed (Wilber et al., 2007, Millet et al., 2010).

The aims of this chapter are twofold: First, to summarize the effects of acute altitude/hypoxia exposure on football-specific qualities measured in the laboratory and/or during games at terrestrial altitude. Second, to discuss the potential benefits of each altitude/hypoxic training method in respect to football-specific physiological and fitness development and/or in-game performance. Special attention will focus on the most innovative altitude/hypoxic methods.

2. ACUTE ALTITUDE EXPOSURE ON FOOTBALL-SPECIFIC QUALITIES

Data collected during official games of the 2010 FIFA World Cup (Nassis, 2013) and in preparation for the 2011 FIFA U~~under~~-20 World Cup (Garvican et al., 2014) reported 3-9% decrease in total distance covered at altitude ranging 1200-1753 m compared to sea level. Furthermore, using a 5 min rolling sample period for analyzis gave an indication of transiently lower output, possibly fatigue, during football games. As a result, there were ~7%, ~21% and ~20% respective reductions in total distance covered, high-velocity running and acceleration frequency in the 5 min subsequent to the peak 5 min period at 1600 m compared to sea level, suggesting transient neuromuscular fatigue (Garvican et al., 2014). This could then hinder footballers’ capacity to repeat intense efforts during a game (Billaut and Aughey, 2013). Non-acclimatized footballers may be at a disadvantage when required to perform at altitude. For instance, during games played 4 days after arrival at a terrestrial altitude of 1600 m, low- (i.e., <15 km h^{-1}) and high-velocity running (i.e., 15–36 km h^{-1}) declined by 8 and 15%, respectively (Garvican et al., 2014). These observations indirectly support the presence of altitude/hypoxia-related anticipatory modification of pacing, possibly owing to altered effort perception (Brocherie et al., 2017a), in addition to the well-known decline in maximal aerobic power with altitude ascent (~7-8% for every 1000 m above 1500 m) (Wehrlin and Hallen, 2006) to prevent excessive fatigue during games.

Althoug there is not a clearcut altitude threshold, it is generally assumed that terrestrial altitude >1000 m negatively affects endurance-based running distance (i.e., >800 m) (Hollings et al., 2012; Hamlin et al., 2015) as well as key game-related activities (i.e., chasing the ball, controlling long passes; the latter being related to the lower air density at terrestrial altitude) (Nassis, 2013; McSharry, 2007). Conversely, short duration efforts (i.e., <45 s) are less affected because of a larger anaerobic contribution. For instance, laboratory-based wingate tests performed at 1900 m and 3700 m compared to sea level resulted in similar performance in University-level footballers (Ogura et al., 2006). As terrestrial altitude level reduces air density (~1% for every 100 m) (Levine et al., 2008), the aerodynamic drag is then modified and facilitates high-velocity runs (Hollings et al., 2012), and decreases its energy cost without reducing energy availability (Peronnet et al., 1991).

When ‘‘all-out’’ efforts are repeated at altitude, sprint performance is impaired to a greater extent than at sea level (Girard et al., 2017). Reportedly, repeating 5 × 5-s sprints (25-s recovery) at a simulated altitude of ~3600 m compared to sea level induced larger sprint decrement score (8% *vs*. 3%) and shorter cumulated distance covered (111 m *vs*. 117 m) (Girard et al., 2016). Furthermore, increasing altitude level (i.e., 3600 m *vs*. 1800 m *vs*. sea level) exacerbates the impairments in repeated sprinting (8 × 5-s sprints – 25-s recovery), thereby suggesting that repeated-sprint decrement does not follow a monotonic (i.e., linear) pattern (Brocherie et al., 2016).

3. ALTITUDE/HYPOXIC TRAINING METHODS FOR FOOTBALL

Live High-Train High

The “traditional” LHTH method is generally used for acclimatization before a competition held at altitude. This training method is mainly based on possible hematological benefits – i.e., an increase in hemoglobin mass (Hb_{mass}) – which most often results in an improvement in maximal oxygen consumption (VO_{2max}). LHTH training camps usually require altitude residence for ~3-4 weeks (Bonetti and Hopkins, 2009), which appears problematic for football squads that do not have sufficiently long preparation period (e.g., pre-season or winter break). That said, in other team sports such as Australian football league, a pre-season training camp of 19-21 days has allowed players to increase their Hb_{mass} by 3-4% (McLean et al., 2013).

It has been speculated recently that the effect of altitude/hypoxic training on Hb_{mass} would depend on its initial level; i.e., players with an already high initial level of Hb_{mass} would not increase their Hb_{mass} much following altitude/hypoxic training; conversely, players with a low initial Hb_{mass} value would demonstrate a greater Hb_{mass} gains (Robach and Lundby, 2012). However, this analyzis was biased and based on inaccurate data and this theory has therefore been refuted (Millet et al., 2017). Hence, 3-4% gains have been observed in highly-trained endurance athletes and elite field hockey players with already high initial Hb_{mass} values (< 14 $g.kg^{-1}$) before the intervention (Saunders et al., 2013; Hauser et al., 2018). That said, if the fitness performance gains from LHTH appear to be dependent on the magnitude of the hypoxia-induced Hb_{mass} increase (Levine and Stray-Gundersen, 2006), and because footballers are generally characterized by low Hb_{mass} and/or average VO_{2max} (Levine and Stray-Gundersen, 2006), it is therefore reasonable to expect an increase in Hb_{mass} in footballers after LHTH intervention.

3.2. Live High-Train Low

Since the first LHTL study (Levine and Stray-Gundersen, 1997), the LHTL paradigm (≥2-weeks training period with a daily hypoxic exposure of ~12 h) is widely recognized as the "gold standard" method in endurance sports and is becoming increasingly used in team sports, mainly football and rugby (Girard et al., 2013). Its success relies on the erythropoietic effect (i.e., the production of erythrocytes or red blood cells stimulated by erythropoietin or EPO) following chronic terrestrial or simulated hypoxic exposure (>5-7 days), while maintaining a high training intensity (oxygen flux) near sea level (Wilber et al., 2007). The LHTL method using artificial hypoxic stimulation (normobaric hypoxic chambers) seems particularly suitable for football. This offers the possibility to overcome the geographical constraints (i.e., staying on the same residence and training site), while allowing individualization of the hypoxic dose (based on level and duration, expressed in hours, kilometer hours (Garvican et al., 2016) or saturation hours (Millet et al., 2016)] and the training contents. A recent meta-analysis indicates that Hb_{mass} increases by ~1% per 100 h altitude/hypoxia, regardless of the type of exposure [LHTH (>2100 m) or LHTL (~3000 m)] (Gore et al., 2013; Wehrlin et al., 2016). For instance, in water polo players, 10 days of LHTL induced an increase in Hb_{mass} (+3-4%), which was also associated with a gain in performance on a specific swim test (Garvican-Lewis et al., 2013). Collectively, this suggests that a 2-week LHTL camp would be effective in improving aerobic fitness in "realistic" conditions as part of a pre-season football preparation, compared to a "classical" 3-4-weeks camp.

3.3. Live Low-Train High

The LLTH training method is associated with limited costs and travel constraints for athletes who can remain in their home environment and maintain their usual lifestyle while training few times a week under hypoxic conditions (McLean et al., 2014). The additional hypoxic stimulus while exercising typically results in a greater reduction of the partial pressure of oxygen in the muscle compared to similar training at sea level (Hoppeler and Vogt 2001). While it is unlikely that a LLTH dose is sufficient to increase Hb_{mass} (Humberstone-Gough et al., 2013), a short and intense hypoxic exercise should induce specific muscular adaptations (e.g., an increase in the number of capillaries per fiber, mitochondrial density and myoglobin concentration). This allows for a better oxygen diffusion and an increase of the enzymatic oxidative activity (e.g., citrate synthase) which does not occur under normoxic conditions, or to a lesser degree (Hoppeler and Vogt, 2001). The technological development of normobaric hypoxic devices had led to the proliferation of promising innovative training methods (Millet et al., 2010, 2013; Girard et al., 2017). Since performance during high-intensity intermittent exercise does not only depend on the oxygen-carrying capacity, LLTH-induced molecular muscle adaptations and neuromuscular system efficiency seem advantageous to meet the requirements of football (i.e., to better resist fatigue in intense periods or at the end of a game).

3.3.1. Continuous Training in Hypoxia

When exercises performed in hypoxia (e.g., ~2000 m) are prolonged (i.e., >30 min) at a fixed submaximal intensity (i.e., <65% VO_{2max}) with the objective of improving aerobic capacity, it is called "continuous hypoxic training" (CHT) (Millet et al., 2013). However, this strategy appears to be relatively inefficient for producing superior gains in performance compared to similar training at sea level. To date, only two studies (not specific to football) have found an additional gain of this type of hypoxic training via a greater mechanical power production during a 30-s cycling sprint test in triathletes (Meeuwsen et al., 2001) and a decrease in the energy cost at submaximal speed in runners (Holliss et al., 2014). A possible explanation relies on the fact that relative training intensity is often similar with and without hypoxic exposure, thereby possibly minimizing the cardio-metabolic load (insufficient intensity) during CHT sessions. In contrast, combining CHT with interval-training sessions with (Hamlin et al., 2010) or without hypoxia (Czuba et al., 2011) seems effective to induce sufficient cardiovascular sollicitation and improve performance.

3.3.2. Intermittent Hypoxic Training

Compared to similar training conducted at sea level, intermittent hypoxic training (IHT) – e.g., 3-5 sets of 2-5 min at intensities of 80-100% VO_{2max} with 2-4 min of recovery at simulated altitudes of 2500-3000 m – could induce some specific molecular changes in skeletal muscle (Zoll et al., 2006) and positively influence the fitness level (i.e., even without obvious changes in oxygen-carrying capacity) (Hoppeler and Vogt 2001, Zoll et al., 2006).

However, a complete analyzis of the scientific literature, based on the results of more than 10 studies including short and intense intervals, shows that IHT does not uniformly improve performance when hypoxic stress is superimposed (Faiss et al., 2013a). For example, eight IHT sessions performed over a 4-week period improve low-intensity locomotor activities among Australian football players during an intermittent 30-min treadmill-based protocol (alterning rest, jogging, running and sprinting) (McLean et al., 2015). However, similar training at sea level appears more effective to improve the total distance covered during the Yo-Yo Intermittent Recovery test level 2 (McLean et al., 2015). The decreased intensity of the training stimulus due to hypoxia remains an inherent limitation of the IHT (McLean et al., 2014). Overall, the majority of IHT studies does not demonstrate any additional benefit in adding hypoxic stress to any intermittent training from which intensity does not exceed the maximal aerobic power or VO_{2max}.

3.3.3. Repeated-Sprint Training in Hypoxia

The "repeated-sprints training in hypoxia" (RSH) paradigm requires the completion of maximal short duration (≤30 s) efforts interspersed with incomplete recovery periods in hypoxic environment. A fundamental difference with IHT is the maximal effort required by RSH, which demands a very high recruitment of fast-twitch fibers. As previously mentioned (see section 2), single sprint performance is well preserved up to altitudes even higher than 3500 m. However, repeating sprints in hypoxia results in power output decrement (Bowtell et al., 2014) with its magnitude being dependant on the exercise:recovery ratio which determines the oxidative and glycolytic contribution (Millet and Faiss-, 2012).

In the first published RSH study (Faiss et al., 2013b), 8 RSH sessions (120 sprints in 4 weeks) delayed fatigue during a repeated-sprint test completed until exhaustion (i.e., 40% increase of the number of sprints completed) whereas a similar number of repetitions before task failure was completed after repeated-sprint training in normoxia (RSN). A team sport-specific study conducted with high-level rugby players also showed an additional gain of 19% on a non-motorized treadmill repeated-sprint test compared to similar training at sea level (Galvin et al., 2013). Similarly, Gatterer et al. (2014) showed that football specific shuttle-run sprint training was associated with greater resistance to fatigue during a repeated-sprint test (lower fatigue slope) when compared to RSN training. In highly-trained youth footballers, the addition of 10 RSH sessions to their regular football practice over a 5-week in-season period was more efficient than RSN at enhancing repeated-sprint and repeated-agility (i.e., including direction changes) abilities (Brocherie et al., 2015a).

RSH is undoubtedly a promising and well-tolerated training model (Brocherie et al., 2017a, b) although its underlying mechanisms remain hypothetical. RSH would be effective through an improved muscle blood perfusion which, in turn, would benefit from optimized oxygen extraction by fast-twitch fibers. With repeated maximal-intensity hypoxic efforts, specific skeletal muscle tissue adaptations may arise through the oxygen-sensing pathway (i.e., capillary-to-fiber ratio, fiber cross-section area, myoglobin content and oxidative enzyme activity such as citrate synthase) that do not occur in normoxia or, if they do so, do so to a lesser degree (Hoppeler and Vogt 2001, Zoll et al., 2006). Thus, RSH studies including muscle biopsies have observed an overexpression of transcription factors involved in oxygen-signaling and oxygen-carrying capacity and mitochondrial metabolism enzymes (Brocherie et al., 2017c), as well as

genes involved in pH regulation (Faiss et al., 2013b). With an expected improved behavior of fast-twitch fibers, notably via compensatory vasodilatation (Casey and Joyner, 2012), greater microvascular oxygen delivery (Cleland et al., 2012) and possible better phosphocreatine resynthesis, these mechanisms may explain the putative benefits of RSH to improve footballers' fitness level.

3.3.4. Resistance Training in Hypoxia

Resistance training is an essential part of footballers' strength and conditioning to improve muscle strength and/or endurance and prevent injury. While passive altitude/hypoxic exposure *per se* does not improve force-producing capacity, resistance training performed in oxygen-deprived environment, known as "resistance training in hypoxia" (RTH), may increase the metabolic stress (i.e., anaerobic system) and therefore the hypertrophic responses (e.g., increased endocrine responses, increased myokine production, accelerated recruitment of higher threshold motor units) (Scott et al., 2014). Historically, hypoxic stress during resistance sessions was first obtained using blood flow restriction (BFR, also known as "Kaatsu") before using systemic hypoxic systems that have been the scope of more recent studies. In a pioneering study (Friedmann et al., 2003), low-intensity RTH training [i.e., 6 sets of 25 repetitions at 30% of maximal repetition (1RM), 3 times per week for 4 weeks] combined with hypoxic exposure (~4000 m) did not show any additional gains in maximal strength compared to similar training performed at sea level. However, to date, in the only study having recruited team-sport athletes (i.e., 30 netball players), RTH (i.e., 5 weeks of training of the extensor and flexor muscles of the knee at 20% 1RM producing an oxygen saturation of ~80%) not only improved maximal strength and muscle hypertrophy but also led to better 5 m and 10 m sprints performance (Manimmanakorn et al., 2013), while smaller changes occured in players who followed an identical training at sea level.

These conflicting results could in part be explained by some methodological differences and generic (non-specific) training methods that have used relatively low loads, contrary to what is currently practiced in football clubs (especially via muscle-strengthening type training based on the improvement of the explosive force). To expect higher gains with RTH, moderate altitude/hypoxic exposures (between 2000 m and 3000 m) with relatively short recoveries between efforts (Scott et al., 2014) should be used. Specifically, in order to produce a sufficient but not exaggerated level of metabolic stress, we suggest recovery times of ~30 s for low loads (20-30% 1RM) and ~60 s for moderate loads (50-70% 1RM).

3.3.5. Local Hypoxia

3.3.5.1. Blood Flow Restriction

Several studies report some positive morphological adaptations and strength gains (albeit small) in low-load resistance exercise training with additional BFR (Scott et al., 2015). This method requires the application of an inflatable cuff around a limb (i.e., proximal to the muscles to be trained), which produces a local hypoxic stress by limiting the blood supply to and from the contracted muscles. Recent studies show some performance gains for single- and repeated-sprint exercises following BFR training (Abe et al., 2005, Manimmanakorn et al., 2013, Cook et al., 2014). For instance, 5 weeks of low-load resistance training combined with BFR improves netball players' 5 m and 10 m sprint performance compared to control (without BFR or hypoxia), with larger gains for the BFR method (Manimmanakorn et al., 2013). To date, there are no uniform recommendations as to the best way to use the BFR method. Recently, the effectiveness of a 30-s repeated-cycling sprints training combined with post-exercise (recovery) BFR period has been investigated by Taylor et al. (2016). While this innovative BFR procedure was effective to increase the VO_{2max} (+4.5%) in trained athletes compared to unconstrained post-exercise recovery, this has failed to significantly improve the time trial (15 km) performance. In this study, the observation of improved hypoxia inducible factor-1α-mediated cell signalling with the addition of post-exercise BFR to increase tissue hypoxia might suggest that this form of hypoxic training has the potential to increase repeated-sprinting performance, but this still needs to be verified.

3.3.5.2. Ischemic Preconditioning

Ischemic preconditioning (IPC) is defined as the successive exposure to brief periods of circulatory occlusion and reperfusion (Incognito et al., 2016) completed several minutes prior to a given exercise. This method has been proposed as an effective ergogenic aid to significantly improve physical performance. Research into the effects of IPC on repeated-sprint performance is relatively recent and remains equivocal. While some studies report an improvement in the mechanical power during repeated sprints following IPC (Kraus et al., 2015, Patterson et al., 2015), others did not observe any change (Gibson et al. 2015, Lalonde and Curnier, 2015) or even showed a detrimental effect on a serie of repeated "Wingate" sprints (Paixao et al., 2014). Furthermore, IPC seems to improve single 100 m (Jean-St-Michel et al., 2011) and repeated 50 m "all-out" efforts (Ferreira et al., 2016) swimming time. Conversely, no effect was apparent during 3 × 30-m runs repeated every minute (Gibson et al., 2013).

The most common IPC protocol (as adopted in all the studies described in this section) requires the application of 3-4 cycles of 5-min occlusion/reperfusion cycles (Incognito et al., 2016). Nonetheless, the large variability of participant characteristics (i.e., IPC responsiveness, training status), exercise modes (e.g., cycling, running, swimming) and study methods (e.g., size/mass of the occluded limb, unilateral or bilateral occlusion, time between IPC and exercise start, cuff inflation pressure) makes the direct comparison of results difficult and may explain the discrepant findings. While IPC is known to increase oxygen saturation during successive "all-out" efforts (Patterson et al., 2015), the level of perceived effort (Gibson et al., 2015, Patterson et al. 2015) and blood lactate levels (Patterson et al., 2015, Ferreira et al., 2016) were not altered. While IPC's mechanisms need further investigations, it seems that it may potentiate muscle activation as well as mitochondrial efficiency and excitation-contraction coupling (Incognito et al., 2016).

3.4. Live High-Train Low and High

An additional option in altitude/hypoxic training is the combination of different altitude/hypoxic training methods (Millet et al., 2010). Assuming that if the LHTL paradigm works to potentiate the aerobic qualities at sea level, and if RSH improves fatigue resistance during repeated sprints (Faiss et al., 2013b; Millet et al., 2013; Brocherie et al., 2015a, 2017b), then the "live high-train low and high" (LHTLH) method should maximize the physiological benefits due to the combination of these two methods. Furthermore, the combination of hypoxic methods would mitigate some side effects (i.e., decreased plasma volume and ATP-asic Na^+/K^+ activity) observed when the methods are used in isolation (Girard et al., 2013).

Recently, a 2-week LHTLH camp (low hypoxic dose, ~200 h) scheduled during an elite field hockey mid-season improved both aerobic and anaerobic fitness of players, compared to LHTL training (with repetition of sprints at sea level) or sea-level training (Brocherie et al., 2015b). In particular, these results highlight an increase in Hb_{mass} [(+3-4%, in agreement with previous LHTL studies conducted on various team sports (Garvican-Lewis et al., 2013, McLean et al., 2013) likely to be maintained up to 20 days post-intervention] and an improvement in aerobic performance (+21-40% in the Yo-Yo intermittent recovery test level 2) following both LHTLH and LHTL compared to control. On the other hand, the superiority of the LHTLH method over LHTL is particularly relevant on the repeated-sprint ability since the benefits were two-fold higher after the intervention (cumulated time: -3.6% *vs.* -1.9%, respectively) and were maintained for LHTLH only for at least 3 weeks after intervention (Brocherie et al., 2015b).

Indeed, the addition of the 6 RSH sessions (~5 h at a simulated altitude of 3000 m) for the LHTLH group had no measurable impact on the Hb_{mass} increase, demonstrating that the hypoxic dose is the main factor responsible of Hb_{mass} increase and that RSH itself has no "erythropoietic" effect. More importantly, this suggests that the increase in Hb_{mass} is not impaired by RSH-induced mechanisms. The proposed mechanisms include molecular adaptations of muscle tissue (Brocherie et al., 2017c), improved efficiency of the neuromuscular system (particularly in the fast-twitch fibers) (Faiss et al., 2013a), improved anaerobic glycolysis (Faiss et al., 2013b) and improved buffering capacity of muscles (Gore et al., 2005).

4. CONCLUSION

Terrestrial altitude negatively affects footballers' endurance-based running distance as well as key game-related activities. Conversely, short duration efforts (i.e., <45 s) are less affected because of a larger anaerobic contribution. The reduction in air density at terrestrial altitude leads to an improved sprinting performance. With the repetition of maximal efforts, however, repeated-sprint ability is more altered at high altitudes (~3000–3600 m) compared to near sea level. Overall, non-acclimatized footballers may be at a disadvantage when required to perform at altitude.

More than 50 years after the first scientific publications on altitude/hypoxic training and the launch of prestigious altitude training centers (e.g., Font-Romeu in France or Saint Moritz in Switzerland) for the preparation of the Mexico 1968 Olympic Games, major progress has been made in improving fitness level and understanding its underlying mechanisms. Beyond the method considered, the choice of the "hypoxic dose" (i.e., level and duration) and the training load (i.e., content, volume, intensity) are essential to optimize the hypoxic benefits and to reach a maximal level of performance in football.

This chapter has shown that there is no single form of altitude/hypoxic training that can be recommended to most effectively improve the performance factors in football (i.e., aerobic capacity and repeated-sprint ability). While various interventions can be targeted to improve the different determinants of performance (i.e., passive chronic hypoxic exposure and maximal high-intensity hypoxic training to maximize oxygen-carrying capacity and muscle utilization, respectively), the combination of different altitude/hypoxic training methods would certainly be the optimal strategy. Many training centers in altitude (Font-Romeu at 1850 m combined with an hypoxic chamber for RTH, RSH or LHTLH) or at sea level now have the facilities for such combination of altitudes, intensities that are paramount for the preparation of footballers in hypoxia. While the implementation of hypoxic equipment in many professional football squads is increasing, the difficulty of combining hypoxic methods to best fit with the overall training program must be overcome in order to achieve the best results. Finally, the link between the increase in physiological qualities following an altitude training period and that of fitness performance in the game will have to be more clearly established.

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