Effect of altitude on football performance

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Altitude will impact football performance through two separate and parallel pathways related to the hypobaric (physical) and hypoxic (physiological) components of terrestrial altitude: (a) the decrease in partial pressure of oxygen reduces maximal oxygen uptake and impairs “aerobic” performance by reducing maximal aerobic power, increasing the relative intensity of any given absolute level of work, and delaying recovery of high-energy phosphates between high-intensity “interval” type efforts; (b) the decrease in air density reduces air resistance which will facilitate high-velocity running, but will also alter drag and lift thereby impairing sensorimotor skills. These effects appear to have their greatest impact very early in the altitude exposure, and their physiological/neurosensory consequences are ameliorated by acclimatization, though the extent of restoration of sea level type performance depends on the absolute magnitude of the competing and living altitudes.

Altitude has profound effects on exercise and sports performance. Hypobaric hypoxia induced by increasing terrestrial altitude has two major effects, physiological and physical, both of which will influence football performance: (a) the reduction in partial pressure of oxygen reduces oxygen flux at every step along the oxygen cascade and thereby decreases the availability of oxygen at the mitochondrial level to produce ATP via oxidative phosphorylation; (b) the decrease in air density reduces air resistance which will alter drag and lift as well as facilitate high-velocity running.

Physiological effects of high-altitude exposure

Success in football at the international level depends on the interaction among multiple characteristics including technical, tactical, and physical factors (Hoff & Helgerud, 2004). Worldclass football players do not necessarily have “elite” physiological performance capacities, such as those seen in predominantly endurance sports like running or cycling, or explosive speed sports like sprinting. The average VO2max of professional football players at sea level is in the 55–65 mL/kg/min range (Brutsaert et al., 2000; Hoff & Helgerud, 2004), though some individuals have been reported to be > 70 mL/kg/min (Hoff & Helgerud, 2004). A typical 90 min football game requires players to run 8–12 km, at an average work rate that is close to their maximal steady-state (lactate or ventilatory threshold) (Bangsbo et al., 1991; Reilly, 1994). Although this is the “average” work rate, a typical football game is a more accurately characterized as a combination of brief bursts of high-intensity running, followed by lower intensity recovery. The higher the maximal oxygen uptake of a football player, the greater the distance covered in a game (Bangsbo, 1994) and the greater the number of sprints attempted (Smaros, 1980), suggesting an important contribution of both oxidative as well as non-oxidative energy sources during a match.

Maximal performance

For short duration bursts of high-intensity activity lasting <1 min, the predominant energy source is substrate level phosphorylation and non-oxidative production of ATP (di Prampero, 2003). Such activities are not impaired at all by high altitude – indeed, in the Mexico City Olympics held at an altitude of 2240 m in 1968, multiple world records were set in the sprint events because the reduced air resistance decreased the energy cost of running at high velocities, without the detrimental effect of reducing energy availability (Peronnet et al., 1991).

Peronnet et al. (1991) have calculated the effect of altitude on running performance and concluded that for all running events up to 400 m, there is a
progressive improvement in running performance with increasing altitude up to an altitude of 2500 m (Fig. 1). For shorter sprints (100 and 200 m) this improvement is sustained even at altitudes up to 4000 m, though the benefit levels off at altitudes above 3000 m when the distance is prolonged slightly to 400 m which involves greater contribution of oxidative energy sources (Peronnet et al., 1991). Thus, for a football player for whom even the longest sprint is rarely longer than 200 m, the velocity at which each individual sprint can be run is likely to be faster at altitude than it is at sea level.

Of course, athletes use many cues to determine the perception of exercise intensity – how fast they cover the ground; how hard they breathe for a given velocity; how fatigued their muscles are, related at least in part to energy metabolism and lactate accumulation. With acute altitude exposure, for the same absolute work intensity, ventilation is higher, heart rate is higher, as is the rate of lactate appearance with concomitant blood lactate accumulation than it is at sea level (Brooks et al., 1991a; Wolfel et al., 1991a). Therefore, a football player may perceive a given exercise effort as “harder”, even though the velocity might be higher than at sea level. This dichotomy between absolute speed and perceived exertion may be most prominent during submaximal exercise, which will be discussed further below.

Moreover, it is not only a single sprint that must be considered in a football game, but rather the consequences of repetitive sprints, which includes recovery. Sophisticated analysis of ATP regeneration after fatiguing exercise has demonstrated that re-synthesis of ATP may be significantly slowed in hypoxia (Haseler et al., 1999, 2004, 2007). Therefore, although a single sprint may be faster at altitude than at sea level, repetitive sprints may be more fatiguing, especially during shorter recovery periods (Brosnan et al., 2000). Ultimately the magnitude of this effect depends on the duration of the sprint, and the work-to-rest ratio. For example, Brosnan et al. (2000) examined repetitive 15 s cycling sprints and showed no difference in peak power over the course of six sprints between low altitude (585 m) and moderate altitude (2100 m) as long as the work:rest ratio was 1:3. For shorter recovery periods, there was a small effect of altitude (approximately 2.5% decrease per 1000 m), though the predominant effect was the fatigue occurring from the repetitive sprint itself. More recently, Feriche et al. (2007) examined repetitive 400 m sprints at sea level and 2320 m with recovery periods lasting from 1 to 5 min. In this study, the athletes were able to run about 10–15% further at sea level than at altitude when only 1 or 2 min recovery were allowed between sprints; however, this difference was eliminated when 5 min between sprints was allowed (Feriche et al., 2007). The specific pattern of exercise and recovery of a football match in hypoxic conditions has not been explicitly studied. However in practical terms, it could be speculated that at 2000 m playing altitude, a footballer would be able to run about 5 m less far, or cover 100 m in about a half a second slower speed at the end of a series of repetitive sprints with limited recovery.

Certainly the most often studied and well-described effect of altitude exposure on exercise performance is the reduction in maximal oxygen uptake (VO$_{2\text{max}}$). More than 20 studies have been reported in untrained and athletic individuals since the early 1980s and were reviewed a decade ago (Fulco et al., 1998). The key take home messages of these studies is that VO$_{2\text{max}}$ decreases by about 1% for every 100 m above 1500 m for non-athletic individuals, though there is substantial individual variability in this response.

At least some of this variability is due to differences in fitness among populations. These data were updated recently to include only studies in which endurance trained athletes were included to improve the precision for athletic populations (Wehrlin & Hallen, 2006) (Fig. 2); when the population being studied was limited in this regard, VO$_{2\text{max}}$ decreased by 7.7% per 1000 m altitude. One important contributing factor is that endurance trained athletes...
with large VO\textsubscript{2max} may have a steeper decline in VO\textsubscript{2max} with altitude, and perhaps more importantly, this decline is demonstrable at altitudes as low 600 m (Terrados et al., 1985; Gore et al., 1997). The mechanism for this greater decline in VO\textsubscript{2max} at altitude in athletes is likely to be their very high cardiac output and consequent pulmonary blood flow which is the most prominent adaptation of an endurance athlete (Fig. 3) (Levine, 2008).

Because the pulmonary circulation is not nearly as plastic or adaptable as the heart and systemic circulation, the very high pulmonary blood flow of the endurance athlete outstrips the diffusing capacity of the lung, especially when the diffusion gradients for O\textsubscript{2} transfer at the pulmonary capillary are lowered by high altitude (Torre-Bueno et al., 1985; Wagner, 1996). This diffusion limitation leads to progressive hypoxemia even at relatively mild altitudes (and often at sea level) in endurance athletes (Dempsey & Wagner, 1999; Levine, 2008).

More recently, Wehrlin & Hallen (2006) have extended this body of knowledge by studying a group of competitive athletes at multiple different altitudes to explicitly test the hypothesis that there is a threshold altitude for reduced VO\textsubscript{2max} in individual athletes. In this creative study, the investigators ensured that subjects ran at least as fast as they did at sea level therefore exercising at the same absolute intensity and avoiding the possibility that reduced voluntary effort/motor recruitment could contribute to the reduced VO\textsubscript{2max} at altitude. They found that there was a quite uniform and highly linear decline in VO\textsubscript{2max} at altitude, beginning as low as 800 m altitude and extending through 2800 m with a rate of decline of 6.3% per 1000 m altitude (range 4.6–7.5%/1000 m). The magnitude of this reduction in VO\textsubscript{2max} is remarkably similar to the 5–8% reduction in 3000 m run time at an altitude of 1800 m observed in a large number of competitive distance runners (n = 48) within the first 5 days of altitude exposure (Levine and Stray-Gundersen, unpublished observations). Because 3000 m is a race, which lasts 8–10 min and is run at or near VO\textsubscript{2max}, it is compelling that the laboratory data are precisely matched by athletic performance data in the field. This study by Levine and Stray-Gundersen also demonstrated two important points that are germane to this discussion. First, for a performance effort at an altitude of 1800 m, the smallest reduction in performance occurred in athletes who lived at the performance altitude – athletes who lived at higher altitudes (2500–2800 m) did worse acutely; for example the impairment in racing time for athletes living at 2800 m was twice the impairment observed in the athletes living at 1800 m, despite the fact that the athletes trained together at the same altitudes. Second, all athletes who lived above 2000 m continued to improve their low altitude racing times over a 4-week-period at altitude at a rate of approximately 1.4% per week. The implication of these observations is (a) that athletes should live at the competition altitude and no higher, especially for performances that must take place within 2 weeks of ascent to altitude; and (b) that altitude performance continues to improve with acclimatization, at least through 4 weeks of moderate altitude residence.

**Fig. 2.** From Wehrlin & Hallen (2006), this figure includes only those studies which included male, unacclimatized endurance trained athletes, with a mean VO\textsubscript{2max} > 60 mL/kg/min. VO\textsubscript{2max} is reduced by 7.7% per 1000 m altitude. With kind permission from Springer Science & Business Media: European Journal of Applied Physiology, Linear decrease in VO\textsubscript{2max} and performance with increasing altitude in endurance athletes, 96, 2006, 404–412, Wehrlin J.P. and Hallen J.

**Fig. 3.** From Levine and Stray-Gundersen (1999) also published in Levine (2008), modified from original calculations published by Johnson RL, *Circulation Research* 1968. Note that the greater the cardiac output and thereby the pulmonary blood flow, (such as observed in endurance athletes), the greater the diffusion limitation at any altitude including sea level. This figure was published in *Sports Medicine Secrets, 2nd* edition, Levine & Stray-Gundersen, Exercise at high altitude, pp. 91–96, Copyright Elsevier (1999).
Wehrlin & Hallen (2006) also measured endurance performance as the time to exhaustion on a test beginning at 95% of the velocity at $\text{VO}_{2\text{max}}$ for 1 min followed by running at 107% $\text{v} \text{ VO}_{2\text{max}}$ till exhaustion (Fig. 4).

This endurance marker basically represents the reduction in the aerobic component of a supramaximal effort, which is decreased at altitude, while the anaerobic component remains unchanged (Medbo et al., 1988). This independence of anaerobic capacity with altitude was confirmed recently in a larger number of athletes running at the same speed at sea level and at a simulated altitude of 2700 m (Friedmann et al., 2007). Therefore, this marker should be representative of the ability to sustain a high-intensity effort in a football match and was reduced by 14% per 1000 m (range 10–18%/1000 m) (Wehrlin & Hallen, 2006). Finally as shown in Fig. 5, endurance time at a lower intensity, i.e., 80% of sea level VO$_{2\text{max}}$ and performance with increasing altitude in endurance athletes, 96, 2006, 404-412, Wehrlin J.P. and Hallen J.

In summary, it is quite clear with a high degree of confidence (level of evidence class I) that VO$_{2\text{max}}$ decreases by somewhere between 0.5% and 1% for every 100 m altitude above sea level in endurance trained athletes, with endurance performance (depending on the intensity) decreasing somewhat more, 1.1–1.5% for every 100 m altitude); this decrease can be expected in professional footballers. Indeed, recent measurement of VO$_{2\text{max}}$ at sea level and altitude in Bolivian football players falls within this range, both for altitude natives descending to sea level (0.4%/100 m), and for sea level natives ascending to altitude (0.6%/100 m) (Brutsaert et al., 2000). Of note, the sea level native footballers in this study were significantly fitter than their altitude trained cohorts with a sea level VO$_{2\text{max}}$ that was about 5% greater, probably because of better training in normoxia at sea level. This difference was reversed in testing at altitude, though the advantage of the altitude natives at altitude was essentially the same as the advantage of the sea level natives at sea level. Single bursts of anaerobic or sprint performance per se are not impaired, and are actually enhanced by low, moderate, or even high altitudes when the duration of the sprint is less than about 1 min; repetitive sprints are likely to be impaired by about 2.5%/1000 m when the work:rest ratio is less than about 1:3.

Submaximal performance

One of the most important physiological consequences of the predictable reduction in VO$_{2\text{max}}$ at altitude is the increase in relative work rate for any given absolute work rate. For example, running at 10 mph (16.1 kph) requires an oxygen cost of approximately 50 mL/kg/min (Lundby et al., 2007). For an athlete with a VO$_{2\text{max}}$ of 65 mL/kg/min, this absolute work rate would represent 77% of VO$_{2\text{max}}$ and for most athletes would be just at, or below their lactate/ventilatory threshold. If this same athlete competes at 2500 m, VO$_{2\text{max}}$ might decrease by 15% to 55 mL/kg/min; because exercise economy at altitudes below 4000 m does not change at altitude (Lundby et al., 2007), running the same speed then would now represent 91% of VO$_{2\text{max}}$. Because the cardiovascular (Levine, 2000) and metabolic re-
sponse to exercise (Braun et al., 2000) is determined predominantly by the relative work rate, the athlete would be unable to sustain these speeds without excessive hyperventilation, increased dependence on carbohydrate and glycolysis for energy, and increased fatigue. Conversely, if the relative work rate is the same at sea level and altitude, endurance time is unaffected and HR and lactate concentrations are only minimally affected, though ventilation is increased even at the same percentage of maximum (Maher et al., 1974; Levine & Stray-Gundersen, 1992, 1997). As noted above, athletes depend on these cues to determine pacing during a competition; at altitude, both runners (Levine & Stray-Gundersen, 1992, 1997) and cyclists (Brosnan et al., 2000) “choose” workrates that are lower than at sea level regardless of intensity, presumably because of these sensations. Thus, football players demonstrate a prominent reduction in energy expenditure during a football match of about 0.5%/100 m (Brutsaert et al., 2000) when it is performed at altitude. It could be speculated that perhaps one of the biggest advantages of an altitude native team performing at altitude is the experience adjusting pacing to avoid excessive and exhaustive relative work. Although the evidence supporting this hypothesis is scant, the data by Brutsaert do at least suggest that the altitude natives are able to sustain a slightly higher average rate of energy expenditure during an altitude match, associated with lower lactate levels and ventilation.

Effect of acclimatization

One of the key questions facing football teams attempting to compete at altitude is the effect of acclimatization on altitude performance. This particular issue will be covered in the presentation by Gore and will only be touched on briefly here. The salient features of the body of evidence in this regard are as follows:

(1). For high altitudes above 4000 m, VO_{2max} does not increase with time spent at altitude despite other aspects of acclimatization, primarily increased ventilation (Saltin, 1967; Saltin et al., 1968; Lundby et al., 2004, 2006). In contrast, submaximal endurance increases prominently, improving by more than 50% after 2 weeks of acclimatization (Maher et al., 1974), depending on the relative intensity in question. Thus, the studies by Maher et al. (1974) used the same relative intensity at SL and altitude and showed actual improvements in altitude endurance. The more recent Pikes Peak Studies (Brooks et al., 1991b, 1992; Wolfel et al., 1991b; Mazzeo et al., 1995; Roberts et al., 1996) consistently used the same absolute workrates at altitude and sea level so that the relative work rate at altitude was always higher. They showed gradual reductions in lactate accumulation due predominantly to lactate appearance rates that were lower than acute altitude exposure, but did not achieve sea level values after 2 weeks of acclimatization (Brooks et al., 1991b, 1992; Roberts et al., 1996).

It appears that the failure to increase VO_{2max} despite increasing arterial content is related to persistently reduced arterial conductance (Lundby et al., 2008), and fundamental limitations of oxygen diffusion caused by minimal PcO2 from reduced barometric pressure (di Prampero, 2003). Thus, increasing arterial O2 content by homologous transfusion of red blood cells (Young et al., 1996), or by chronic injection of erythropoietin (Lundby & Damsgaard, 2006) fails to increase VO_{2max} at altitude, while increasing CaO2 by acute augmentation of PIO2 increases VO_{2max} immediately (Savard et al., 1995; Boushel et al., 2001).

(2). At lower altitudes, closer to 2000–2500 m, VO_{2max} can be restored to close to sea level values, particularly if individuals are not elite athletes and training occurs while at altitude (Mairbaurl et al., 1986). For elite athletes at these altitudes, VO_{2max} peak power, and even endurance can be increased substantially by acclimatization with a steady rise over 2 weeks reducing the initial deficit by about half (6% absolute improvement over 14 days at 2340 m) (Schuler et al., 2007) (Fig. 5). However, the improvement in most variables seems to plateau after 2 weeks at altitudes of about 2500 m. If the altitude is even lower, such as 1800 m, athletes continue to improve by 0.5–1.5% per week and can achieve sea level racing performance by 3–4 weeks of acclimatization (Levine and Stray-Gundersen, unpublished observations).

Physical effects of high altitude “Bend it Like Beckham” (in Bolivia)

Although most of the focus in the medical literature is on the physiological effect of altitude on performance, the physical effects of altitude (Fuchs 1991, 1995) may actually be equally or even more important, especially for sports for which success depends substantially on a high degree of technical skill with a ball, as opposed to aerobic power and endurance. In the United States, it has been often discussed that altitude resident teams in Denver, Colorado at 1609 m have much better home records than they do away records. Indeed there was even talk about a “negative acclimatization” effect when the Denver Broncos football team traveled to sea level to play because their visiting record was so poor. However, American football and baseball are sports in which aerobic endurance (and oxygen) plays almost no role. Plays last for <10 s at a time, with at least 30 s rest between plays acutely (work:rest ratio >1:3), and more so when offense and defense alternate. Another example was the poor performance of the US Men’s
Olympic Volleyball team in the Sydney Olympics. In 1997, they switched their primary training site to the US Olympic Training Center in Colorado Springs at an altitude of 1839 m, from sea level in California. They did not win a single match in the 2000 Olympics in Sydney! So why should these teams be at an advantage at altitude, but a disadvantage at sea level? The often overlooked answer probably lies in the effects of altitude on ball aerodynamics, which directly affects the ball flight characteristics.

The lateral deflection of a spinning ball in flight used by many famous footballers like David Beckham during a free kick is generally known as the “Magnus effect” named after the German physicist Gustav Magnus who investigated the deflection of spinning cylinders in the mid-19th century. The two components of the total aerodynamic force that act on a spinning soccer ball flying through the air are the drag force which slows the ball down and the lift or side force which makes the ball dip or curve (Mehta, 1985). The drag force acts along the direction of motion whereas the lift force acts in a direction normal to it. The drag (\(D\)) and lift (\(L\)) forces are defined as:

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D = C_D \times (0.5 \rho U^2 A), \quad L = C_L \times (0.5 \rho U^2 A)
\]

where \(C_D\) and \(C_L\) are the drag and lift coefficients, respectively, \(\rho\) is the air density and \(A\) is the cross-sectional area of the soccer ball. So it is quite apparent, that for a given force coefficient, the drag and lift coefficients are directly proportional to the air density. Now it turns out that the air density decreases with increasing altitude. An approximate relation gives about a 3% reduction in air density for every 305 m increase in altitude. Therefore, in a match played in Mexico City at an altitude of 2240 m, the air density will be about 22% lower than that at sea level. This translates into a 22% decrease in the drag and lift forces. In practical terms this means that a soccer ball will generally fly further and curve less at high altitude. This effect is well appreciated and demonstrated in baseball. The Colorado Rockies play at a park which is at an altitude of 1609 m and it is well documented that it is easier to hit home runs at this park because the pitched ball does not “break” as much (due to the reduced lift) and it travels further (due to reduced drag).

The effect of altitude on soccer ball aerodynamics becomes particularly important and relevant when a team trains at a certain altitude and then has to suddenly play at a stadium at a very different altitude without enough time to retrain and readjust. For example, for a free kick in football at sea level: assuming that the velocity of the ball is 25–30 m/s (about 70 mph) and that the spin is about 8–10 revolutions/s, then the lift force turns out to be about 3.5 N. The regulations state that a professional foot-
contact, the brain uses an internal model of the acceleration due to gravity, which is combined with sensory information and enables a prediction to be made. Intriguingly, the system did not rapidly adapt to the spaceflight environment, but instead maintained earth gravity type predictive behaviors. Moreover, errors made consistently over the course of 2 weeks in space were immediately corrected in the first few hours of return to earth (see Fig. 6) (McIntyre et al., 2001). Thus, astronauts raised in a gravitational environment seemed to rely on neural networks hard wired on the ground.

Of course, it is also well known that there is substantial neural plasticity in many parts of the brain and visual system. For example, classic prism experiments demonstrate that humans can rapidly correct motor function to at least this static distortion of the external world (Kandel et al., 2000). However, this plasticity requires multiple repetitions to occur and sustain. Although there are no data regarding the impact of changing aerodynamic forces due to altitude on anticipation in football, it would seem reasonable to hypothesize that sea level natives who rely on ball skills honed at 1 full atmosphere would be hampered at high altitude and it might require multiple repetitions and practice at altitude to optimize technical skills. If this theory is correct, similar problems should occur for altitude native teams when they come down to sea level and indeed that is the case. In fact, Bolivian players typically train with a heavier ball while at altitude in preparation for a competition at sea level (Enrique Vargas, M.D., personal communication). As noted by Gore, the detrimental result of sea level teams traveling to play away games at altitude is nearly exactly matched by the poor results of altitude teams when they compete at sea level (McSharry, 2007) (It should be noted that this conclusion, while supported by the data presented, is somewhat different from the conclusions of the author of this report). This type of technical problem would then also explain the difficulties of other altitude-based teams when they play away from home in American football or baseball.

Conclusions and recommendations

(1) VO2max decreases by somewhere between 0.5% and 1% for every 100 m altitude above sea level in endurance trained athletes, with endurance performance (depending on the intensity) decreasing somewhat more, 1.1–1.5% for every 100 m altitude); this decrease can be expected in professional footballers who will either have to adjust their pacing strategies during a game, or experience excessive fatigue. The level of evidence for this conclusion is class I.

(2) Impairments in repetitive sprint performance are more difficult to quantify than changes in aerobic power, and depend on the duration of the sprint and the work:recovery ratio. No more than 2.5% reductions in performance per 1000 m altitude after multiple sprints should be expected and are likely to be balanced at least in part by the improvement in single sprint efforts from reduced air resistance.

(3) Altitude acclimatization clearly improves performance at altitude (class I), though the magnitude of this improvement depends on the absolute altitude, the altitude gained, and the duration of acclimatization. For moderate altitudes above 1800 m, 5–7 days of acclimatization provides a significant amount of ventilatory acclimatization and a measurable improvement in maximal performance; however, a full 2 weeks of acclimatization is likely necessary to restore near sea level competitive performances. It should be noted that at high altitudes closer to 4000 m, maximal endurance performance likely never recovers towards sea level values, though submaximal performance may still be substantially improved by 2 weeks of acclimatization.

(4) The effects of reduced air resistance on ball aerodynamics are large and affect both sea level teams ascending to moderate or high altitudes, as

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Fig. 6. From McIntyre Nature Neuroscience 2001. Reprinted by permission from Macmillan Publishers Ltd: Nature Neuroscience, copyright 2001. These are derived from experiments where an astronaut is asked to catch a ball on earth (1G) and after 3, 9 and 15 days in space (0G) aboard the Space Shuttle. Note that the astronaut makes crude anticipatory forearm rotations that are abnormal (start too soon), and never recover over 15 days in space.
well as altitude teams descending to sea level. There are no data at all regarding the neural plasticity and adaptability of this problem.

**Open questions and areas for future research**

(1) Sport (and position) specific quantification of football performance and the impact of low and moderate altitude are necessary to extrapolate existing data to football game performance. Such measures should include quantification of fatigue and recovery from multiple sprints of different durations, effect of pacing strategies, magnitude of improvement with acclimatization, and the effect of specific altitudes.

(2) A detailed investigation into neural strategies for judging ball flight and the effect of changes in altitude should be performed both for ascending to altitude and descending to sea level. The magnitude and rate of adjustment should be quantified in terms of days and number of repetitions, as well as the sustainability of the effect (i.e., how long does it last after a “normal” residence environment is restored).

**Key words:** hypoxia, exercise, hypobaria, soccer.

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