

Effect of 5 weeks of HIIT in hypoxia on physiological profiles measured in situ by GPS with elite soccer players

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Headline

Altitude training has seen significant development over the last few decades to enhance athletes' capabilities in team sports (Bishop & Girard, 2013). Recently, High-Intensity Intermittent Training (HIIT) has been proposed and integrated into athletes' training programs (Faiss et al., 2013; Millet & Girard, 2017). This training process is highly attractive due to the expected physiological improvements, such as enhanced aerobic capacity (Westmacott et al., 2022) and improved high-intensity performance in team sports (Hamlin et al., 2018). Furthermore, recent technological advancements have enabled the use of altitude training with normobaric hypoxia in dedicated rooms or with single generator connected to a facemask. However, it is important to note that few studies have investigated the effects of such training methodologies on professional team sport players during a real season, and even fewer have provided individual results to interpret these effects on performance.

Aim of the paper

To understand the effect of HIIT in hypoxia on professional team sport players during a season, we recruited volunteers from a professional soccer team (Ligue 1). These volunteers performed their traditional HIIT training sessions on ergometers in a hypoxic environment, while the rest of the team performed their exercises under normoxic conditions. The aim of this protocol was to investigate the differences between both groups based on Global Positioning System (GPS) data, which included all locomotor performances during training sessions. Given that all players did not perform for equivalent match durations, we included only training sessions in our analysis. Previous studies have shown that matches allow players to achieve higher performances, particularly at high intensities (Biedermann et al., 2023; Gómez-Carmona et al., 2018).

Additionally, we aimed to investigate individual improvements in players before and after HIIT, with or without hypoxia, to identify potential responders and non-responders (Mattioni Maturana et al., 2021). Finally, we interviewed athletes throughout the training protocol and afterwards to understand their perceptions of this approach and to gather feedback for improving future training protocols.

Methodology

Experimental design

This study was conducted retrospectively using data collected from the follow-up of soccer players during a professional season (Ligue 1). Traditionally, this team used two HIIT sessions per week during competitive periods. We proposed that some players perform these training sessions under hypoxic

conditions for five weeks, while the rest of the team performed similar exercises under normoxic conditions. The protocol included one week of acclimation to ensure player safety and adaptation to hypoxia, as none of the players had previously experienced such training.

Players

First 12 players of the team volunteer for this protocol were allocated to the hypoxic group (HYP) whereas the rest of the team was composing the control group (CON). HYP (n=9) characteristics were ; size 1.82 ± 0.04 m, weight 79.8 ± 5.9 Kg, maximum aerobic speed (VamEval) 17.1 ± 0.6 km·h⁻¹, maximal oxygen uptake (VO₂max) 60.3 ± 4.1 mL·min⁻¹·Kg⁻¹ when CON (n=10) characteristics were size 1.81 ± 0.04 m, weight 74.5 ± 5.7 Kg, maximum aerobic speed (VamEval) 17.0 ± 0.5 km·h⁻¹, VO₂max 61.7 ± 4.4 mL·min⁻¹·Kg⁻¹. Initially, both groups were composed by 12 players, but some players were injured (HYP: 1, CON: 2) or did not complete all training sessions (HYP:2, CON:0). To do not interfere in results, we removed these players from the studies.

HIIT Sessions

All HIIT sessions have been performed on a Wattbike ergometer (Wattbike, West Bridgford, UK) after soccer training as a mandatory top-up. These sessions were performed two times a week (day 2 and day 4 following the official match) from week 2 to week 5. First week was dedicated to low intensity exercises to check players reactions to hypoxia that will be detailed latter. These sessions were performed under the supervision of a technician with 6 players in the simultaneously.

These HIIT sessions were composed by 3 sets of 5 exercise bouts all-out as follows; set 1. 15s exercise – 20s recovery, Set 2. 15s exercise – 20s recovery, Set 3. 8s exercise – 15s recovery.

Hypoxic Training

HIIT sessions were performed at the same time as normoxic sessions, with two players simultaneously exercising in a tent (2.10 x 2.10 x 1.95h meters) at a simulated altitude of 3000 meters (Girard et al., 2013). The setup was installed at sea level. Altitude simulation was achieved by blowing hypoxic air with 14.08% O₂ into the tent, produced by a Cloud9 generator (Sporting Edge, Basingstoke, UK). To control the air composition in the tent, O₂ and CO₂ gas sensors were placed inside and linked to a computer. The Mooky Center software (Mtraining, Ecole, Valentin, France) was used to capture and display gas sensor information (O₂ and CO₂) in order to manually regulate the generator's flow or tent leakage using zip-

pered openings. Based on this information, technicians could regulate the altitude level during the session with less than 5% accuracy (2850-3150 meters). Furthermore, the displayed gas information allowed monitoring of CO₂ level increases during exercise to ensure the players' safety. For the same reason, blood oxygen saturation was also recorded and displayed simultaneously by the software.

During the first week of training, individual responses to hypoxia were assessed during two sessions. The first session consisted of two bouts of 5 minutes of exercise at an intensity

set at 30% of the players' maximal power output. The second session comprised two sets of 8 repetitions of 15 seconds of all-out exercise followed by 20 seconds of recovery. The following 4 weeks included 2 hypoxic sessions in addition to the normoxic HIIT training, as described: 3 sets of 5 all-out exercise bouts as follows; Set 1: 15 seconds of exercise followed by 20 seconds of recovery, Set 2: 15 seconds of exercise followed by 20 seconds of recovery, Set 3: 8 seconds of exercise followed by 15 seconds of recovery (Figure 1).

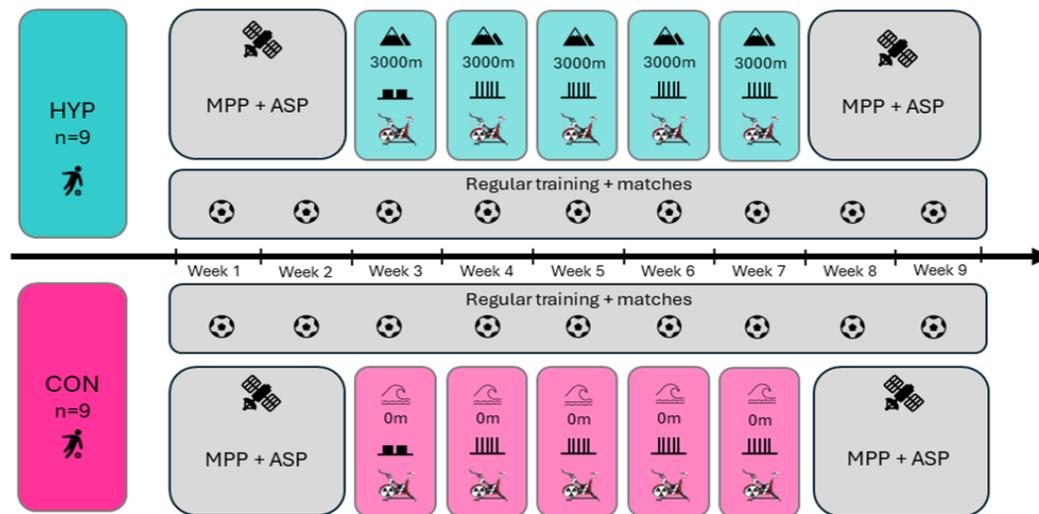


Fig. 1. Temporal flowchart of the measurements and training interventions.

GPS data and processing

To track physical performances from players from both groups' during this study, locomotor performances were collected during all training sessions using GPS (Gpexe Pro², Exelio, Udine, Italy). We investigated the maximal capabilities of players by generating the Metabolic Power profile (MPP) (Cassirame et al., 2022) and Acceleration/Speed Profile (ASP) (Morin et al., 2020) of each player during the two weeks preceding and following the training interventions.

The MPP permitted to obtain the best metabolic power values (di Prampero & Osgnach, 2018; Osgnach & di Prampero, 2018) reached by player in large number of durations from 3 seconds to 45 minutes (Duthie et al., 2018). The ASP allowed the calculation of the best theoretical acceleration of players (a₀) and the theoretical maximal speed (s₀) based on all sprints performed by athletes during the period selected (Komino et al., 2022). Both profiles have been generated by gpexe webapp (Exelio, Udine, Italy) during the periods of interest.

We assumed that two weeks was sufficient to evaluate the maximal capabilities of the players using these methodologies. We did not select other metrics, such as the number of accelerations or distances covered at different speeds, because these metrics are too sensitive to the training duration, or the specific exercises proposed by the coaches.

Statistical analysis

To interpret the differences in performance between the two weeks preceding and following the training interventions, we compared both conditions individually and used magnitude-based inferences for grading improvements. Probabilities were calculated to establish whether the true changes were lower than, similar to, or higher than the smallest worthwhile

changes (SWC, $0.2 \times$ between-subjects SD) for HYP group against HYP group for maximal for metabolic power of any durations (MPP), as well as a₀ and s₀ from the ASP. The changes in the HYP group were then compared to these benchmarks to determine the true difference between groups. The following scale was used to grade these differences: 0-0.2 trivial, 0.2-0.6 small, 0.6-1.2 moderate, >1.2 large (Hopkins et al., 2009).

The probability of these effects was also graded using the percentage of individual players meeting the magnitude of interest. The following scale was used: 25-75% possible, 75-95% likely, 95-99% very likely, >99% almost certain. (Hopkins et al., 2009).

Results

Our results showed that both groups (HYP and CON) increased their MPP across all durations, ranging from 3 to 2700 seconds (Table 1 and Figure 2). Additionally, we observed improvements in ASP (Anaerobic Speed and Power) for both HYP and CON groups (Table 2 and Figure 4). A comparison between the two groups indicated that the ASP profile improved similarly: HYP saw a 4.4% increase in v₀ and a 4.6% increase in a₀, while CON showed a 5.1% increase in v₀ and a 3.9% increase in a₀ (Table 2). However, the individual evolution of ASP before and after the training intervention did not reveal a greater improvement for the HYP group.

In contrast to ASP, we observed that the HYP group showed a significantly better increase in average MP across all durations, ranging from a 14% increase for 3 seconds up to a 28.9% increase for 600 seconds, whereas the CON group showed variations from no change (0%) for 1800 seconds to a 7.6% increase for 60 seconds (Table 1). Analysis of individual changes in the

HYP athletes revealed probabilities of effect ranging from possibly small for 60, 900, and 2700-second durations to certainly moderate for 15 seconds (Table 1 and Figure 3).

Table 1. Metabolic power profile values ($W \cdot Kg^{-1}$) for HYP and CON groups before and after the training intervention for all durations and evolution in $W \cdot Kg^{-1}$ and percentage. Qualitative inferences associated for the evolutions between HYP and CON are displayed in right column.

Dur. (s)	HYP				CON				Qualitative inferences
	Before	After	Dif	Dif %	Before	After	Dif	Dif %	
3	62,1	70,7	+8,7	+14,0%	63,0	65,4	+2,4	+3,8%	Likely moderate
5	49,7	57,2	+7,5	+15,1%	51,6	53,3	+1,7	+3,3%	Likely moderate
10	34,7	41,0	+6,2	+17,9%	36,0	36,9	+0,9	+2,4%	Likely large
15	28,9	34,3	+5,4	+18,6%	28,7	28,7	+0,1	+0,2%	Certainly moderate
30	21,3	26,3	+4,9	+23,2%	21,7	23,1	+1,5	+6,8%	Likely small
60	15,7	19,3	+3,6	+22,8%	16,3	17,5	+1,2	+7,6%	Possibly small
180	11,8	14,8	+3,0	+25,4%	12,4	12,5	+0,1	+1,1%	Likely moderate
300	10,6	12,9	+2,4	+22,2%	11,0	11,1	+0,1	+0,8%	Likely moderate
600	9,0	11,6	+2,6	+28,9%	9,2	9,9	+0,7	+7,9%	Likely small
900	8,6	10,1	+1,5	+17,0%	8,9	9,0	+0,2	+2,1%	Possibly small
1800	7,3	8,7	+1,4	+19,6%	7,4	7,4	+0,0	+0,0%	Likely small
2700	6,7	8,1	+1,4	+20,6%	6,7	6,9	+0,2	+3,2%	Possibly small

Table 2. V_0 ($km \cdot h^{-1}$) and a_0 ($m \cdot s^{-2}$) values for HYP and CON groups before and after the training intervention. Qualitative inferences associated for the evolutions between HYP and CON are displayed in right column.

	HYP				CON				Qualitative inferences
	Before	After	Dif	Dif %	Before	After	Dif	Dif %	
V_0 ($km \cdot h^{-1}$)	31.1	32.5	+1.4	+4.4%	30.9	32.5	+1.6	+5.1%	Trivial
a_0 ($m \cdot s^{-2}$)	6.7	7.0	+0.3	+4.6%	6.6	6.9	+0.3	+3.9%	Trivial

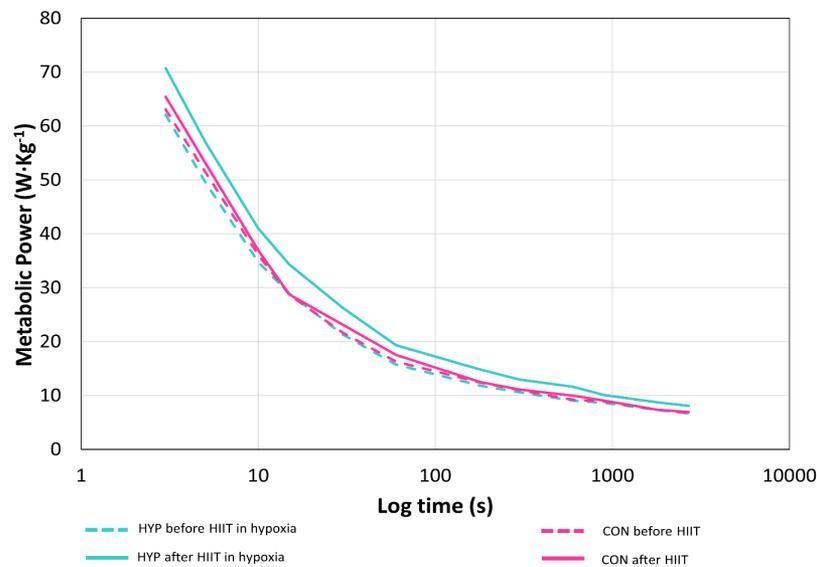


Fig. 2. Metabolic power profile for both groups, HYP (hypoxic) and CON (control), before and after the respective training intervention. The X-axis represents the logarithm of time in seconds, while the Y-axis represents the average of the maximum metabolic power achieved by players from both groups at the corresponding durations.

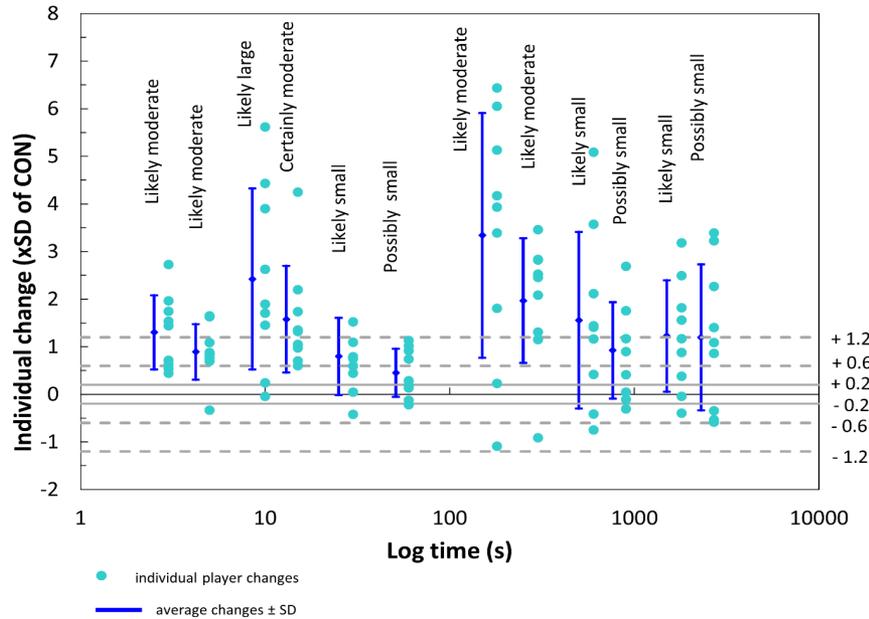


Fig. 3. Comparison of individual changes in players from the HYP (hypoxic) group against the variation in the CON (control) group for each duration of the metabolic power profile. The X-axis represents the logarithm of time in seconds, while the Y-axis represents the change in individual players relative to the average changes in the CON group. Positive values indicate that HYP players improved their metabolic power more than the CON group at the corresponding duration, whereas negative values indicate a lesser improvement for HYP players compared to the CON group.

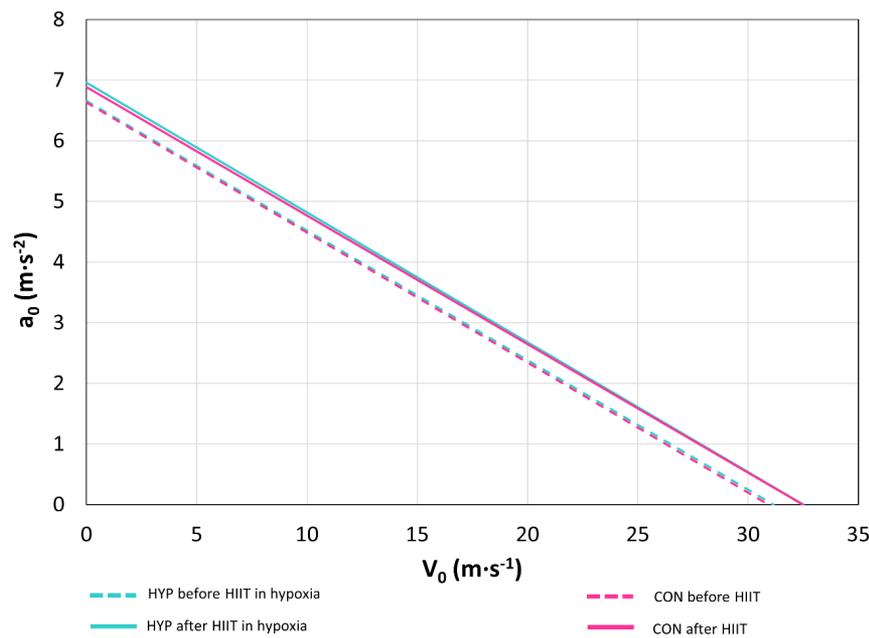


Fig. 4. Acceleration speed profile for both groups, HYP (hypoxic) and CON (control), before and after the respective training intervention. The X-axis represents the theoretical maximal speed, while the Y-axis represents the theoretical maximal acceleration.

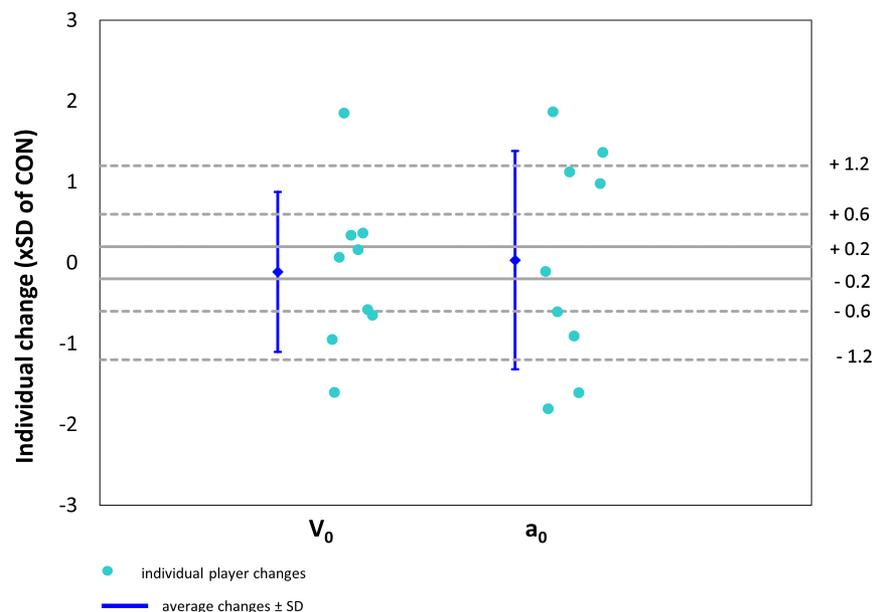


Fig. 5. Comparison of individual changes in players from the HYP (hypoxic) group against the variation in the CON (control) group for V_0 and a_0 of the acceleration speed profile. The Y-axis represents the change in individual players relative to the average changes in the CON group. Positive values indicate that HYP players improved their values more than the CON group for V_0 or a_0 , whereas negative values indicate a lesser improvement for HYP players compared to the CON group.

Discussion

This experiment, conducted during a real professional soccer season, revealed that high-intensity interval training (HIIT) on a bike, both in normoxia and hypoxia (equivalent to 3000 meters altitude), improved the MPP of the players. Fang et al. already reported that HIIT in normoxia performed on bike could improve cardiorespiratory fitness (peak of oxygen consumption) and anaerobic power (wingate test) in adolescent soccer players (Fang et al., 2021).

This experiment, conducted during a real professional soccer season, revealed that both high-intensity interval training (HIIT) on a bike in normoxia and hypoxia (equivalent to 3000 meters altitude) improved the MPP of players. Previous studies, such as those by (Galvin et al., 2013) or soccer (Gatterer et al., 2014) have reported that hypoxic training, particularly HIIT, is an effective way to enhance performance in team sports like rugby and soccer, often yielding better results than equivalent training in normoxia. However, these studies primarily used traditional tests and physiological variables, such as the Wingate test, Yo-Yo intermittent recovery test (Bangsbo et al., 2008), or repeated sprint ability, to measure improvements. The transposability of these effects to real soccer conditions remains questionable and may not be entirely effective. Additionally, these studies were mostly conducted with young athletes, who generally have greater potential for improvement than elite professional athletes.

Due to the competitive context of our study in a professional first-division soccer league, it was not feasible to organize isolated test sessions for all players. Instead, we measured improvements in real soccer practice during all training sessions using MPP and ASP, which represent the maximal physiological values achieved by athletes over various durations and the best theoretical acceleration and velocity capabilities, re-

spectively.

Regarding ASP, our results did not show a significantly better improvement for the HYP group compared to the CON group in terms of v_0 and a_0 (Figures 4 and 5). Similar results were observed in a study by Brocherie et al., where young soccer players underwent five weeks of repeated sprint training in hypoxia at a simulated altitude of 2900 meters (Brocherie et al., 2015). In this study, no significant differences in performance improvements were noted between the hypoxic and placebo groups for sprint times over 10, 20, 30, and 40 meters, although both groups improved their performances. Furthermore Galvin et al. or Gatterer et al (Galvin et al., 2013; Gatterer et al., 2014) did not report better improvements in 20-meter sprint or 40-meter shuttle-run sprint times when compared with similar training in normoxia. These findings suggest that hypoxic training, especially on a bike, may be equally effective as normoxic training for single maximal neuromuscular events like sprints or jumps. Such exercises, which involve strength or technical skills, are less influenced by adaptations induced by local oxygen deprivation.

Studies involving multiple sprint tests, such as repeated sprints or agility exercises up to the Yo-Yo intermittent recovery test, have yielded more varied results (Lundby & Robach, 2016). However, the literature generally indicates that hypoxic training can lead to superior gains in longer high-intensity exercises involving repetitions (Brocherie et al., 2017). Consistent with this finding, MPP measured during real soccer activities showed small to moderate superior improvements for hypoxic training. MPP spans a wide range of durations, from 3 to 2700 seconds, where energy supply relies on glycogenolysis, phosphocreatine hydrolysis, and non-oxidative glycolysis to resynthesize ATP (Bishop & Girard, 2013).

Both training groups improved their performances after the intervention, but the HYP group showed small to moderate superior improvements compared to the CON group, with metabolic power increases ranging from 14% to 28.9%. We also observed that the magnitude of improvement was more pronounced for durations from 30 to 600 seconds, which are typical durations for training exercises such as small-sided games or technical drills. Regarding MPP, we hypothesize that physiological adaptations in convective and oxidative capacities at the muscular level could play a major role in these improvements (Hoppeler et al., 2003; Puype et al., 2013; Ter-rados et al., 1988). consequently, maximal oxygen consumption could be improved by altitude training, leading to performance increases in maximal aerobic speed achieved during the Yo-Yo test (Bishop & Girard, 2013; Galvin et al., 2013). As shown in Figure 3, the majority of individual players in the HYP group achieved better improvements than those in the CON group, although there was significant variability in responses. HYP players varied from -1 to +6.5 standard deviations compared to CON, highlighting the need for technical staff to closely monitor and optimize adaptations while avoiding negative responses from players.

This study was the first to use GPS trackers to evaluate the effectiveness of a specific intervention with professional players during a real season. Both ASP and MPP could potentially be influenced by the training content proposed by coaches, which is why we primarily analysed the differences between groups rather than focusing solely on HYP improvements. Even though HIIT in hypoxia appears to provide better results in soccer practice, several factors could confound these findings. Firstly, the players in the HYP group were volunteers and potentially more motivated in training than the rest of the team. Given that the exercises involved all-out effort bouts, it is possible that they exerted more intensity during these sessions. Unfortunately, we did not collect any power output data during training sessions to support or refute this hypothesis.

Additionally, HYP exercises were performed in an inflatable tent with minimal leakage, by two players simultaneously. During these sessions, the temperature inside the tent gradually increased, often reaching 34-36°C, while the CON group trained at a temperature of around 26°C. Heat stress during training has been reported as a potential catalyst for physiological adaptations and performance improvements (Lorenzo et al., 2010; Sawka et al., 2011). However, recent studies suggest that combined training involving both heat and simulated altitude stress does not improve performance more than training with each stressor separately (Girard et al., 2024; McCleave et al., 2020). Therefore, we cannot attribute the observed benefits solely to hypoxia, and future research should explore whether heat stress alone could provide similar benefits.

Player testimonials and coach interpretations

Based on the experience of this study with players, we gathered feedback and testimonials to gain a clearer understanding of the mechanisms at play and to interpret their observations. Below, we provide several of their testimonies accompanied by our analysis.

Player.: 'After the intervention, during the most demanding phases, we found it easier to breathe during recovery, allowing us to resume efforts more quickly than before.'

Coach.: 'When fatigue increases during exercise, easier breathing reduces the perceived exertion and facilitates the ini-

tiation of efforts, particularly in defensive withdrawals. This improvement in MPP was achieved by increasing the number of movements and reducing recovery time.'

Player.: 'During the training interventions, the perceived effort was very high, and the stress generated by altitude and heat made us feel like we were suffocating. By the end of training, we felt proud to have completed it.'

Coach.: 'Players can sometimes be complacent and forget the importance of effort and overachievement. Completing such demanding training sessions can shift their perception of effort in subsequent activities, including both training and matches, ultimately improving performance.'

Player.: 'This supplementary training included close SpO₂ and environmental monitoring by the staff, which provided high supervision of our performance during training, pushing us to perform at our best.' **Coach:** 'The control measures, implemented for safety and protocol management during the study, led to greater player engagement. The use of advanced technology and the novelty of such a training program likely also contributed to the increased engagement of the players.'

Player.: 'After several high-intensity events, we felt less fatigued than before, which allowed us to be more relaxed and aware during game situations.'

Coach.: 'This shift in perception, along with easier breathing, led to greater confidence during physically demanding periods. This allowed players to focus less on the physical strain and more on other tasks, such as tactical execution.'

Conclusion

HIIT in hypoxia with professional soccer players can be implemented during the competitive period without reducing performance. This type of training helps to improve the metabolic power of players across a wide range of durations. Although improvements in metabolic power were observed in both the hypoxia (HYP) and control (CON) groups, the increase was significantly greater for the HYP group. This suggests that players in the HYP group were capable of generating more energy during movements in real soccer contexts. However, our study did not find significant differences between the groups in v_0 and a_0 from ASP. This finding, consistent with the literature, indicates that single maximal intensity events are not particularly sensitive to altitude training.

Practical applications

- Simulated altitude training can be effectively performed in inflatable tents, but the associated generators must be appropriately matched to the tent's volume, the number of athletes, and the type of activity to properly manage O₂ and CO₂ levels.
- We recommend that staff continuously monitor the environmental characteristics, including O₂, CO₂, and temperature levels, as well as each athlete's SpO₂, to ensure safety and appropriately manage the training.
- Training in the tent can also induce heat stress and significant hydration variation in athletes. We recommend carefully monitoring hydration status and implementing strategies to address these needs.
- Begin the training process with low-intensity sessions, ideally simulating an altitude of around 2000 meters, to observe individual responses from the players.

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