Effects of high-intensity interval training under hypoxic conditions on energy system performance in collegiate football players

Efectos del entrenamiento en intervalos de alta intensidad en condiciones hipóxicas sobre el rendimiento del sistema energético en futbolistas universitarios

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Abstract

Introduction: High-Intensity Interval Training (HIIT) is widely recognized for enhancing athletic performance. However, whether simulated hypoxic conditions amplify the physiological effects of HIIT especially in sports like football that rely on multiple energy systems, remains underexplored.
Objective: To investigate whether simulated hypoxic HIIT elicits greater improvements in aerobic and anaerobic performance compared to normoxic HIIT and standard training in collegiate football players.
Methodology: Twenty-four male collegiate football players were randomly assigned to three groups: Hypoxic HIIT, Normoxic HIIT, or Control. Over a four-week intervention period, the experimental groups engaged in sport-specific HIIT under their respective environmental conditions, while all participants continued standard team training. Pre- and post-training assessments included VO_2max, Yo-Yo Intermittent Recovery Test Level 1 (Yo-Yo IR1), Running-Based Anaerobic Sprint Test (RAST), and 30-meter flying sprint.
Results: The Hypoxic HIIT group showed significant improvements in VO_2max and Yo-Yo IR1 distance ($p < 0.01$), with moderate gains in RAST peak power. Minimal changes were observed in ATP-PC system performance. These adaptations exceeded those observed in the Normoxic and Control groups.
Discussion: The findings indicate that hypoxic stress provides an additive stimulus to aerobic conditioning. This aligns with existing literature on the role of hypoxia in enhancing oxygen transport, mitochondrial function, and endurance capacity.
Conclusions: Simulated hypoxic HIIT effectively enhances aerobic capacity and selectively improves anaerobic performance. It represents a time-efficient and evidence-based conditioning strategy for competitive football.

Keywords

Aerobic capacity; anaerobic power; football conditioning; hypoxic training; interval training.

Resumen

Introducción: El HIIT es eficaz para mejorar el rendimiento deportivo, pero sus efectos bajo hipoxia simulada frente a condiciones normóxicas siguen siendo poco estudiados, especialmente en deportes intermitentes como el fútbol.
Objetivo: Evaluar si el HIIT en hipoxia simulada mejora más el rendimiento aeróbico y anaeróbico que el HIIT en normoxia y el entrenamiento convencional en futbolistas universitarios.
Metodología: Veinticuatro futbolistas universitarios fueron asignados aleatoriamente a tres grupos: HIIT en hipoxia, HIIT en normoxia y control. Durante cuatro semanas, los grupos experimentales realizaron HIIT específico al fútbol en condiciones asignadas, mientras todos continuaron con su entrenamiento regular. Se evaluaron VO_2max, Yo-Yo IR1, RAST y sprint de 30 metros antes y después de la intervención.
Resultados: El grupo HIIT en hipoxia mostró mejoras significativas en VO_2max y en la distancia del Yo-Yo IR1 ($p < 0.01$), así como mejoras moderadas en la potencia máxima del RAST. El rendimiento del sistema ATP-PC mostró pocos cambios. Estas mejoras fueron superiores a las de los otros grupos.
Discusión: La hipoxia simulada parece actuar como un estímulo adicional que favorece la adaptación aeróbica, en línea con estudios previos sobre la mejora del transporte de oxígeno y la función mitocondrial.
Conclusiones: El HIIT en hipoxia simulada mejora eficazmente la capacidad aeróbica y aspectos clave del rendimiento anaeróbico, siendo una estrategia de acondicionamiento eficiente para el fútbol competitivo.

Palabras clave

Capacidad aeróbica; capacidad anaeróbica; preparación física en fútbol; entrenamiento en hipoxia; entrenamiento por intervalos.

Introduction

Football demands a unique combination of short bursts of explosive actions and sustained effort, requiring players to sprint, change direction quickly, and maintain physical output throughout a 90-minute match. (Martin-Smith et al., 2020; Wu & Karim, 2023). To meet such complex physical demands, athletes must engage all three major energy pathways ATP-PCr, anaerobic glycolysis, and aerobic metabolism in a coordinated and efficient manner that supports both power output and recovery (Ito, 2019; Wing et al., 2022). Enhancing the efficiency of these energy pathways is therefore essential for optimizing competitive performance.

In recent years, high-intensity interval training (HIIT) has emerged as a time-efficient method for improving both aerobic capacity (VO_2max) and anaerobic output. HIIT induces accelerated physiological responses within shorter time frames than conventional endurance methods, making it a preferred strategy for maximizing gains in minimal training periods (Feito et al., 2018; Marques Neto et al., 2020; Mahatme et al., 2022). Mechanistically, HIIT stimulates mitochondrial biogenesis, improves oxygen utilization, and induces favorable adaptations in cardiovascular and metabolic health indicators (Camacho-Cardeñosa et al., 2017; Viscor et al., 2018; Sanches et al., 2021).

Recent research in team sports contexts such as soccer and futsal has demonstrated that running-based HIIT incorporating changes of direction can significantly improve agility and aerobic fitness in female athletes (Paprancová et al., 2025). Similarly, embedding HIIT protocols within large-sided game formats has been shown to enhance anaerobic power and functional fitness among student futsal players (Kusuma et al., 2025).

Concurrently, hypoxic training performed under conditions of reduced oxygen availability has been shown to stimulate erythropoietin release, increase red blood cell mass, and enhance muscular adaptations linked to endurance and strength (Neporadna & Popel, 2019; Ferguson et al., 2021; Weng et al., 2021; Tongwu & Chuanwei, 2025). By mimicking the physiological stress of high-altitude exposure, hypoxic environments can trigger distinct responses that may further potentiate athletic performance beyond normoxic training alone.

While both HIIT and hypoxia training are beneficial on their own, limited research has explored their synergistic effects on energy system efficiency in athletes, especially in high-intensity intermittent sports like football. Most research has examined each modality in isolation (Ulupınar et al., 2021; Hostrup & Bangsbo, 2023; Thomakos et al., 2023; Psarras & Bogdanis, 2024), offering limited insight into how their integration affects the performance of the ATP-PCr, glycolytic, and aerobic systems in trained populations.

This study seeks to examine the impact of high-intensity interval training (HIIT) conducted in hypoxic compared to normoxic environments on energy system performance in collegiate football athletes. Specifically, we assess changes in maximal sprint speed, anaerobic power, and aerobic capacity across three groups: (1) HIIT under hypoxia, (2) HIIT under normoxia, and (3) a control group without HIIT. We hypothesize that HIIT conducted under hypoxic conditions will produce superior adaptations across all three energy systems, offering a time-efficient and physiologically robust strategy to enhance football-specific performance.

Method

Study Design

A quasi-experimental, quantitative approach with a controlled pretest-posttest structure was implemented to assess the impact of high-intensity interval training (HIIT) under both hypoxic and normoxic conditions on energy system function in collegiate football players. This investigation aimed to identify causal links between the training protocols and physiological outcomes associated with the phosphagen, glycolytic, and aerobic systems. Ethical clearance was granted by the Human Research Ethics Committee of Nakhon Ratchasima Rajabhat University (NRRU), Thailand (Approval No. HE-013-2025). All human subject procedures adhered to institutional regulations and conformed to the ethical standards outlined in the Declaration of Helsinki.

Participants

Twenty-four male collegiate football players (aged 19–22 years) were purposively recruited from the university's varsity team. Inclusion criteria were: (1) medically healthy status with no history of musculoskeletal injuries or cardiopulmonary contraindications; (2) no previous exposure to hypoxia-based training; (3) official selection to compete in the National University Games; and (4) provision of written informed consent. Participants were excluded if they (a) completed less than 80% of the training sessions, (b) sustained injury or illness during the study period, or (c) withdrew due to academic or personal reasons.

To ensure baseline equivalence, participants were stratified into three groups (n = 8 per group) based on their initial maximal oxygen uptake (VO2max):

Group 1 (Hypoxic HIIT): Engaged in high-intensity interval training under normobaric hypoxic conditions ($FiO_2 \approx 14.5\%$, simulating an altitude of ~3,085 meters).

Group 2 (Normoxic HIIT): Completed the same HIIT protocol under ambient sea-level conditions ($FiO_2 = 20.9\%$).

Group 3 (Control): Continued routine team-based training and did not participate in the HIIT intervention.

Adherence to the training program was high across all groups. The Hypoxic HIIT and Normoxic HIIT groups achieved 100% session attendance, while the Control group achieved 95.8% adherence. Attendance was tracked daily by supervising staff to ensure protocol fidelity and internal validity.

Procedure

Prior to the commencement of the study, the complete training protocol and related procedures received ethical approval from the Human Research Ethics Committee at Nakhon Ratchasima Rajabhat University (Certificate No. HE-013-2025). Each participant was informed in detail about the study's goals, procedures, and any associated risks. All volunteers gave their written consent before joining the trial. Pre-intervention testing was conducted one week before the training phase, and post-testing occurred within one week following the program's completion.

Based on initial VO_2max scores, participants were allocated randomly into three experimental arms:

Group 1 (Hypoxic HIIT): Performed high-intensity interval training in simulated low-oxygen (hypoxic) conditions.

Group 2 (Normoxic HIIT): Followed the same protocol under normal oxygen levels.

Group 3 (Control): Participated in standard team practice without HIIT intervention.

The program lasted four weeks, comprising five training sessions per week. Both experimental groups followed the same session format and volume, with the only distinction being the oxygen concentration of the training environment. Training was categorized into two main components:

High-Intensity Interval Training (Tuesdays and Thursdays):

Each HIIT day included two circuits of functional, bodyweight exercises:

Series 1 (12-minute EMOM [Every Minute on the Minute], 2 sets):

Squats – 20 repetitions

Leg lunges – 20 repetitions

Push-ups – 20 repetitions

Glute bridges – 20 repetitions

Plank – 30 seconds

Russian twists – 20 repetitions

Series 2 (8-minute EMOM [Every Minute on the Minute], 2 sets):

Mountain climbers – 30 repetitions

Jumping jacks – 30 repetitions

High knees – 30 repetitions

Burpees – 20 repetitions

Each session was conducted at an exercise intensity of approximately 85–95% of the participant's estimated maximum heart rate (HRmax), with 2-minute rest intervals between sets. Group 1 trained using the Hypoxico Altitude Training System ($FiO_2 \approx 14.5\%$) simulating ~3,085 meters of altitude. Group 1 trained using the Hypoxico Altitude Training System ($FiO_2 \approx 14.5\%$), simulating an altitude of approximately 3,085 meters. Training under hypoxic conditions was conducted in a dedicated room equipped with the Hypoxico Altitude Training System, which maintained a constant fraction of inspired oxygen (FiO_2) at approximately 14.5%. Oxygen levels were continuously monitored using an inline oxygen analyzer to ensure fidelity throughout the intervention. Group 2 trained under normal oxygen conditions ($FiO_2 = 20.9\%$).

Strength, Power, and Speed Training (Mondays, Wednesdays, Fridays):

In addition to HIIT, Groups 1 and 2 followed a standardized training protocol focused on muscular strength, endurance, and speed development:

Monday: Classic resistance training (e.g., squats, deadlifts, bench press, shoulder press) at 75–85% 1RM, with 1–2 minutes rest.

Wednesday: Mixed resistance and TRX training (e.g., lat pulldown, chest press, DB lunges, TRX row, TRX plank knee-to-elbow).

Friday: Speed, change of direction (COD), agility, and plyometric drills based on MAS (Maximum Aerobic Speed) and ASR (Anaerobic Speed Reserve).

Control Group (Group 3):

Participants in this group did not undergo the structured HIIT or structured strength/speed sessions. They continued their standard football team training under the supervision of team coaches, which included technical and tactical practice but no structured conditioning component.

All sessions were conducted under supervision by certified strength and conditioning professionals. Heart rate was continuously monitored using Polar Team2Pro sensors to ensure intensity compliance. Safety protocols, including medical personnel and first-aid readiness, were implemented throughout.

Performance outcomes were evaluated before and after the intervention across all participants using the following measures:

ATP-PCr system: 30-meter flying sprint test

Anaerobic system: RAST (Running-Based Anaerobic Sprint Test)

Aerobic system: Yo-Yo IR1 (Intermittent Recovery Test Level 1) with VO_2max estimation

In addition to performance metrics, physiological indicators including body mass index (BMI), baseline heart rate, oxygen saturation (SpO_2), and blood pressure were assessed at both time points to evaluate training-induced adaptations.

Data Collection

Data gathering followed a structured timeline divided into three phases: prior to training, during the intervention, and immediately afterward. All procedures were reviewed and approved by the Human Research Ethics Committee at Nakhon Ratchasima Rajabhat University (Certificate No. HE-013-2025). Permission was also obtained to access the laboratories and equipment of the Sports Science Program, Faculty of Education, Rajabhat Mahasarakham University, where all data collection activities were conducted.

Participant Recruitment and Screening

Participants were recruited using purposive sampling based on predefined inclusion criteria. Each volunteer received a written information sheet and underwent a comprehensive verbal briefing outlining the study's objectives, testing protocols, and data collection procedures. Written informed consent was obtained prior to enrollment. All participants underwent a pre-participation medical screening conducted by licensed physicians at the RMU Health Center, ensuring eligibility for high-intensity physical activity.

Pre-Intervention Assessments

Baseline testing was performed one week before the training intervention under consistent laboratory conditions and with oversight from trained research personnel to ensure reliable data collection. The following measurements were obtained:

Anthropometric Data: Body height and weight were recorded and subsequently used to compute Body Mass Index (BMI) via the standard equation: mass (kg) divided by height in meters squared.

Resting Heart Rate: Monitored following 10 minutes of seated rest using a Polar heart rate strap (Finland).

Oxygen Saturation (SpO_2): Measured using a Nonin pulse oximeter (USA).

Blood Pressure: Both systolic and diastolic values were captured using an automatic digital sphygmomanometer.

Perceived Exertion: Subjective fatigue levels were assessed using the Borg RPE scale (ranging from 0 to 10).

Maximal Sprint Speed: Measured using a 30-meter flying sprint test; participants completed two trials with 30 seconds of rest, and the fastest time was recorded.

Anaerobic Power (RAST): Participants performed six 35-meter maximal sprints with 10-second rest intervals. Sprint times were used to calculate peak power, average power, minimum power, and fatigue index, using the BrianMac performance calculator (www.brianmac.co.uk/rast.htm).

Aerobic Capacity (Yo-Yo IR1 Test): Participants performed 20-meter shuttle runs at progressively increasing speeds guided by an audio signal. A 10-second active recovery was included between repetitions. Total distance covered (in meters) was recorded, and VO_2max was estimated using www.theyoyotest.com.

All participants were acquainted with the testing methods and intervention protocol prior to the commencement of the formal training session.

During-Intervention Monitoring

Throughout the 4-week training intervention, the following parameters were regularly monitored:

Heart Rate: Continuously tracked during HIIT sessions to ensure target intensity of 85–95% HRmax.

SpO_2 and RPE: Collected before, during, and after training sessions to assess internal workload and fatigue.

Safety Measures: First-aid kits and an emergency medical transport plan were available at all training venues.

Recovery Support: Drinking water was provided throughout each session, and light snacks were distributed following each training day to support recovery and hydration.

Participants were allocated to one of three groups—Hypoxic HIIT, Normoxic HIIT, or Control—based on VO_2max stratification to ensure baseline comparability. Hypoxic training was conducted using the Hypoxico Altitude Training System ($FiO_2 \approx 14.5\%$, simulating ~3,085 meters elevation), while the normoxic and control groups trained under ambient sea-level conditions ($FiO_2 = 20.9\%$).

Post-Intervention Assessments

Post-testing was performed within one week after the final training session, using the same protocols, equipment, personnel, and environmental conditions as in the baseline assessments. The following outcome variables were reassessed: Body Mass Index (BMI), Resting Heart Rate, Blood Oxygen Saturation (SpO_2), Blood Pressure (systolic and diastolic), 30-meter Sprint Time, RAST: peak, average, minimum power, and fatigue index, Yo-Yo IR1 Test: total distance and estimated VO_2max, Rating of Perceived Exertion (RPE)

Data analysis

Statistical processing was carried out using IBM SPSS Statistics version 26.0 (IBM Corp., Armonk, NY, USA). Summary statistics—means and standard deviations (M ± SD) were computed for all variables. The Shapiro–Wilk test assessed data normality for each dependent measure.

For within-group comparisons (pre- vs. post-test), either paired-sample t-tests were used for normally distributed data, or the Wilcoxon signed-rank test was employed for non-parametric cases.

Training-induced differences between groups (delta scores: post minus pre) were examined via one-way analysis of variance (ANOVA). If significant main effects emerged, Bonferroni-adjusted comparisons were performed to determine specific intergroup differences. In the event of ANOVA assumption violations (e.g., non-normality or unequal variances), the Kruskal–Wallis H test served as an alternative.

Effect sizes were reported to quantify the strength of observed outcomes: Cohen's d for within-group comparisons and eta squared (η^2) for between-group differences.

A threshold of $p < 0.05$ was adopted to determine statistical significance throughout all tests.

Results

This section presents the outcomes of the high-intensity interval training (HIIT) intervention under hypoxic and normoxic conditions on energy system performance among collegiate football players. Results are structured in accordance with the study objectives, comparing pre- and post-intervention changes in anaerobic and aerobic performance across three groups: Hypoxic HIIT, Normoxic HIIT, and Control.

Baseline Characteristics

At baseline, participants across all three groups exhibited comparable anthropometric and physiological profiles. As shown in Table 1, no statistically significant differences were observed in age, height, weight, or body mass index (BMI) among groups ($p > 0.05$), confirming the effectiveness of the VO_2max-based stratified randomization process. Mean BMI values for all groups fell within the "normal" range as defined by the Asian BMI classification system.

Table 1. Baseline Characteristics of Participants by Group

Group	Age	Height (cm)	Weight (kg)	BMI	BMI Category
Hypoxic HIIT (n = 8)	20.63	171.50	64.63	22.01	Normal
Normoxic HIIT (n = 8)	19.75	169.79	61.50	21.61	Normal
Control (n = 8)	19.38	171.50	64.75	21.99	Normal

Note: Values are expressed as Mean ± SD

Statistical analysis via one-way ANOVA revealed no significant baseline differences between groups for any anthropometric measure ($p > 0.05$). These findings confirm that participants began the intervention from physiologically equivalent starting points, thereby enhancing the internal validity of the training effect comparisons in subsequent analyses.

Within-Group Comparison

To evaluate the effects of the training interventions within each group, paired-sample t-tests were conducted to compare pre- and post-intervention values across all measured performance variables. The results, including effect sizes (Cohen's d), are summarized in Table 2.

Table 2. Within-Group Comparison of Performance Variables Pre- and Post-Intervention

Group	Exercise Variable	Pre-Training (Mean ± SD)	Post-Training (Mean ± SD)	*t*-value	*p*-value	Cohen's d
Hypoxic HIIT	ATP-PC System (s)	3.78 ± 0.18	3.56 ± 0.20	-2.280	0.057	-0.81
	ATP-PC System (km/h)	28.85 ± 2.21	28.58 ± 2.03	0.178	0.884	0.06
	Anaerobic Glycolysis (Max Power, W)	589.38 ± 44.19	712.50 ± 111.52	3.572	0.009 **	1.26
	Anaerobic Glycolysis (Min Power, W)	311.00 ± 68.43	412.38 ± 77.82	3.675	0.008 **	1.30
	Anaerobic Glycolysis (Avg Power, W)	468.25 ± 55.91	562.50 ± 76.42	2.816	0.026 *	1.00
	Yo-Yo IR1 Distance (m)	1264.63 ± 541.92	2395.00 ± 688.33	4.497	0.003 **	1.59
	VO_2max (ml/kg/min)	46.84 ± 4.70	54.79 ± 6.28	4.366	0.003 **	1.54
Normoxic HIIT	ATP-PC System (s)	3.70 ± 0.18	3.66 ± 0.18	-1.026	0.339	-0.36

	ATP-PC System (km/h)	29.09 ± 1.53	29.04 ± 1.73	-0.122	0.906	-0.04
	Anaerobic Glycolysis (Max Power, W)	607.00 ± 57.68	622.75 ± 111.00	0.348	0.738	0.12
	Anaerobic Glycolysis (Min Power, W)	359.88 ± 35.37	414.75 ± 76.22	1.611	0.151	0.57
	Anaerobic Glycolysis (Avg Power, W)	489.63 ± 47.65	503.50 ± 68.71	0.491	0.639	0.17
	Yo-Yo IR1 Distance (m)	1104.50 ± 324.79	1473.13 ± 330.16	2.946	0.022 *	1.04
	VO_2max (ml/kg/min)	45.89 ± 1.29	48.98 ± 3.16	2.228	0.061	0.79
Control Group	ATP-PC System (s)	3.83 ± 0.09	3.81 ± 0.81	-0.923	0.378	-0.33
	ATP-PC System (km/h)	27.61 ± 1.72	27.51 ± 1.83	-0.389	0.713	-0.14
	Anaerobic Glycolysis (Max Power, W)	571.24 ± 57.61	580.99 ± 64.67	1.504	0.176	0.53
	Anaerobic Glycolysis (Min Power, W)	381.76 ± 26.82	407.26 ± 68.23	0.978	0.361	0.35
	Anaerobic Glycolysis (Avg Power, W)	476.74 ± 41.13	513.61 ± 76.75	1.060	0.324	0.37
	Yo-Yo IR1 Distance (m)	1150.28 ± 359.08	1150.28 ± 359.08	–	–	-
	VO_2max (ml/kg/min)	46.79 ± 2.77	45.97 ± 2.64	1.000	0.351	0.35

Note: Values are expressed as Mean ± SD; n = 8 per group; *p < 0.05, *p < 0.01

The Hypoxic HIIT group exhibited the most substantial improvements among all groups, with large and consistent gains observed across both anaerobic and aerobic performance measures. Specifically, anaerobic power outputs measured via the Running-based Anaerobic Sprint Test (RAST) showed marked increases: Max Power (Cohen's d = 1.26), Min Power (d = 1.30), and Average Power (d = 1.00), indicating a high magnitude of change in explosive energy system capacity. Similarly, aerobic capacity demonstrated notable enhancements, with Yo-Yo Intermittent Recovery Test Level 1 (IR1) distance increasing significantly (p = 0.003, d = 1.59) and VO_2max showing a large effect size as well (d = 1.54, p = 0.003). Sprint performance improved as evidenced by a reduction in ATP-PC sprint time (d = –0.81), approaching statistical significance (p = 0.057). However, sprint speed (km/h) remained largely unchanged, supported by a negligible effect size (d = 0.06).

In the Normoxic HIIT group, moderate performance improvements were primarily confined to aerobic measures. Yo-Yo IR1 distance increased significantly (p = 0.022) with a large effect size (d = 1.04), while VO_2max showed a moderate effect (d = 0.79) but did not reach statistical significance (p = 0.061). Anaerobic outputs and sprint variables exhibited only small or negligible changes, with effect sizes for all such metrics remaining below d = 0.60.

The Control group, which did not undergo any structured high-intensity intervention, exhibited no statistically significant differences across all measured variables. Effect sizes for most outcomes were small to negligible, confirming that the observed performance gains in the experimental groups were attributable to the training interventions. A moderate effect was noted in anaerobic max power (d = 0.53), but it was not statistically significant (p = 0.176), further supporting the conclusion that structured HIIT, particularly under hypoxic conditions, was effective in enhancing energy system performance.

Between-Group Comparisons

To evaluate differential training responses, independent-sample t-tests were conducted comparing post-intervention performance between the Hypoxic HIIT group and the other two groups: Normoxic HIIT and Control. The results, including effect sizes (Cohen's d), are summarized in Table 3.

Table 3. Post-Intervention Performance Comparisons between Groups

Variable	Hypoxic HIIT	Normoxic HIIT	t	p	Group 1 vs Group 2	Cohen's d	Control	t	p	Group 1 vs Group 3	Cohen's d
ATP-PC Time (s)	3.61 ± 0.24	3.70 ± 0.21	-0.858	0.404	NS	-0.4	3.88 ± 0.28	-2.136	0.050	*	-1.04
ATP-PC Speed (km/h)	28.28 ± 2.27	28.69 ± 1.94	-0.412	0.686	NS	-0.19	26.88 ± 2.98	1.096	0.290	NS	0.53
RAST Max Power (W)	704.00 ± 107.39	631.33 ± 106.97	1.438	0.170	NS	0.68	566.86 ± 44.00	3.360	0.004	**	1.67
RAST Min Power (W)	401.67 ± 79.56	408.00 ± 74.12	-0.175	0.863	NS	-0.08	433.51 ± 83.50	-0.805	0.433	NS	-0.39
RAST Avg Power (W)	553.22 ± 76.71	504.78 ± 64.39	1.451	0.166	NS	0.68	535.11 ± 98.27	0.426	0.676	NS	0.21
Yo-Yo IR1 Distance (m)	2351.11 ± 657.20	1420.56±346.77	3.757	0.002	**	1.77	1175.28 ± 354.05	4.502	<0.001	**	2.23
VO_2max (ml/kg/min)	54.81 ± 5.87	48.62 ± 3.14	2.787	0.013	*	1.31	47.30 ± 2.65	3.320	0.005	**	1.65

Note: NS = Not Significant; comparisons are between Hypoxic HIIT and each of the other groups; *p < 0.05, **p < 0.01

Hypoxic HIIT vs. Normoxic HIIT: Although differences in anaerobic performance variables between the Hypoxic and Normoxic groups did not reach statistical significance ($p > 0.05$), the Hypoxic group consistently demonstrated higher post-intervention mean values across all anaerobic metrics. Notably, moderate to large effect sizes were observed for RAST Max Power ($d = 0.68$) and Average Power ($d = 0.68$), suggesting meaningful physiological improvements that may not have been captured by statistical thresholds due to sample size. In contrast, aerobic performance outcomes significantly favored the Hypoxic group. Yo-Yo Intermittent Recovery Level 1 (Yo-Yo IR1) distance showed a robust between-group difference ($p = 0.002$) accompanied by a very large effect size ($d = 1.77$). VO_2max also improved significantly ($p = 0.013$) with a large effect size ($d = 1.31$), indicating enhanced aerobic adaptations attributable to the hypoxic stimulus.

Hypoxic HIIT vs. Control: Compared to the Control group, the Hypoxic group demonstrated statistically and practically significant improvements across multiple key variables. RAST Max Power ($p = 0.004$, $d = 1.67$), Yo-Yo IR1 distance ($p < 0.001$, $d = 2.23$), and VO_2max ($p = 0.005$, $d = 1.65$) all reflected very large effect sizes, highlighting the superiority of the Hypoxic HIIT protocol in both anaerobic and aerobic domains. Additionally, ATP-PC sprint time was significantly reduced ($p = 0.050$, $d = -1.04$), indicating a performance-enhancing decrease in sprint duration. The negative effect size appropriately reflects a beneficial outcome, as shorter sprint times denote improved performance.

These between-group comparisons demonstrate that high-intensity interval training performed under hypoxic conditions elicits superior physiological adaptations compared to both normoxic HIIT and conventional football training. The improvements were particularly pronounced in aerobic capacity and select anaerobic performance variables. The inclusion of effect size data reinforces the practical relevance of these outcomes, supporting the strategic use of hypoxic HIIT protocols to optimize energy system development in elite football players.

Correlation and Regression Analysis

To further explore the associations between key physiological variables and training-induced performance outcomes, Pearson's correlation coefficients (r) and simple linear regression analyses were conducted. This analysis focused on post-intervention data from the Hypoxic HIIT and Normoxic HIIT groups. The results are summarized in Table 4.

Table 4. Correlation and Regression Analysis between Selected Physiological Variables and Performance Outcomes

Variable	Pearson (r)	p-value (r)	Regression Coefficient (β)	R^2 (Predictive Power)
ATP-PC Time (s)	0.078	0.843	0.09	0.006
RAST Max Power (W)	0.233	0.546	0.234	0.054
VO_2max (ml/kg/min)	0.319	0.403	0.596	0.102

Note: r = Pearson correlation coefficient; β = regression coefficient; R^2 = coefficient of determination

ATP-PC Time (s): The correlation between sprint time and overall training outcomes was negligible and statistically non-significant ($r = 0.078$, $p = 0.843$). Regression analysis also revealed minimal predictive value ($R^2 = 0.006$), indicating that short-burst anaerobic performance offered little explanatory insight in this context.

RAST Max Power (W): A weak positive association was observed ($r = 0.233$), though it did not reach statistical significance ($p = 0.546$). The regression coefficient ($\beta = 0.234$) and low R^2 value (0.054) suggest that while anaerobic peak power may reflect some influence on training outcomes, its predictive strength remains limited.

VO_2max (ml/kg/min): Among the tested variables, VO_2max demonstrated the strongest association with training outcomes ($r = 0.319$), albeit still statistically non-significant ($p = 0.403$). The relatively high regression coefficient ($\beta = 0.596$) and modest explanatory power ($R^2 = 0.102$) support the potential relevance of aerobic capacity—particularly under hypoxic conditions where oxidative adaptations are more pronounced.

Discussion

The current investigation assessed how high-intensity interval training (HIIT), conducted in environments with either reduced or normal oxygen levels, influenced energy system efficiency among collegiate football players. The findings lend strong support to the main hypothesis: conducting HIIT in simulated hypoxic settings yields greater physiological enhancements, particularly in aerobic capacity when compared with both normoxic and standard training approaches.

Enhanced Aerobic Adaptation in Hypoxic HIIT

The most notable result was the statistically significant improvement in VO_2max and Yo-Yo IR1 outcomes observed in the group undergoing hypoxic HIIT. These performance increases surpassed those of the control and normoxic training groups, emphasizing the aerobic advantage associated with reduced-oxygen training protocols. These observations are consistent with previous literature indicating that hypoxia enhances erythropoietin (EPO) synthesis, promotes red blood cell production, and improves oxygen transport and utilization efficiency (Nowak-Lis et al., 2021; Park et al., 2022; Weng et al., 2021).

At the cellular level, hypoxic exposure activates hypoxia-inducible factor 1-alpha (HIF-1α), which upregulates genes associated with erythropoiesis, angiogenesis, and mitochondrial biogenesis (Berlian et al., 2019; Hirota, 2020). These processes collectively enhance mitochondrial density, oxidative enzyme activity, and capillary perfusion, allowing muscles to extract and utilize oxygen more efficiently during high-intensity intermittent efforts (Bonilla et al., 2021; Krammer et al., 2022; Mangano et al., 2022). These physiological mechanisms explain the robust improvements observed in both VO_2max and Yo-Yo IR1 performance key indicators of aerobic endurance and recovery in football.

Anaerobic Performance: Selective Gains

While the hypoxic HIIT group showed improvements in anaerobic performance, particularly RAST max power, only the comparison with the control group reached statistical significance. No significant between-group differences were observed between hypoxic and normoxic HIIT in RAST average or minimum power. However, the trend toward greater values in the hypoxic group suggests that anaerobic energy systems may still benefit from altitude-equivalent training, likely due to increased glycolytic enzyme activity and muscle buffering capacity. These findings partially support earlier studies suggesting that combined HIIT and hypoxic stress can augment both aerobic and anaerobic performance in team sport athletes (Yamaguchi et al., 2020; Kim et al., 2021; Maciejczyk et al., 2023).

Anaerobic Output: Selective but Functional Gains

The hypoxic group also exhibited increases in RAST max power, which was significantly higher than in the control group, though differences with the normoxic HIIT group did not reach statistical significance. However, the trend toward superior anaerobic performance in the hypoxic condition is noteworthy. Prior studies suggest that hypoxia enhances glycolytic enzyme expression, lactate buffering, and fast-twitch muscle fiber recruitment, factors contributing to improved anaerobic output (Brocherie et al., 2015; Żebrowska et al., 2019; Guardado et al., 2020).

The lack of significant changes in RAST minimum and average power may reflect the relatively short duration of the intervention. Nonetheless, even selective gains in peak power are practically relevant for sports like football, where explosive actions such as sprinting, pressing, and counter-attacking are crucial.

ATP-PC System: Limited Responsiveness to Hypoxia

Short-duration sprint performance, evaluated through ATP-PC sprint time and peak velocity, exhibited only modest post-intervention changes. While the hypoxic HIIT group showed a slight improvement in sprint time ($p = 0.057$), this did not reach statistical significance. These findings suggest that the phosphagen system is less sensitive to hypoxic stress, largely because ATP resynthesis via creatine phosphate does not rely on oxygen availability, but rather on immediate intramuscular stores (Warnier et al., 2020; Archacki et al., 2024).

This limited responsiveness has been echoed in previous work. For instance, Takei et al. (2021) found that acute hypoxia had minimal effect on performance in efforts lasting under 6 seconds, despite elevated cardiovascular strain. Similarly, Girard et al. (2017) reported that short sprint performance was unaffected by simulated altitude exposure, suggesting that hypoxia-related benefits primarily influence systems with longer time constants, such as glycolysis and aerobic metabolism.

However, some studies suggest that under longer or repeated sprint protocols, neuromuscular fatigue can accumulate faster under hypoxia, which might indirectly affect phosphagen-based actions. Hagiwara et al. (2023) observed that repeated sprint training in hypoxia enhanced buffering capacity and delayed fatigue, even though peak power outputs remained unchanged. This suggests a role for hypoxic stimuli in recovery and repeated-sprint maintenance, more so than in improving absolute peak power in single-effort scenarios.

Performance Predictors: Aerobic Capacity Leads

Among all variables analyzed, VO_2max emerged as the most promising performance predictor, showing the highest regression coefficient ($\beta = 0.596$) and the largest coefficient of determination ($R^2 = 0.102$). While this relationship did not achieve statistical significance ($p = 0.403$), the trend supports the idea that aerobic fitness is central to performance in intermittent sports, where athletes must repeatedly engage in high-intensity efforts with short recovery intervals.

This finding aligns with prior research. Michailidis. (2024) demonstrated that VO_2max significantly correlates with distance covered in the Yo-Yo IR1 test, suggesting aerobic capacity influences high-intensity performance in young soccer players. Additionally, Kavanagh et al. (2023) found that VO_2max was a significant predictor of performance in a 1200m shuttle run test, reinforcing its relevance to field-based endurance. Furthermore, Ramadhan et al. (2022) reported that VO_2max improved significantly following interval training, highlighting the adaptability of aerobic capacity in response to targeted conditioning. These studies reinforce the notion that aerobic capacity underpins repeated sprint ability and recovery.

Interestingly, the lower predictive values of RAST Max Power and ATP-PC sprint time (R^2 = 0.054 and 0.006, respectively) suggest that anaerobic peak performance alone may not predict training responsiveness in a multifaceted sport like football. Instead, training adaptations may be more closely tied to aerobic metabolism, which sustains overall work rate and buffers fatigue during prolonged play.

Comparative Research Support

The present findings are consistent with an expanding range of literature supporting the efficacy of combining high-intensity interval training (HIIT) with hypoxic exposure to enhance various aspects of physiological performance. For instance, Westmacott et al. (2022) conducted a systematic review and concluded that six weeks of HIIT performed under simulated altitude conditions produced significantly greater improvements in VO_2max and hematological indicators (e.g., hemoglobin levels) than the same training conducted in normoxic settings among trained athletes. Cardinale et al. (2019) similarly found that cyclists exposed to hypoxia demonstrated superior mitochondrial function and aerobic endurance relative to those training in normal oxygen environments, even though VO_2max remained largely unchanged. These outcomes emphasize the synergistic role of hypoxic exposure and HIIT in promoting both central (cardiopulmonary) and peripheral (muscle and cellular) physiological improvements.

In applied settings, Pramkratok et al. (2022) reported that implementing repeated sprint training under hypoxic stress (RSH) in team sport athletes significantly improved VO_2peak and sprint repetition capacity compared to equivalent training under normoxia. After a six-week regimen in rugby sevens players, marked enhancements were observed in time-to-exhaustion and fatigue resistance, alongside a 7.5% rise in aerobic capacity. These adaptations were linked to increased mitochondrial efficiency, improved oxygen kinetics in the working muscles, and higher levels of hypoxia-responsive markers such as HIF-1α and VEGF—both of which play vital roles in metabolic and vascular adaptation.

At the molecular level, Lanfranchi et al. (2024) demonstrated that RSH induces specific muscular adaptations not observed under normoxia. Using muscle biopsies, they found that nine sessions of RSH significantly increased expression of mitochondrial biogenesis proteins and upregulated S100A13—a protein linked to cellular stress response and vascular regulation. These changes were accompanied by activation of the Akt signaling pathway, a key mediator of endurance-related muscular remodeling. This dual-stimulus model—mechanical stress from high intensity and chemical stress from oxygen deprivation—likely accelerates the molecular processes underlying adaptation.

This study contributes to that literature by showing that even a short-term, four-week RSH intervention under normobaric hypoxia can meaningfully improve both aerobic and anaerobic performance in football players. These results offer a practical and time-efficient strategy for enhancing conditioning in competitive team sports environments.

Practical Implications for Football Conditioning

The findings have direct practical applications for football-specific conditioning. The ability to repeat high-intensity actions (e.g., sprints, tackles, accelerations) with minimal fatigue is essential for match performance. By improving VO_2max and Yo-Yo IR1 performance, hypoxic HIIT can enhance both aerobic recovery between sprints and overall work capacity. The observed gains in RAST max power also suggest added benefits for explosive efforts, such as short sprints and directional changes.

Thus, integrating hypoxic HIIT protocols whether through altitude chambers, hypoxic masks, or simulated environments can be a valuable tool in periodized training, especially during pre-season or intensive conditioning phases. Coaches and strength and conditioning specialists should consider its application to accelerate fitness adaptations within a short training window.

Limitations

Despite the strengths of this study, several limitations should be acknowledged. First, the intervention period was relatively short (4 weeks), which may not have been sufficient to capture the full extent of physiological adaptations or training plateaus. A longer training duration could provide a more comprehensive understanding of the sustained impact of hypoxic HIIT on performance outcomes.

Second, the sample size was modest (n = 24), limiting the statistical power to detect subtle between-group differences and increasing the potential for Type II errors. Future studies with larger sample sizes are warranted to validate and generalize the findings.

Third, the study exclusively involved male collegiate football players, which restricts the generalizability of results to female athletes or individuals from other populations. Gender-based physiological differences may influence training responses, and future research should aim to include more diverse participant groups.

Lastly, no follow-up testing was conducted to assess the long-term retention of performance gains after the intervention. As a result, it remains unclear whether the observed improvements persist beyond the immediate post-training period. Incorporating follow-up assessments would provide valuable insights into the durability of the adaptations induced by hypoxic HIIT.

Practical Recommendations for Coaches

Based on the findings of this study, several practical guidelines can assist strength and conditioning professionals in effectively integrating hypoxic high-intensity interval training (HIIT) into pre-season football conditioning programs.

First, the recommended duration for a hypoxic HIIT block is between four to six weeks, ideally implemented during the pre-season when players are preparing for the competitive phase. During this period, coaches should aim to conduct two to three hypoxic HIIT sessions per week to elicit meaningful physiological adaptations without inducing overtraining.

Various hypoxic training setups can be utilized depending on available resources. These include altitude chambers, hypoxic masks, or simulated environments using systems like the Hypoxico Altitude Training System. The target oxygen concentration should be set to simulate an altitude of approximately 3,000 meters ($FiO_2 \approx 14.5\%$), with oxygen levels monitored continuously using an inline oxygen analyzer to ensure fidelity.

The most effective exercise modes include running-based intervals, repeated sprint training, and small-sided games, which are all highly specific to football demands. Each interval should be performed at 90–95% of the player's maximum heart rate (HRmax), with work-to-rest ratios typically ranging from 1:1

(e.g., 30 seconds work followed by 30 seconds rest) to 2:1 (e.g., 30 seconds work followed by 15 seconds rest).

Monitoring is essential to ensure training quality and safety. Coaches should track both heart rate responses and perceived exertion (RPE) and maintain strict control over environmental oxygen levels. Importantly, all players should be screened for cardiopulmonary risk factors before participating in hypoxic sessions, and coaches should remain alert for signs of excessive fatigue, dizziness, or other adverse responses during training.

By following these recommendations, practitioners can harness the performance-enhancing potential of hypoxic HIIT to accelerate fitness adaptations in a time-efficient and sport-specific manner.

Conclusions

This research investigated how performing high-intensity interval training (HIIT) in low-oxygen (hypoxic) versus standard-oxygen (normoxic) environments influences the energy system performance of collegiate football athletes.

The results indicate that hypoxic HIIT led to greater physiological benefits, particularly in aerobic function, as demonstrated by notable enhancements in VO_2max and Yo-Yo IR1 outcomes—surpassing the gains observed in both normoxic training and standard routines. These outcomes support the central hypothesis and fulfill the study's objective of evaluating whether oxygen availability modulates training-induced adaptations across the phosphagen, glycolytic, and oxidative energy systems. While the most pronounced improvements were observed in aerobic markers, the hypoxic group also exhibited selective gains in anaerobic peak power (RAST max), suggesting additional benefits for high-intensity performance in football contexts. In contrast, adaptations within the ATP-PCr system were limited, indicating a lower responsiveness of short-duration sprint performance to hypoxic stimuli.

Importantly, this study demonstrates that even a relatively short four-week intervention using normobaric hypoxia can yield meaningful performance improvements in trained athletes. The data also reinforce the predictive value of aerobic fitness particularly VO_2max as a key determinant of repeated sprint ability and fatigue resistance in intermittent sports such as football.

Future study should examine the long-term consequences of hypoxic high-intensity interval training (HIIT), the influence of individualized oxygen dosing protocols, and the optimal integration of hypoxic training within in-season microcycles. Further exploration of neuromuscular and recovery-related adaptations may also enhance the practical application of altitude-equivalent conditioning strategies in elite team sport environments.

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