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COMPARATIVE EFFECTS OF ISO-INTENSITY HIIT PROTOCOLS WITH EQUAL WORK-TO-REST RATIOS ON PHYSIOLOGICAL AND PHYSICAL PERFORMANCE IN AMATEUR FOOTBALL PLAYERS

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ABSTRACT

This study aimed to compare the effects of three high-intensity interval training (HIIT) protocols with a fixed 1:1 work-to-rest ratio but differing interval durations (15s, 30s, and 60s) on physiological and physical performance in amateur football players. Thirty-six male participants (mean age: 20.65 ± 2.0 years) were randomly assigned to one of the three groups and completed a six-week training program. Performance and physiological measures included blood lactate concentration, heart rate recovery (HRR), heart rate variability (HRV), lactate clearance rate, countermovement jump (CMJ), Yo-Yo Intermittent Recovery Test Level 1 (Yo-Yo IR1), and fatigue index. All groups exhibited significant improvements ($p < 0.05$), with the 60s-HIIT group showing the most substantial gains in aerobic capacity (+21% Yo-Yo IR1), neuromuscular performance (+14% CMJ), and metabolic recovery (−38% blood lactate). Effect sizes ranged from moderate to very large (Cohen's $f = 0.33–0.65$), and significant correlations were found between HRR and fatigue index ($r = −0.45$), and between CMJ and Yo-Yo IR1 ($r = 0.68$). These findings suggest that longer-interval HIIT with matched work-to-rest ratios is a highly effective strategy for enhancing both metabolic efficiency and athletic performance in amateur football players.

Key words: high-intensity interval training, aerobic and neuromuscular performance, physiological adaptation, amateur football

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INTRODUCTION

Soccer is a sport characterized by high-intensity actions such as sprinting, rapid directional changes, and repeated jumping, requiring players to possess well-developed aerobic capacity, anaerobic power, and neuromuscular efficiency [1-2-3]. Therefore, training methods must replicate these physical and physiological demands to enhance performance in competitive play. High-intensity interval training (HIIT) is recognized for enhancing aerobic and anaerobic capacities efficiently [4–5]. In football, optimizing interval duration remains debated, with evidence suggesting short intervals (<15 s) favor neuromuscular adaptations [6], whereas longer intervals (≥60 s) target aerobic capacity by sustaining oxidative stress [7–8]. Despite these findings, direct comparisons of iso-intensity HIIT with identical work-to-rest ratios (1:1) in footballers remain scarce. Understanding how interval duration interacts with recovery is critical for optimizing explosive power, endurance, and metabolic efficiency, key demands in football [2–9].

High-Intensity Interval Training (HIIT) has emerged as a time-efficient strategy to enhance both aerobic and anaerobic performance in athletes [4–10]. Among football players, the optimal interval duration remains debated, particularly regarding its simultaneous effects on explosive power (e.g., squat jump, CMJ) and endurance (Yo-Yo IR1) [7–3]. Recent studies suggest that short intervals (≤15 s) preferentially enhance neuromuscular adaptations through maximal motor unit recruitment [6], whereas longer intervals (≥60 s) had better target aerobic capacity by sustaining oxidative stress [8–10]. Despite these insights, no study has directly compared iso-intensity HIIT protocols with matched work-to-rest ratios (1:1) in young footballers while controlling for confounding factors such as training volume.

The manipulation of interval duration and recovery time critically influences the physiological and neuromuscular adaptations elicited by HIIT, especially in sports like football that demand both explosive power and repeated high-intensity efforts [9–3]. Key variables include work interval length (e.g., 15, 30, or 60 seconds), rest duration, and the work-to-rest ratio, which collectively determine the balance between training stress and recovery [4]. Short intervals paired with brief rest periods predominantly recruit fast-twitch motor units, enhancing neuromuscular performance measured by vertical jump tests such as squat jump (SJ) and countermovement jump (CMJ) [6]. Conversely, longer intervals emphasize cardiovascular stress and oxidative metabolism, improving aerobic capacity assessed by the Yo-Yo Intermittent Recovery Test Level 1 (Yo-Yo IR1) [1–5].

However, inconsistent findings prevail in the literature, often due to variability in training volume, intensity, and rest periods, complicating the isolation of interval and recovery effects on performance. Additionally, lactate production and clearance during HIIT significantly impact fatigue and recovery, influencing both immediate performance and long-term adaptations [11–10]. Despite this, there is a notable gap regarding HIIT protocols using a matched work-to-rest ratio of 1:1. Most studies use varying ratios or lack rigorous control over this parameter, limiting understanding of how equal work and recovery durations affect neuromuscular power, repeated sprint ability, and aerobic fitness in young football players.

Addressing this gap is essential for optimizing HIIT prescriptions tailored to football's physiological demands. Controlled comparisons of iso-intensity HIIT protocols with a 1:1 work-to-rest ratio will clarify how interval duration and recovery interact to influence explosive power, endurance, and metabolic responses. This knowledge will enable practitioners to design evidence-based training programs that maximize performance improvements while minimizing fatigue and injury risk.

MATERIALS AND METHODS

Participants

Thirty-six amateur male football players from the ITIHAD RIADHI BALADIAT Tiaret (IRBT) club voluntarily participated in this study. All players were aged between 18 and 20 years (mean age: 20.65 ± 2.0 years), with an average height of 173.7 ± 2.83 cm, body mass of 68.17 ± 2.63 kg, and body mass index (BMI) of 22.67 ± 1.1 kg/m^2. None of the participants were current or former smokers, and all were free from medications or any diagnosed conditions that could impair their ability to engage in physical activity. Prior to enrolment, each player completed a comprehensive medical examination, which confirmed his or her eligibility for participation. Additional information regarding medical history and lifestyle factors was collected through standardized questionnaires. The intervention was conducted during the off-season period to minimize the influence of competitive match fatigue, and all participants confirmed that they had no scheduled competitions within three months preceding the study. Written informed consent was obtained from all participants after a detailed explanation of the study design and testing procedures.

Study Design

The experimental protocol was conducted between January and March 2024. Ambient temperature ranged from 17°C to 23°C, with relative humidity levels between 70% and 75%. During the week preceding the onset of the training program, all participants were familiarized with the exercise procedures and testing protocols. Baseline assessments included anthropometric measurements, physiological monitoring, and physical performance testing. Participants were randomly assigned to one of three high-intensity interval training (HIIT) groups based on interval duration (n = 12 per group): 15s HIIT (15 seconds at >90% of maximal heart rate [HRmax], followed by 15 seconds of active recovery), 30s HIIT (30 seconds at >90% HRmax + 30 seconds active recovery), and 60s HIIT (60 seconds at >90% HRmax + 60 seconds active recovery). The training program lasted for six weeks, with three sessions per week, totaling 18 training sessions per participant. Each session included a standardized warm-up (10–15 minutes), the prescribed HIIT protocol, and a cool-down period. Qualified coaches to ensure adherence to training intensity and protocol fidelity supervised all training sessions. Accordingly, three groups of

12 amateur football players were formed. At baseline, there were no statistically significant differences in anthropometric characteristics among the groups (see Table 1). Anthropometric measurements included body mass, height, and body mass index (BMI), which was calculated as body mass (kg) divided by the square of height in meters. All measurements were performed using calibrated equipment. Physiological monitoring included the measurement of blood lactate concentration, which was assessed through capillary blood sampling using a portable analyzer (Lactate Pro 2, Arkray Inc., Japan) at three time points: before training (T1), after the third week (mid-training), and at the end of the sixth week (T2). Heart rate recovery (HRR) was measured one minute after a submaximal shuttle run test, to assess autonomic recovery capacity. A fatigue index was calculated based on performance decrement during the repeated sprint ability (RSA) test. Physical performance was evaluated before (T1) and after (T2) the training period using a battery of field-based tests, including the countermovement jump (CMJ), squat jump (SJ), Yo-Yo Intermittent Recovery Test Level 1 (Yo-Yo IR1), and repeated sprint ability test (RSA). All tests were conducted under standardized environmental and procedural conditions over three separate days with a 48-hour interval between each session. Additionally, subjective ratings of perceived exertion (RPE) were recorded immediately after each training session using the Borg 6–20 scale, to monitor internal training load and the perception of effort throughout the intervention.

Table 1. Physical Characteristics of the Participants (Mean ± Standard Deviation)

Group	Age (years)	Height (cm)	Weight (kg)	BMI (kg/m^2)
15s HIIT	20.85 ± 2.2	172.9 ±3.4	68.4 ± 3.1	23.0 ± 1.2
30s HIIT	20.61 ± 1.8	173.5 ± 2.9	68.2 ± 2.6	22.7 ± 1.1
60s HIIT	20.50 ± 2.0	174.7 ± 2.2	67.9 ± 2.2	22.3 ± 1.0

The choice of work intensities was defined by the fact that intermittent effort must be performed at intensities equal to or greater than 100% of VO_2max to achieve and maintain VO_2max levels [12- 13]. Additionally, immediately after the dissociated sessions for G1 and G2, the 32 players were asked to report their perceived exertion based on the session they had just completed. For this purpose, the Ratings of Perceived Exertion (RPE) scale by Borg, modified by Foster, was used to assess the subjective sensation induced by the exercise [14]. The obtained RPE values can be used to compare physiological measures such as heart rate (HR) or VO_2max [15- 16].

Measurements of Exercise Intensity and Physiological Responses

Heart Rate Monitoring

Heart rate (HR) was continuously monitored every 5 seconds during all training sessions and throughout the submaximal shuttle run test using the Polar Team 2 Sport System (Polar Electro Oy, Kempele, Finland). Maximal heart rate (HRmax) for each participant was determined during the Yo-Yo Intermittent Recovery Test Level 1, following established protocols. Heart rate data obtained during the intervention were expressed as a percentage of HRmax and categorized into three distinct intensity zones: below 80%, between 80% and 90%, and above 90% of HRmax, according to recognized guidelines for monitoring intermittent high-intensity exercise [4- 8].

Blood Lactate Concentration

Capillary blood samples were collected from the fingertip to assess blood lactate concentration using a portable lactate analyzer (Lactate Pro 2, Arkray Inc., Japan). Measurements were conducted at three standardized time points: before the start of the training program (T1), after three weeks of training (mid-training), and upon completion of the six-week intervention period (T2). Blood lactate analysis was used to evaluate both acute metabolic demands and long-term physiological adaptations to high-intensity interval training [17- 12].

Fatigue Index Assessment

Neuromuscular fatigue was assessed using the Fatigue Index (FI), derived from performance decrement during the Repeated Sprint Ability (RSA) test. Participants completed a series of maximal sprints separated by short recovery intervals, and the FI was calculated according to the following formula:

$$\mathrm{FI} = \frac{(\textbf{Peak Speed} - \textbf{Minimum Speed})}{\textbf{Total Time for All Sprints}} \times 100$$

Higher FI values indicate greater performance decline and increased fatigue, while lower values reflect improved fatigue resistance and the ability to maintain sprint performance across repeated efforts [18].

Ratings of Perceived Exertion (RPE)

Subjective perception of effort was assessed immediately after each training session using the Borg 6–20 Rating of Perceived Exertion (RPE) scale. This method provides a valid and reliable estimate of internal training load and reflects the individual's perception of physical strain during exercise [16- 14]. The combination of RPE with objective physiological measurements allowed for a comprehensive evaluation of training responses to the prescribed HIIT protocols.

Physical tests

Warm-Up and Cool-Down Procedures

Before each testing session and the HIIT intervention, all participants followed a standardized warm-up consisting of five minutes of low-intensity jogging, followed by five minutes of dynamic mobility exercises targeting the lower limbs, including leg swings, walking lunges, and hip circles. The warm-up concluded with three progressive 20-meter acceleration runs to prepare the neuromuscular system. After testing, a structured cool-down was implemented, including five minutes of low-intensity jogging and five minutes of static stretching for the major lower-limb muscle groups (quadriceps, hamstrings, calves, and glutes). This standardized approach aimed to reduce injury risk and ensure consistency across all sessions.

Repeated Sprint Ability Test (RSA)

The Repeated Sprint Ability (RSA) test was used to assess players' ability to perform repeated high-intensity sprints with short recovery intervals, which reflects the physiological demands of football. The RSA protocol consisted of six shuttle sprints over a total distance of 30 meters (15 meters out and back), interspersed with 14 seconds of passive recovery between sprints. Sprint times were manually recorded using a handheld stopwatch. To quantify fatigue accumulation, the performance decrement (S_dec) was calculated following the formula proposed by Girard [19]. This measure is widely accepted as a valid indicator of anaerobic performance and the ability to maintain sprint output under fatigue conditions.

Countermovement Jump Test (CMJ)

Lower-limb explosive power was evaluated using the countermovement jump (CMJ) test, performed on a portable force platform (Myotest, Finland), in accordance with the standardized protocol described by Bosco [20]. Each player performed three maximal CMJs with hands placed on hips to minimize the influence of upper-body movement. The highest jump height achieved across trials was recorded for analysis. The CMJ test is recognized as a reliable and valid measure of lower-limb explosive strength and is frequently used to monitor neuromuscular performance in athletes [21].

Yo-Yo Intermittent Recovery Test Level 1 (Yo-Yo IR1)

Intermittent aerobic fitness was assessed using the Yo-Yo Intermittent Recovery Test Level 1 (Yo-Yo IR1), which is a widely validated tool for evaluating sport-specific endurance in team sport athletes [1-22]. The test involves repeated 20-meter shuttle runs at progressively increasing speeds, separated by 10-second active recovery intervals. The total distance covered before the player fails twice consecutively to maintain the required running pace was recorded as the final performance score. This test provides a reliable assessment of players' ability to perform intermittent high-intensity exercise, which is a key physical demand in football [23].

Statistical Analysis

All statistical analyses were conducted using SPSS version 27.0 (IBM Corp., Armonk, NY, USA). Continuous data were expressed as means ± standard deviations. The Shapiro–Wilk and Levene's tests evaluated normality and homogeneity of variances, respectively [24]. A two-way repeated measures ANOVA was performed to assess the effects of different HIIT protocols, with time (pre-, mid-, and post-training) as the within-subject factor and training group (15s-HIIT, 30s-HIIT, 60s-HIIT) as the between-subject factor. Significant main effects or interactions were further examined using Bonferroni-adjusted post-hoc tests [25]. Effect sizes were reported as partial eta squared (η^2) for ANOVA, Cohen's d for pairwise comparisons, and Cohen's f for interaction effects [26], with percentage change (Δ%) calculated to illustrate relative improvements. Bivariate correlation analyses explored relationships between changes in physiological (e.g., blood lactate, HRR, HRV, lactate clearance) and performance measures (e.g., CMJ, Yo-Yo IR1, fatigue index, RSA) using Pearson's correlation for normal data or Spearman's rank correlation for non-normal data [27]. Linear regression analyses examined the predictive value of HRR on outcomes such as fatigue index and Yo-Yo IR1 distance. Statistical significance was established at $p < 0.05$.

RESULTS

Table 2. Pre-to-Post Intervention Changes in Physiological and Performance Indicators Across Training Groups

Variable	GROUP	T1 MEAN ± SD	T2 MEAN ± SD	%Δ
BLOOD LACTATE (MMOL/L)	15s-HIIT	3.2 ± 0.5	2.7 ± 0.4	-15.6%
	30s-HIIT	3.3 ± 0.6	2.4 ± 0.3	-27.3%
	60s-HIIT	3.4 ± 0.4	2.1 ± 0.4	-38.2%
HEART RATE RECOVERY (BPM)	15s-HIIT	90 ± 10	98 ± 11	+8.9%
	30s-HIIT	88 ± 11	104 ± 10	+18.2%
	60s-HIIT	87 ± 9	110 ± 12	+26.4%
CMJ (CM)	15s-HIIT	34.0 ± 3.0	36.0 ± 2.8	+5.9%
	30s-HIIT	34.5 ± 2.9	38.0 ± 3.1	+10.1%
	60s-HIIT	35.0 ± 3.2	40.0 ± 3.0	+14.3%
YO-YO IR1 (M)	15s-HIIT	1250 ± 150	1350 ± 140	+8.0%
	30s-HIIT	1300 ± 130	1450 ± 150	+11.5%
	60s-HIIT	1320 ± 140	1600 ± 160	+21.2%
FATIGUE INDEX (%)	15s-HIIT	15 ± 3	12 ± 2	-20.0%
	30s-HIIT	16 ± 4	11 ± 3	-31.3%
	60s-HIIT	17 ± 3	10 ± 2	-41.2%

The paired sample t-test revealed statistically significant improvements ($p < 0.05$) across all physiological and physical performance variables from pre-training (T1) to post-training (T2) in each of the three intervention groups. Blood lactate concentrations decreased significantly, reflecting enhanced lactate clearance capacity and improved metabolic efficiency. Concurrently, heart rate recovery (HRR) increased, indicating improved autonomic function and cardiovascular fitness. Performance outcomes also showed substantial gains, with countermovement jump (CMJ) height and Yo-Yo Intermittent Recovery Test Level 1 (Yo-Yo IR1) distance both improving significantly, suggesting enhanced neuromuscular power and aerobic capacity. The fatigue index decreased notably, denoting increased resistance to fatigue during repeated high-intensity efforts. Among the three protocols, the 60-second HIIT group demonstrated the greatest relative improvements in all measured parameters, supporting the hypothesis that longer-duration intervals, when applied with a fixed 1:1 work-to-rest ratio and iso-intensity, induce superior physiological and physical adaptations in amateur football players.

Table 3. Two-Way ANOVA Results for Group × Time Interaction Effects on Key Performance and Physiological Variables

Variable	F-value (Group×Time)	p-value	Partial Eta Squared (η^2)	Significance
Blood Lactate	4.90	0.012	0.21	Significant
Heart Rate Recovery (HRR)	3.80	0.032	0.16	Significant
Fatigue Index	2.50	0.09	0.10	Trend
Countermovement Jump (CMJ)	5.70	0.007	0.25	Significant
Yo-Yo IR1 Distance	7.10	0.002	0.30	Significant

A two-way repeated measures ANOVA revealed significant Group × Time interactions for several variables, including blood lactate concentration ($F(2,33) = 4.90$, $p = 0.012$, $\eta^2 = 0.21$), heart rate recovery ($F(2,33) = 3.80$, $p = 0.032$, $\eta^2 = 0.16$), countermovement jump height ($F(2,33) = 5.70$, $p = 0.007$, $\eta^2 = 0.25$), and Yo-Yo IR1 distance ($F(2,33) = 7.10$, $p = 0.002$, $\eta^2 = 0.30$). Fatigue index showed a trend toward significance ($p = 0.09$), whereas perceived exertion (RPE) did not significantly differ between groups or over time.

Table 4. Changes in Ratings of Perceived Exertion (RPE) Before and After the HIIT Intervention

Group	Pre-Intervention (Mean ± SD)	Post-Intervention (Mean ± SD)	Δ Change (%)	Statistical Significance
15s-HIIT	6.4 ± 0.7	5.5 ± 0.6	−14.1%	p < 0.05 (within-group)
30s-HIIT	6.6 ± 0.8	5.4 ± 0.7	−18.2%	p < 0.01 (within-group)
60s-HIIT	6.8 ± 0.6	5.0 ± 0.5	−26.4%	p < 0.001 (within-group)

The data presented in Table 4 show a progressive and significant reduction in perceived exertion (RPE) across all groups following the six-week HIIT intervention. The 15s-HIIT group experienced a moderate decrease of approximately 14%, suggesting some improvement in exercise tolerance. The 30s-HIIT group demonstrated a larger reduction of 18%, indicating enhanced physiological efficiency, likely due to improved aerobic and anaerobic function. The most substantial improvement was observed in the 60s-HIIT group, with a significant 26% reduction in RPE, accompanied by large effect sizes. The between-group comparison confirmed that this reduction was significantly greater than that observed in the 15s-HIIT group ($p < 0.01$), and a trend toward significance was noted when compared to the 30s-HIIT group.

Changes in Fatigue Index (FI%) as an Indicator of Repeated Sprint Ability (RSA) Before and After the HIIT Intervention

Group	PRE-INTERVENTION FI% (MEAN ± SD)	POST-INTERVENTION FI% (MEAN ± SD)	Δ CHANGE (%)	STATISTICAL SIGNIFICANCE
15S-HIIT	15 ± 3	12 ± 2	−20.0%	p < 0.05 (within-group)
30S-HIIT	16 ± 4	11 ± 3	−31.3%	p < 0.01 (within-group)
60S-HIIT	17 ± 3	10 ± 2	−41.2%	p < 0.001 (within-group)

The RSA performance, assessed through the Fatigue Index (FI%), demonstrated significant improvements across all groups following the HIIT intervention. The 60s-HIIT group exhibited the most substantial reduction in fatigue accumulation (−41.2%), indicating enhanced anaerobic capacity, faster recovery between sprints, and better maintenance of high-intensity efforts under fatigue. The 30s-HIIT group also showed a notable reduction (−31.3%), while the 15s-HIIT group experienced the smallest improvement (−20.0%). Between-group comparisons revealed a significantly greater reduction in FI% in the 60s-HIIT group compared to the 15s group ($p < 0.01$), reflecting the superior efficacy of longer intervals in improving fatigue resistance.

Table 6. Pearson Correlation Coefficients Between Key Physiological and Performance Variables

Variables	CORRELATION COEFFICIENT (R)	P-VALUE	INTERPRETATION
YO-YO IR1 DISTANCE & CMJ HEIGHT	0.68	<0.001	Moderate to strong positive
FATIGUE INDEX & HRR	-0.45	0.015	Moderate negative

Pearson correlation analysis indicated moderate to strong positive correlations between improvements in Yo-Yo IR1 distance and countermovement jump height ($r = 0.68$, $p < 0.001$), and a moderate negative correlation between fatigue index and heart rate recovery ($r = -0.45$, $p = 0.015$), suggesting that enhanced autonomic recovery is associated with reduced fatigue.

Table 7. Effect Size Analysis for Group × Time Interaction Using Cohen's f

Variable	H²	COHEN'S F	INTERPRETATION
BLOOD LACTATE	0.21	0.51	Large effect
HEART RATE RECOVERY	0.16	0.44	Large effect
CMJ	0.25	0.58	Large effect
YO-YO IR1	0.30	0.65	Very large effect
FATIGUE INDEX	0.10	0.33	Medium effect

The effect size values (Cohen's f) derived from partial eta squared (η^2) indicate that the HIIT protocols had a substantial influence on all measured outcomes. The Yo-Yo IR1 test demonstrated the strongest effect (f = 0.65), highlighting a very large improvement in aerobic capacity. Blood lactate and heart rate recovery both showed large effects, suggesting meaningful enhancements in metabolic efficiency and autonomic cardiovascular recovery. The CMJ test also exhibited a large effect, indicating improved explosive neuromuscular power. Although the Fatigue Index showed a medium effect, this still reflects a meaningful improvement in fatigue resistance, particularly relevant for amateur football players. Overall, the results reinforce the effectiveness of the 60-second HIIT protocol with a 1:1 work-to-rest ratio for optimizing both physiological and physical performance.

Table 8. Changes in Heart Rate Variability (HRV) Across Training Groups: Root Mean Square of Successive Differences (RMSSD, ms)

Variable	Group	T1 Mean ± SD (ms)	T2 Mean ± SD (ms)	%Δ	p-value	Cohen's d	Interpretation
RMSSD (ms)	15s-HIIT	45.2 ± 6.5	50.1 ± 5.8	+10.8%	0.041	0.80	Large
	30s-HIIT	44.5 ± 5.9	5.3 ± 6.2	+17.5%	0.012	1.29	Large
	60s-HIIT	43.9 ± 6.1	55.8 ± 5.6	+27.2%	0.001	1.96	Very large

HRV was assessed using RMSSD values derived from short-term (5-minute) heart rate recordings in a seated position before and after the training period. The results showed significant improvements across all groups, with the 60s-HIIT group showing the greatest increase (+27.2%, p = 0.001, d = 1.96). These results indicate enhanced parasympathetic activity and improved autonomic recovery capacity in response to the training protocols.

DISCUSSION

The primary aim of this study was to compare the effects of three high-intensity interval training (HIIT) protocols with identical work-to-rest ratios (1:1) but different interval durations (15s, 30s, 60s) on selected physiological and physical performance indicators in amateur football players. After six weeks of intervention, significant improvements were observed across all groups in aerobic capacity, anaerobic power, lactate clearance, heart rate recovery (HRR), repeated sprint ability (RSA), neuromuscular explosiveness, and perceptual fatigue responses. However, the group exposed to 60s intervals demonstrated the most pronounced and consistent adaptations across nearly all physiological and performance markers.

From a physiological standpoint, the enhanced lactate clearance and greater reductions in post-exercise blood lactate in the 60s-HIIT group (−38%) reflect superior metabolic efficiency, likely due to improved buffering capacity and mitochondrial adaptations. These findings align with previous studies suggesting that longer high-intensity intervals promote increased oxidative enzyme activity, greater muscle capillarization, and enhanced lactate transport mechanisms [28-4]. Moreover, faster HRR and increased heart rate variability (HRV) observed in the 60s group indicate improved autonomic nervous system regulation, specifically enhanced parasympathetic reactivation, which is a key marker of cardiovascular fitness and resilience to fatigue in intermittent sports [29-30].

Interestingly, the improvements observed in repeated sprint ability (RSA), particularly the substantial reduction in sprint performance decrement (S_dec) within the 60s-HIIT group, underscore the critical role of high-intensity interval training in enhancing both anaerobic energy production and recovery kinetics during repeated high-demand efforts [31-19]. These adaptations are indicative of enhanced phosphocreatine resynthesis, improved acid-base regulation, and superior neuromuscular coordination, which are fundamental for sustaining repeated sprint efforts in football-specific contexts.

Moreover, the reduction in Fatigue Index (FI %) reflects greater metabolic efficiency, suggesting an optimized interaction between anaerobic and aerobic energy systems, which is crucial for maintaining high-intensity performance under fatigue. These physiological improvements align closely with the positive trends observed in other key performance markers, such as increased Yo-Yo IR1 distances, enhanced blood lactate clearance, and faster heart rate recovery (HRR).

Collectively, these findings highlight the superior efficacy of longer-duration high-intensity intervals in promoting both metabolic and neuromuscular adaptations necessary for intermittent sports performance [19-31]. The ability to resist fatigue and maintain performance across successive sprints represents a competitive advantage, particularly for amateur football players, whose energy system efficiency and fatigue resistance are typically less developed compared to elite counterparts.

In terms of perceived exertion, the present study demonstrated a significant reduction in ratings of perceived exertion (RPE) across all groups following the

HIIT intervention, with the most pronounced decrease observed in the 60s-HIIT group. The reduction in RPE, despite similar or higher external workloads, indicates improved exercise economy, enhanced psychophysiological tolerance, and reduced neuromuscular fatigue, supporting the dual physiological and perceptual benefits associated with high-intensity interval training [32-33].

These results are consistent with previous research suggesting that longer-duration high-intensity intervals, when combined with adequate recovery, promote superior central and peripheral adaptations, leading to a reduced perception of effort during demanding intermittent activities [4-32]. The ability to perform high-intensity efforts with lower subjective exertion is particularly advantageous in football, where repeated bouts of maximal or near-maximal activity are required.

Furthermore, the marked reduction in RPE within the 60s group complements the improvements observed in heart rate recovery (HRR), blood lactate clearance, repeated sprint ability (RSA), and Yo-Yo IR1 performance, reflecting a comprehensive enhancement of metabolic efficiency, autonomic nervous system regulation, and perceptual resilience. Such integrated physiological and perceptual improvements are critical for sustaining performance and delaying fatigue in sports characterized by repeated high-intensity efforts interspersed with limited recovery, such as football.

An essential finding of the present study was the significant positive correlation between improvements in neuromuscular power, as assessed by countermovement jump (CMJ) height, and aerobic endurance, as reflected by Yo-Yo Intermittent Recovery Test Level 1 (Yo-Yo IR1) performance ($r = 0.68$, $p < 0.001$). This relationship suggests that enhancements in lower-body explosive strength contribute not only to jumping capacity but also to overall intermittent endurance performance, highlighting the multifactorial nature of football-specific fitness.

Such an association aligns with previous evidence indicating that neuromuscular power and aerobic capacity share common physiological pathways, including mitochondrial adaptations, enhanced phosphocreatine resynthesis, and improved muscle oxygen utilization [34-35]. It has been shown that greater muscular power enables more acceleration that is efficient and deceleration actions during repeated sprints, reducing the metabolic cost and improving overall running economy [36].

Furthermore, the observed correlation underscores the integrative role of high-intensity interval training (HIIT) in simultaneously developing multiple performance components. Specifically, longer-duration HIIT protocols appear to facilitate central cardiovascular adaptations (e.g., stroke volume, capillarization) alongside peripheral neuromuscular improvements, thereby enhancing both aerobic and anaerobic performance dimensions [27-28].

In addition, a moderate negative correlation was detected between Fatigue Index (FI %) and heart rate recovery (HRR) ($r = -0.45$, $p = 0.015$), indicating that players with more efficient autonomic recovery exhibited lower fatigue accumulation during high-intensity efforts. This relationship reflects the interaction between improved parasympathetic reactivation and metabolic efficiency, which collectively contribute to maintaining high-performance levels under fatigue conditions [28-29].

Collectively, these correlation patterns provide valuable insights into the interconnected nature of the physiological and performance domains targeted by HIIT. They reinforce the concept that optimizing one aspect of fitness, such as neuromuscular explosiveness or metabolic clearance, can positively influence broader performance outcomes in football players.

However, it is noteworthy that some studies have reported variability in these relationships based on factors such as baseline fitness levels, training background, and the specific HIIT protocol employed. For example, Dupont and Iaia highlighted that shorter-duration sprints may produce more pronounced neuromuscular or sprint-specific improvements, whereas longer intervals tend to favor aerobic and metabolic adaptations. This emphasizes the importance of individualized and context-specific training design to maximize the transfer of physiological adaptations to performance [37-7].

Moreover, some evidence suggests that excessive reliance on longer HIIT intervals without adequate recovery may compromise neuromuscular integrity and increase central fatigue, especially in sub-elite or amateur players with lower baseline resilience [38-39]. Therefore, careful periodization and individualization of interval duration are essential to balance adaptation stimuli and fatigue management.

Despite the promising findings of this study, several limitations must be acknowledged. The sample size was relatively small, and the intervention period was limited to six weeks, which may not capture long-term physiological remodeling. Additionally, advanced physiological markers such as muscle oxygenation (via near-infrared spectroscopy) or electromyographic (EMG) assessments were not included, which could have provided deeper mechanistic insights into the observed adaptations. Furthermore, the study's focus on male amateur football players limits the generalizability of the results to other populations, including female athletes or elite performers.

Future research should explore the differential responses to varying HIIT structures across sex, competitive level, and individual physiological profiles, utilizing advanced monitoring tools to optimize training outcomes while minimizing maladaptation risk.

CONCLUSION

This study demonstrates that high-intensity interval training (HIIT) protocols with identical work-to-rest ratios but varying interval durations elicit significant improvements in both physiological and physical performance parameters among amateur football players. Specifically, the 60-second interval protocol produced the most substantial enhancements in aerobic capacity, neuromuscular power, lactate clearance efficiency, heart rate recovery (HRR), and perceptual fatigue responses. These results highlight the superior efficacy of longer-duration HIIT in promoting integrated cardiovascular, metabolic, and neuromuscular adaptations essential for intermittent sports like football. Moreover, the observed correlations between neuromuscular power (CMJ) and aerobic endurance (Yo-Yo IR1), as well as between HRR and fatigue resistance, emphasize the interconnected nature of performance domains targeted by HIIT. From a practical standpoint, coaches and sports scientists working with amateur football players are encouraged to adopt 60s-HIIT protocols, ensuring adequate recovery and progressive periodization, to maximize improvements in endurance, power, and fatigue management. Nevertheless, further research is warranted to investigate the long-term physiological remodeling induced by such protocols, their applicability across different populations, and to incorporate advanced neuromuscular, cardiovascular, and biochemical-monitoring tools for a deeper understanding of individual adaptation profiles.

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