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Research article

Modified Sprint Interval Intervention Produces Lower Inter-Subject Variability in Physiological and Performance Adaptations Across Collegiate Soccer Players

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Abstract
This experiment investigated the uniformity of the adaptations to high-intensity-interval training (HIIT) prescribed using anaerobic speed reserve (ASR_{HIIT} [The difference between maximal sprint speed and maximal aerobic speed]), maximal aerobic speed (MAS_{HIIT}), and a load-matched sprint interval training (SIT) in male collegiate soccer players. Thirty collegiate male soccer players with 4-6 years of training experience (age = 21.6 ± 4.8 years; height = 182.4 ± 4.4 cm; body mass = 84.1 ± 3.3 kg; body fat = 13.1 ± 3.6%) were randomized to three experimental groups performing either ASR_{HIIT} or MAS_{HIIT} (4 sets of 4 - 7 repetitions of 30-sec running at Δ%30ASR (MAS + 0.3×ASR) or 130% MAS, from the 1st to the 7th session) or a load-matched SIT. Participants underwent a series of lab- and field-based tests to evaluate measures of cardiorespiratory fitness (i.e., maximal oxygen uptake, cardiac hemodynamics and ventilatory threshold), anaerobic power (i.e., peak and average power), and bio-motor abilities (i.e., maximal sprint speed, change of direction, and jumping ability). Homogeneity of the adaptive changes was investigated by comparing residuals in individual changes and calculating the coefficient of variation in mean group changes. All three interventions adequately stimulated the adaptive mechanisms involved in the enhancement of the qualities mentioned above ($p < 0.05$). Linear sprint speed improved solely in response to SIT ($p = 0.001$). Moreover, load-matched SIT led to significantly greater enhancements in measures of bio-motor abilities compared to ASR_{HIIT} and MAS_{HIIT} ($p < 0.05$). ASR_{HIIT} and SIT resulted in lower inter-subject variability in adaptive responses in cardiorespiratory fitness measures ($p < 0.05$). Optimizing homeostatic stress through load-matched SIT leads to more homogenous adaptations across individuals and significantly greater adaptations in bio-motor abilities than the other prescription approaches. It's worth noting that genetic variability, motivation, diet, sleep quality, and psychological factors can influence inter-individual responses. These aspects were not accounted for in the current experiment and represent potential limitations.

Key words: Interval training, external load, exercise intensity, aerobic fitness, cardiac function, anaerobic power, athletic performance.

Introduction

Improving physical fitness is critical for enhancing in-match soccer performance. Coaches utilize a variety of exercise interventions tailored to target soccer's sport-specific attributes, aiming to enhance overall athletic performance (Strudwick, 2016). Soccer is characterized by frequent bursts of intense activities involving repetitive accelerations, decelerations, sprints, changes in direction, jumps, turns, ball shooting, and physical contact. Anaerobic metabolic pathways predominantly fuel these actions (Dai and Xie, 2023). These movements are separated by low- to moderate-intensity walking or running, during which the aerobic metabolic system prevails. Elevated aerobic power accelerates recovery and facilitates sustaining high-intensity activities throughout the game (Rodríguez-Fernández et al., 2019). Hence, aerobic and anaerobic capacities are crucial to enhancing physical abilities in soccer, directly affecting the quality of technical and tactical performances (Arazi et al., 2017).

High-intensity interval training (HIIT) is a frequently used intervention for enhancing cardiorespiratory fitness, anaerobic power, and athletic performance in soccer players. Soccer athletes periodically incorporate various forms of HIIT into their regular training schedule. HIIT can be tailored to individual athletes through a variety of methods designed to ensure precise control over exercise intensity. Rating of perceived exertion (RPE), maximal aerobic speed and power ($v/p\dot{V}O_{2max}$), 30 - 15 intermittent fitness test known specific HIIT protocols in team settings, and anaerobic speed or power reserve - representing the athlete's ability to sustain exercise above the velocity or power corresponding to maximal oxygen uptake ($v/p\dot{V}O_{2max}$), which is a critical factor for calibrating supramaximal efforts. Heart rate and power meter-based systems are considered highly reliable for optimizing HIIT intensity, while all-out sprint training is tailored to the unique demands of the sport (Laursen and Buchheit, 2019).

Multiple factors are taken into consideration when prescribing HIIT, with the duration and intensity of both the exercise and rest intervals standing as the key determinants (Dai and Xie, 2023; Laursen and Buchheit, 2019). HIIT for maximal intensities is commonly prescribed based on the maximal aerobic speed (MAS), also known as the minimal velocity required to elicit maximal oxygen uptake ($v\dot{V}O_{2max}$) (Buchheit and Laursen, 2013). However, in supramaximal intensities (i.e., beyond maximal aerobic speed), both aerobic and anaerobic metabolic pathways are actively engaged, and determining the intensity of interval interventions based on fixed proportions of the maximal anchor such as $\dot{V}O_{2max}$ would not optimize training requiring anaerobic metabolism (Collison et al., 2022; Sandford et al., 2021). During supramaximal intensity exercise, optimal responses are associated with the proportion of anaerobic speed reserve (ASR), defined as the disparity between maximal sprint speed (MSS) and maximal aerobic speed (Wang and Zhao, 2023). Individualizing HIIT inter-

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ventions using anaerobic speed (maximal aerobic speed + %anaerobic speed reserve) results in optimal adaptive changes in physiological and performance measures across athletes with diverse profiles [Dai and Xie, 2023; Wang and Zhao, 2023; Du and Tao, 2023; Luo et al., 2024; Wang and Ye, 2024). In this experiment, we will compare this training approach with other methods of individualization to identify the most effective strategy for achieving an optimal adaptive response to various interventions among athletes with diverse profiles.

Adaptive changes to training protocols are commonly reported as a general mean value, assuming that this accurately depict individual responses to the exercise interventions. However, the adaptations to a standardized intervention exhibit discrepancies among individuals with diverse profiles (Dai and Xie, 2023; Sheykhlouvand and Gharaat, 2024; Song and Sheykhlouvand, 2024; Mann et al., 2014). Although tailoring the training stimulus according to an individual's fixed percentage of reference intensities (i.e., % maximal aerobic speed) effectively enhances physiological and performance adaptations, such individualization approaches fail to ensure consistent metabolic stress among participants (Vollaard et al., 2009; McPhee et al., 2010; Mann et al., 2013; Jamnick et al., 2020; Meyler et al., 2021; Meyler et al., 2023). $\dot{V}O_{2max}$ relies on the transfer of oxygen from the atmosphere to the bloodstream, the oxygen-carrying capacity, and the extraction and utilization of delivered oxygen by mitochondria in the working muscles. The mitochondria's capacity for oxygen utilization exceeds the cardiovascular system's maximum capability to deliver oxygen (Bassett and Howley, 2000; di Prampero, 1985; Levine, 2008; Saltin and Calbet, 2006), and in case of oxygen delivery limitation, $\dot{V}O_{2max}$ will not represent the active muscle's full oxygen uptake capacity. As a result, $\dot{V}O_{2max}$ and its associated reference intensities (e.g., anaerobic speed reserve) may not serve as valid measures of the maximum aerobic capacity of active muscles, and establishing the training load as a proportion of whole-body $\dot{V}O_{2max}$ does not guarantee that the exercise intensity imposed on the body will be tailored to the individual's actual capacity (McPhee et al., 2010). Consequently, this diversity can affect individuals' exercise tolerance, physiological requirements, and adaptive responses. Hence, discovering a training strategy capable of eliciting consistent adaptive responses among individuals with different profiles holds significant value.

Research indicates that as exercise intensity increases, the variability of measured physiological parameters tends to decrease (Bagger et al., 2003). Engaging in exercise at higher absolute intensities is expected to help participants maintain their exercise intensity within a narrower range (O'Grady, 2021) and experience consistent levels of homeostatic stress. Hence, it is reasonable to speculate that employing the maximum limit of supramaximal intensity (i.e., *all-out*) for conducting HIIT (i.e., sprint interval training [SIT]) may fully engage individuals' capacity and diminish heterogeneity in the adaptive changes across individuals. Since these interventions are executed using maximal exertion, they can be prescribed without the need to assess an individual's physiological ceilings (e.g., $\dot{V}O_{2max}$) for adjusting the intensity efforts (Laursen and Buchheit, 2019). By doing so, athletes may undergo 100% of their capacity and experience similar levels of homeostatic stress. Accordingly, the objective of this study was to compare the HIIT interventions individualized using individuals' anaerobic speed reserve and maximal aerobic speed with a load-matched SIT on the uniformity of the adaptations in collegiate male soccer players. Given the abovementioned rationales, we hypothesized that a load-matched SIT would result in more homogenized changes in physiological and performance adaptations than HIIT prescribed using anaerobic speed reserve and maximal aerobic speed in collegiate soccer players (Dai and Xie, 2023).

Methods

Study design

This study consisted of three experimental groups performing HIIT prescribed using ASR (ASR_{HIIT}), MAS (MAS_{HIIT}), and a load-matched SIT. Prior to and following the 7-week period, participants completed a lab-based incremental exercise test to evaluate cardiorespiratory fitness measures, including $\dot{V}O_{2max}$, cardiac output (CO_{max}), stroke volume (SV_{max}), and ventilatory thresholds (VT_1 and VT_2). On a separate day, they underwent an *all-out* lower-body Wingate test to determine peak and average power output (PPO and APO). On the third day, linear sprint speed, vertical jump (VJ), and change of direction ability (COD) were measured. A 24-hour recovery period was implemented between testing sessions and the athletes were advised to refrain from caffeine and alcohol and engaging in strenuous exercise. Approximately 48 hours after the third testing day, participants engaged in the first training session, and two days following the final HIIT session, participants repeated the tests, maintaining the same sequence and conditions as the pre-test.

Participants

Thirty collegiate male soccer players (age = 21.6 ± 4.8 years; height = 182.4 ± 4.4 cm; body mass = 84.1 ± 3.3 kg; body fat = 13.1 ± 3.6%) competing at inter-college events took part in the study. Following a detailed explanation of the intervention's risks and benefits, participants voluntarily signed informed consent forms. The participants were required to have at least 4 - 6 years of soccer experience and at least three sessions per week of soccer training for the last 6 months, and lack of injuries affecting training quality (Gharaat et al., 2025). All participants were involved in regular soccer training for 3 - 4 sessions a week. They were familiar with the HIIT interventions, and following medical screening to detect any complications that might pose a risk during high-intensity efforts, they were matched based on their playing positions (i.e., fullbacks, goalkeepers, midfielders, forwards, center backs). Then, they were randomly assigned to ASR_{HIIT}, MAS_{HIIT}, or the load-matched SIT group. Group allocation was decided through the use of a computerized random number generator, leading to group assignments that were unpredictable and based on chance. Participants and researchers were blinded to group allocation. Players with any current musculoskeletal injuries, cardiovascular or respiratory conditions, or other health issues that could interfere with the interventions or assessments were excluded from participation. All procedures were confirmed by the ethical committee of the Henan Normal University and the study was performed in accordance with the ethical guidelines of the World Medical Association (Declaration of Helsinki).

Incremental exercise test

Following a ten-minute warm-up, which included five minutes of jogging and five minutes of dynamic stretching, athletes undertook a progressive exercise test on a treadmill (Technogym, Italy). The test commenced at an initial intensity of 8 $km \cdot h^{-1}$, with the velocity progressively increasing by one $km \cdot h^{-1}$ every 3 minutes (Dai and Xie, 2023). Between stages, there were 30-second rest intervals, for measuring blood lactate concentration from the earlobe (Lactate Scout+, SensLab, Leipzig, Germany). A breath-by-breath gas analyzer (MetaLyzer 3B-R2, Cortex, Germany) continuously analyzed physiological parameters, and an impedance cardiography device (PhysioFlow, Manatec, France) continuously determined cardiac hemodynamics (i.e., CO_{max} and SV_{max}). The $\dot{V}O_{2max}$ was determined as the highest 30-second average of the $\dot{V}O_2$ values, and reaching $\dot{V}O_{2max}$ was confirmed according to the previously established criteria including: I) $\dot{V}O_2$ plateauing despite workload increase; II) Respiratory exchange ratio surpassing 1.1; III) Blood lactate concentration equal to or exceeding 8 mmol/L; IV) Maximum heart rate reaching or exceeding 95% of age-predicted maximum (220–age); V) Voluntary exhaustion. MAS was defined as the minimal speed at which $\dot{V}O_{2max}$ occurred. The second ventilatory threshold (VT_2) was determined independently by two experts using the criterion of a continuous rise in the $\dot{V}_E$ equivalent for O_2 ($\dot{V}_E/\dot{V}O_2$) and the $\dot{V}_E$ equivalent for CO_2 ($\dot{V}_E/\dot{V}CO_2$) ratio curves in relation to the decrease in end-tidal O_2 tension ($P_{ET}O_2$). The first ventilatory threshold (VT_1) was also established as the point where an increase in $\dot{V}_E/\dot{V}O_2$ and $P_{ET}O_2$ occurred without a simultaneous rise in the $\dot{V}_E$ $\dot{V}CO_2^{-1}$ (Alejo et al., 2022).

Lower-body Wingate test

Peak power output (PPO) and average power output (APO) were evaluated using an all-out 30-second Wingate test. At the beginning of the test, Participants were directed to pedal against the ergometer inertial resistance (894E, Monark, Sweden) with maximum exertion. Afterward, a resistance equivalent to 0.075 kg per kilogram of body weight was applied (Li and Sheykhlouvand, 2025). Consistent verbal encouragement was given throughout the test, and the software integrated into the device was utilized to calculate PPO and APO (Dai and Xie, 2023). The PPO and APO represented the maximum power reached at the 5-second mark and the average power sustained throughout the test, respectively (Ning and Sheykhlouvand, 2025).

Linear sprint speed

Participants completed two consecutive 40-meter sprint tests with 10-meter splits, and the Maximum Sprint Speed (MSS) was established as the fastest 10-meter split time. They were encouraged to sprint between photoelectric cells (Brower Timing Systems, Draper, UT, USA), and split times were measured at the nearest 0.01 sec. A 5-minute rest separated tests, and the best performance was utilized for the subsequent analysis (Buchheit et al., 2012).

Vertical jump

The participants' jumping ability was assessed using squat jump (SJ) and countermovement jump (CMJ). Participants adopted a stance for the SJ by placing hands on hips, positioning shoulders, and spreading their feet wide apart. Subsequently, they flexed knees to ~90-degree angle, holding this posture for three seconds. After this preparatory phase, participants exerted maximal effort to execute the VJ (Ramírez-Campillo et al., 2013). They began to perform the CMJ by positioning hands on hips and spreading their feet and shoulders widely. Without any prescribed knee angle limitations, they descended before launching into a maximal vertical jump (Ojeda-Aravena, et al., 2021). Each participant performed two trials with approximately 120 seconds between trials. The trial resulting in the highest performance measured by a Globus electronic contact mat system (Codognè, Italy) was selected for subsequent statistical analysis.

Change of direction

The assessment of COD performance utilized the MAT test, an adapted version of the T-test, which appraises athletes' agility across various directional movements such as multi-directional running speed, linear sprints, lateral shuffles, and backpedaling. Unlike the conventional T-test, the MAT test is tailored to the demands of sports, particularly due to its inclusion of repeated sprints involving changes in direction over short distances, rendering it a more reliable measure of agility (Sassi et al., 2009). Participants began the test by sprinting forward from cone A to cone B, touching its base. They then proceeded with a lateral shuffle to cone C, maintaining a forward-facing stance without crossing their feet. This was followed by a shuffle to the right toward cone C, touching it before shuffling back to cone B. The test concluded with participants backpedaling to the starting point at cone A, as outlined in Figure 1.

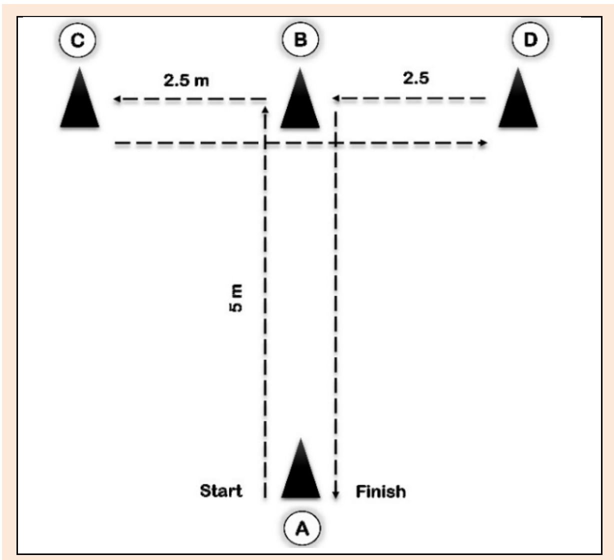

Figure 1. **MAT-test for evaluation of change of direction ability.**

Training interventions

Two days after the last testing session, participants commenced the three weekly HIIT interventions comprising 21 sessions over the 7-week training period. Players were engaged in three weekly sessions of typical soccer training consisting of technical and tactical drills lasting 70-90 minutes on Sunday, Tuesday, and Thursday. They completed HIIT programs on Saturday, Monday, and Wednesday in the afternoon (~ 5:00 P.M.). The interventions consisted of four sets comprising 4, 4, 5, 5, 6, 6, and 7 repetitions of 30 seconds running at Δ%30 ASR (MAS + 0.3 × ASR) or 4, 4, 5, 5, 6, 6, and 7 repetitions of 30 seconds running at 130% MAS, from the 1st to the 7th session. The SIT group completed a distance equivalent to individual 30-second efforts at Δ%30 ASR with maximal exertion. Initially, participants' Δ%30 ASR was evaluated, and they ran for 30 seconds at this intensity. The distance covered at this intensity was then recorded, and participants were instructed to run this distance with maximal effort. The training load for SIT was controlled by recording the rating of perceived exertion (RPE) with the Borg 0 - 10 scale to verify that participants exerted maximal effort throughout the sessions.

The rest intervals between efforts and sets were set at 1 and 3 minutes, respectively.

Statistical analysis

The sample size has been estimated using G*Power software based on the statistical methods used in this experiment. Statistical analyses were conducted using SPSS software (version 24, IBM®, Chicago, IL). After the testing normality of distribution and homogeneity of variances using Shapiro-Wilk's and Levene's test, a two-factor time (pre- vs post-training) × group (ASR_{HIIT}, MAS_{HIIT}, and SIT) repeated measure analysis of variance (ANOVA) analyzed the data. Tukey's post hoc examined interactions or main effects if a significant F-ratio was observed. The homogeneity of the adaptive changes was tested by determining inter-individual variability in the adaptations using two methods. Initially, the percent of individual changes was calculated for each parameter. The coefficient of variation (CV) in adaptive alterations was subsequently established by dividing the standard deviation by the mean group change. Then, individual residuals in adaptive alterations were computed as the square root of the squared disparity between the individual change and the mean percentage change for each assessed parameter and the difference in residuals were subsequently compared among groups. A commonly used interpretation is to refer to effect sizes as small (d = 0.2), medium (d = 0.5), and large (d = 0.8) based on benchmarks suggested by Cohen (1988). Alpha level was wet at 0.05.

Table 1. Effects of the employed interventions on cardiorespiratory fitness measures.

	ASR_{HIIT}		MAS_{HIIT}		SIT	
	Pre	Post	Pre	Post	Pre	Post
$\dot{V}O_{2max}$ (ml·kg^{-1}·min^{-1})	52.5 ± 3.2	55.4 ± 3.8	52.4 ± 2.4	54.5 ± 3.1	51.7 ± 2.3	54.5 ± 2.4
%Δ	5.5 *		4.0 *		5.4 *	
P-value	0.004		0.005		0.002	
ES (d)	0.8		0.7		1.2	
CV of %Δ	18%		45%		11%	
Residuals in %Δ	0.83 †		1.65		0.51 †	
VT_1 (%$\dot{V}O_{2max}$)	73.8 ± 3.3	77.6 ± 3.3	73.2 ± 3.3	76.5 ± 3.2	73.1 ± 3.6	77.4 ± 3.7
%Δ	5.1 *		4.5 *		5.9 *	
P-value	0.003		0.009		0.002	
ES (d)	1.1		1.0		1.3	
CV of %Δ	17%		40%		11%	
Residuals in %Δ	0.78 †		1.53		0.56 †	
VT_2 (%$\dot{V}O_{2max}$)	86.3 ± 4.5	89.0 ± 4.6	85.5 ± 5.3	87.6 ± 5.4	85.1 ± 5.1	87.9 ± 4.9
%Δ	3.1 *		2.4 *		3.3 *	
P-value	0.002		0.009		0.001	
ES (d)	0.6		0.4		0.5	
CV of %Δ	20%		47%		16%	
Residuals in %Δ	0.57		0.79		0.35	
CO_{max} (l·min^{-1})	31.5 ± 1.4	32.9 ± 1.3	31.7 ± 1.8	32.9 ± 1.5	31.4 ± 2.0	33.3 ± 2.2
%Δ	4.4 *		3.9 *		6.0 *	
P-value	0.001		0.005		0.001	
ES (d)	1.0		0.7		0.9	
CV of %Δ	18%		41%		12%	
Residuals in %Δ	0.67 †		1.37		0.58 †	
SV_{max} (ml·beat^{-1})	159.3 ± 7.0	167.7 ± 7.7	158.4 ± 7.7	165.1 ± 8.2	156.8 ± 6.1	165.6 ± 6.7
%Δ	5.2 *		4.2 *		5.6 *	
P-value	0.003		0.008		0.0091	
ES (d)	1.1		0.8		1.4	
CV of %Δ	20%		36%		11%	
Residuals in %Δ	0.91		1.40		0.53	

Values are means ± S; $\dot{V}O_{2max}$, maximum oxygen uptake; VT_1, first ventilatory threshold; VT_2, second ventilatory threshold; CO_{max}, maximal cardiac output; SV_{max}, stroke volume; N = 10 for each group. * Significantly greater than pre-training value (P < 0.05). † Significantly lower than MAS_{HIIT}.

Table 2. Effects of the employed interventions on anaerobic power and bio-motor abilities.

	ASR_{HIIT}		MAS_{HIIT}		SIT	
	Pre	**Post**	**Pre**	**Post**	**Pre**	**Post**
PPO (W)	806.2 ± 46.7	846.1 ± 51.2	797.0 ± 61.8	834.7 ± 66.5	804.2 ± 60.9	854.1 ± 61.9
%Δ	4.9 *		4.7 *		6.2 *	
P-value	0.002		0.005		0.001	
ES (d)	0.8		0.6		0.8	
CV of %Δ	21%		31%		11%	
Residuals in %Δ	0.88 †		1.12		0.59	
APO (W)	591.0 ± 56.6	620.6 ± 57.0	617.2 ± 46.0	645.7 ± 47.1	630.8 ± 41.5	667.8 ± 45.6
%Δ	5.0 *		4.6 *		5.8 *	
P-value	0.003		0.007		0.001	
ES (d)	0.6		0.5		0.8	
CV of %Δ	18%		22%		15%	
Residuals in %Δ	0.84		0.86		0.69	
Linear speed (km·h^{-1})	30.46 ± 1.6	30.59 ± 1.4	30.48 ± 1.5	30.64 ± 1.6	30.45 ± 1.3	31.37 ± 1.4
%Δ	0.4		0.5		3.0 *⁑‡	
P-value	0.315		0.190		0.001	
ES (d)	0.1		0.08		0.7	
CV of %Δ	-		-		30%	
Residuals in %Δ	0.90		1.12		0.72	
COD (sec)	8.07 ± 0.24	7.85 ± 0.24	8.03 ± 0.26	7.86 ± 0.26	7.95 ± 0.29	7.65 ± 0.25
%Δ	–2.8 *		–2.1 *		–3.9 *⁑‡	
P-value	0.001		0.008		0.001	
ES (d)	0.9		0.6		1.1	
CV of %Δ	19%		26%		17%	
Residuals in %Δ	0.44		1.44		0.47	
SJ (cm)	38.3 ± 1.4	39.8 ± 1.9	37.9 ± 1.6	39.3 ± 1.6	37.5 ± 2.0	39.5 ± 2.0
%Δ	3.9 *		3.7 *		5.3 *⁑‡	
P-value	0.001		0.003		0.001	
ES (d)	0.9		0.8		1.0	
CV of %Δ	19%		24%		14%	
Residuals in %Δ	0.60		0.75		0.63	
CMJ (cm)	43.0 ± 1.4	44.8 ± 1.4	43.1 ± 1.8	44.9 ± 1.6	42.7 ± 1.7	45.8 ± 1.8
%Δ	4.2 *		4.1 *		7.2 *⁑‡	
P-value	0.005		0.008		0.001	
ES (d)	1.3		1.0		1.7	
CV of %Δ	19%		22%		16%	
Residuals in %Δ	0.68		0.80		0.69	

Values are means ± SD; PPO, peak power output; APO, average power output; COD, change of direction; SJ, squat jump; CMJ, countermovement jump. N = 10 for each group. * Significantly greater than pre-training value (P < 0.05). † Significantly lower than MAS_{HIIT}. ⁑ Significantly greater than MAS_{HIIT}. ‡ Significantly greater than MAS_{ASR}.

Results

No between-group difference was observed for the measured variables at the baseline. All groups significantly enhanced all physiological parameters and bio-motor abilities from pre- to post-training (Table 1 and Table 2). However, maximal sprint speed only enhanced in response to SIT intervention (Table 2).

Comparative analysis of residuals in adaptive changes indicated significant time-regimen interactions for $\dot{V}O_{2max}$ ($F_{2,27}$ = 9.44, p = 0.001), VT_1 ($F_{2,27}$ = 6.47, p = 0.005), CO_{max} ($F_{2,27}$ = 4.85, p = 0.016), and SV_{max} ($F_{2,27}$ = 6.53, p = 0.005). Post hoc analysis revealed that in comparison to MAS_{HIIT}, ASR_{HIIT} and SIT interventions resulted in lower residuals in individual changes in $\dot{V}O_{2max}$ (p = 0.014, 95%CI = -1.49 to -0.15; p = 0.001, 95%CI = -1.81 to –0.47), VT_1 (p = 0.034, 95%CI = -1.45 to -0.05; p = 0.005, 95%CI = -1.67 to -0.27), CO_{max} (p = 0.046, 95%CI = -1.38 to -0.01; p = 0.022, 95%CI = -1.47 to -0.10), and SV_{max} (only SIT vs. MAS_{HIIT}: p = 0.003, 95%CI = -1.46 to -0.27) (Table 1, Figure 2 and Figure 3).

ASR_{HIIT} and SIT groups demonstrated lower coefficient of variations (CVs) in mean group changes in measures of cardiorespiratory fitness (Figure 2 and Figure 3), anaerobic power (Figure 4), and bio-motor abilities (Figure 5 and Figure 6) than MAS_{HIIT}.

Significant time-regimen interactions were observed in the magnitude of changes in linear sprint speed ($F_{2,27}$ = 16.60, p = 0.001), COD ($F_{2,27}$ = 20.02, p = 0.001), SJ ($F_{2,27}$ = 10.55, p = 0.001), and CMJ ($F_{2,27}$ = 4.91, p = 0.016) (Figure 5 and Figure 6). A Tukey post hoc test revealed that in comparison to ASR_{HIIT} and MAS_{HIIT}, SIT resulted in greater changes in linear sprint speed (p = 0.001, 95%CI = 1.15 to 3.68; p = 0.001, 95%CI = 1.12 to 3.57, respectively), COD (p = 0.002, 95%CI = -1.69 to -0.36; p = 0.001, 95%CI = –2.35 to -1.02), SJ (p = 0.002, 95%CI = 0.52 to 2.41; p = 0.001, 95%CI = 0.67 to 2.57), and AMJ (p = 0.013, 95%CI = 0.09 to 2.13; p = 0.033; 95%CI = 0.08 to 2.12) (Table 2, Figure 5 and Figure 6).

Also, CVs in mean group changes in all parameters in SIT group was lower than those of ASR_{HIIT} group (Table 1, Table 2, Figure 2, Figure 3, Figure 4, Figure 5 and Figure 6).

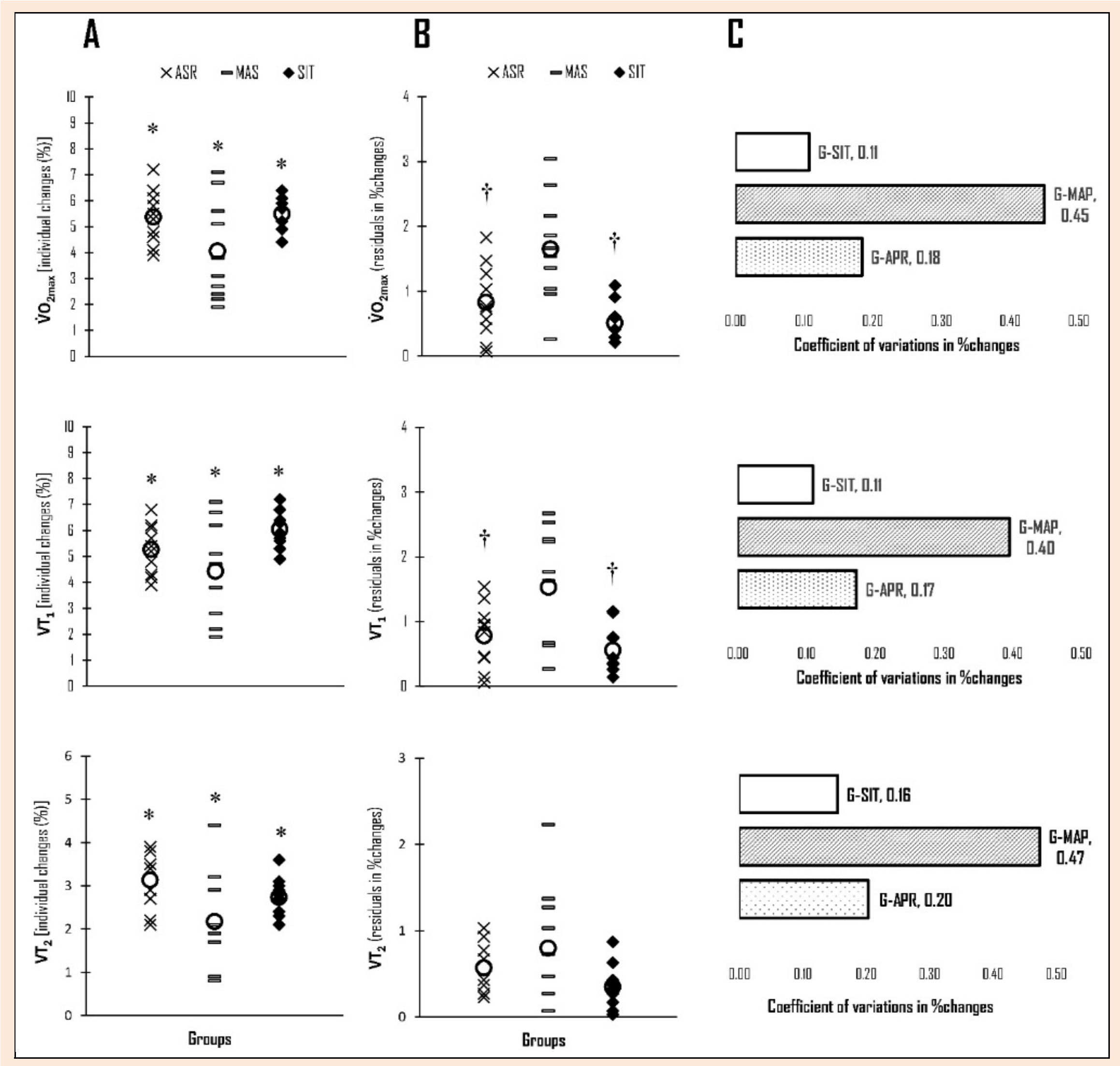

Figure 2. Individual changes (A), residuals in individual changes (B), and (C) coefficient of variations (CV) in mean group changes in maximum oxygen uptake ($\dot{V}O_{2max}$), first ventilatory threshold (VT_1), and second ventilatory threshold (VT_2) in response to seven weeks of high-intensity interval training prescribed using anaerobic speed reserve (ASR_{HIIT}), maximal aerobic speed (MAS_{HIIT}) and maximal exertion [i.e., sprint interval training (SIT)]. Circles indicate represent the group mean response. * Significant difference *vs.* pre-training ($p \leq 0.05$). † Significantly lower *than* MAS_{HIIT} group ($p \leq 0.05$).

Discussion

This study stands as the first endeavor to compare the homogeneity of the adaptations in physiological and performance parameters to interval interventions prescribed using fixed reference intensities of ASR and MAS and a load-matched SIT in collegiate male soccer players. The most remarkable discovery of this study was that ASR_{HIIT} and SIT result in lower inter-individual variability in the adaptive alterations in $\dot{V}O_{2max}$, VT_1, CO_{max}, and SV_{max} than MAS_{HIIT}. More importantly, the load-matched SIT leads to greater adaptive changes in linear sprint speed, COD, and jumping ability than HIIT interventions prescribed using individual reference intensities. Also, CVs in mean group changes following SIT were lower than in the MAS_{HIIT} and ASR_{HIIT} groups.

Our results corroborate previous studies presenting the efficacy of ASR-based HIIT in inducing uniform homeostatic stress leading to consistent adaptive responses in physiological parameters than HIIT prescribed based on the individuals' MAS (Dai and Xie, 2023; Wang and Zhao, 2023; Du and Tao, 2023; Luo et al., 2024; Wang and Ye, 2024). In a comparative analysis of HIIT interventions prescribed using 130% anaerobic power reserve or 130% maximal aerobic power, Luo and colleagues (Luo et al., 2024) indicated that setting the intensity of supramaximal HIIT at a fixed proportion of APR induces consistent load across athletes with varying profiles and leads to more uniform physiological demands and adaptations in cardiorespiratory fitness measures. Likewise, Dai and Xie (2023) indicated that two sets of 6-9 min intervals consisting of 15 s running at Δ%20ASR and 15 s passive recovery performed over six weeks leads to lower inter-individual variability (CV) in the alterations in $\dot{V}O_{2max}$, VT_1, and VT_2 compared to HIIT intensity set at 120% MAS. Although this training approach effectively enhances cardiorespiratory fitness measures, our result indicates that, in comparison to ASR_{HIIT}, a load-matched SIT results in markedly lower residuals in individual changes and CVs in mean group changes, implying its superior potential over ASR_{HIIT} and MAS_{HIIT}. These findings support our hypothesis that exercise at higher intensities could effectively diminish inter-individual variability in adaptations. As we mentioned earlier, $\dot{V}O_{2max}$ depends on the central (i.e., oxygen delivery) and peripheral components (i.e., oxygen utilization by active muscles) of aerobic fitness (Sheykhlouvand et al., 2022; Gharaat et al., 2024). Heterogeneity in the imposed external load due to inaccurate assessment of the maximal aerobic capacity of working muscles may result in inconsistent adaptation across individuals (McPhee et al., 2010). It seems that performing HIIT efforts with maximal exertion (i.e., *all-out*) decreases the body's reliance on oxygen cascade, as the anaerobic metabolism prevails in *all-out* efforts. This approach fully engages working muscles and takes all influencing parameters in the adaptive changes into consideration, leading to more homogenized adaptations in cardiorespiratory fitness. The unexplained variance among subjects, characterized as residuals and CVs, may stem from the athletes' baseline training levels and, more importantly, the variability in subjects' "trainability," which could be influenced by genetic differences (Bray et al., 2009; Lippi et al., 2010). Research on genotype-training interactions (Bray et al., 2009) suggests that genetic variability within a group leads to differences in training responses. Approximately half of the diversity in individual responses to training interventions in $\dot{V}O_{2max}$ is thought to be attributable to genetic backgrounds (Mann et al., 2014; Bouchard et al., 1999; Bossi et al., 2024). Therefore, it is crucial to carefully choose participants to maintain consistency in their baseline condition.

The observed increases in cardiac output and stroke volume reflect enhanced central cardiovascular function, which directly supports improved oxygen delivery during high-intensity efforts. In soccer, this translates to better maintenance of maximal sprint speed and quicker recovery between explosive bouts, as a more efficient cardiovascular system replenishes oxygen stores and clears metabolic byproducts faster. Enhanced CO_{max} and SV_{max} thus improve players' ability to repeatedly perform high-intensity sprints and rapid changes of direction - key components of agility and endurance in match play.

Another noteworthy discovery in this study was that the load-matched SIT yielded significantly greater improvements in bio-motor abilities compared to ASR_{HIIT} and MAS_{HIIT}, suggesting that the load-matched SIT approach may be a more favorable intervention. Moreover, only the SIT group enhanced maximal sprint speed, a critical sport-specific attribute linked to successful soccer performance (Strudwick, 2016). These results support the efficacy of this approach in optimizing interval interventions to maximize soccer-specific qualities. Although SIT resulted in lower residuals and CVs in measures of anaerobic power and bio-motor abilities, no statistically significant difference in individual residual in the changes was observed in sprint speed, COD, jumping ability, and anaerobic power. The lack of consistent enhancement in these parameters through our individualization methods suggests that additional intervening factors such as motivation and anxiety, endurance, buffering capacity, and biochemical content of the muscles involved (e.g., creatine) may influence the ability to sustain the work rate during the test (Wang and Ye, 2024). Variations in these parameters could potentially affect power measures and sport-specific physical performance and increase inter-individual variability.

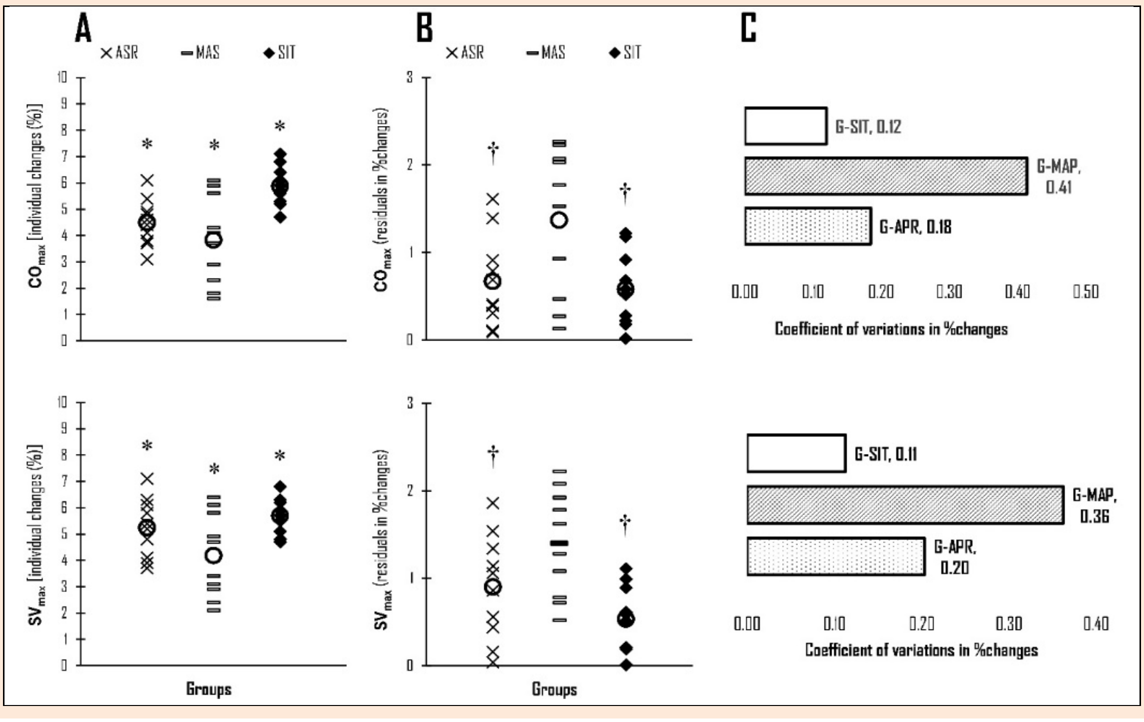

Figure 3. Individual changes (A), residuals in individual changes (B), and (C) coefficient of variations (CV) in mean group changes in maximal cardiac output (CO_{max}) and stroke volume (SV_{max}) in response to seven weeks of high-intensity interval training prescribed using anaerobic speed reserve (ASR_{HIIT}), maximal aerobic speed (MAS_{HIIT}) and maximal exertion [i.e., sprint interval training (SIT)]. Circles indicate represent the group mean response. * Significant difference *vs.* pre-training ($p \leq 0.05$). † Significantly lower *than* MAS_{HIIT} group ($p \leq 0.05$).

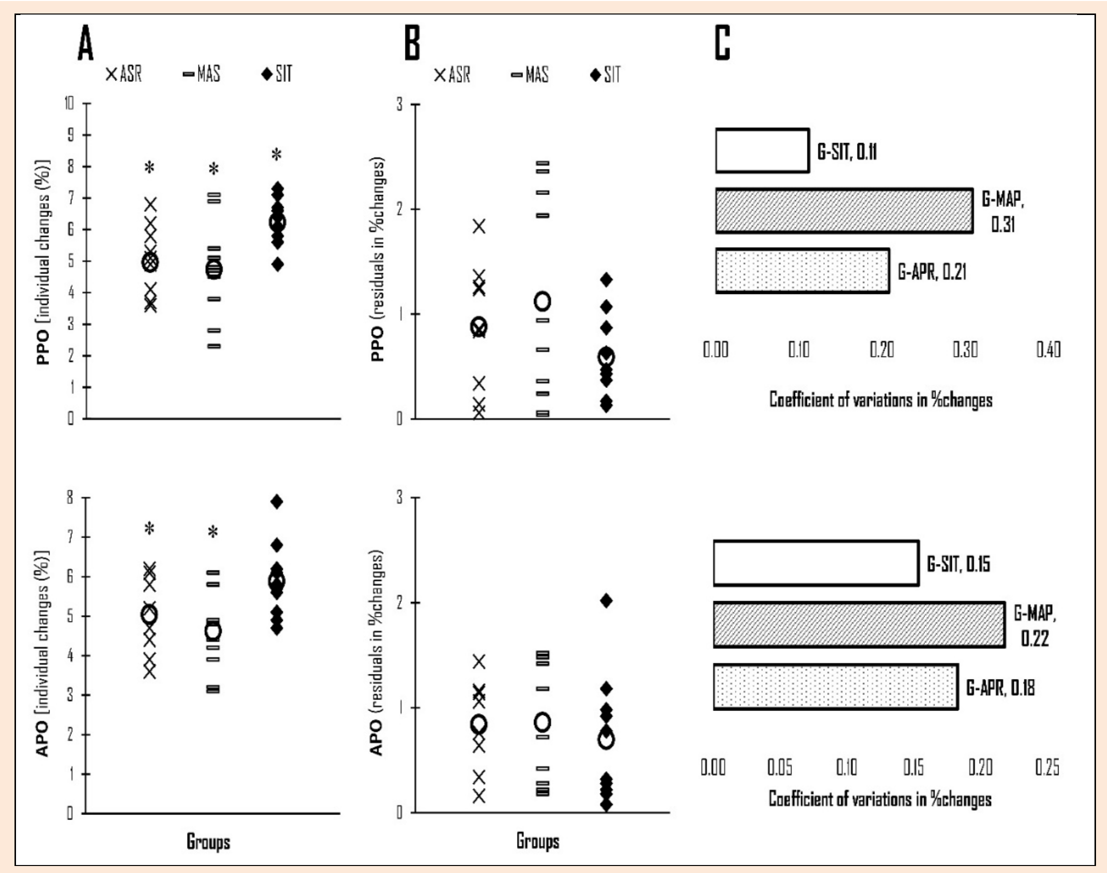

Figure 4. Individual changes (A), residuals in individual changes (B), and (C) coefficient of variations (CV) in mean group changes in peak power output (PPO) and average power output (APO) in response to seven weeks of high-intensity interval training prescribed using anaerobic speed reserve (ASR_{HIIT}), maximal aerobic speed (MAS_{HIIT}) and maximal exertion [i.e., sprint interval training (SIT)]. Circles indicate represent the group mean response. * Significant difference *vs.* pre-training ($p \leq 0.05$). † Significantly lower *than* MAS_{HIIT} group ($p \leq 0.05$).

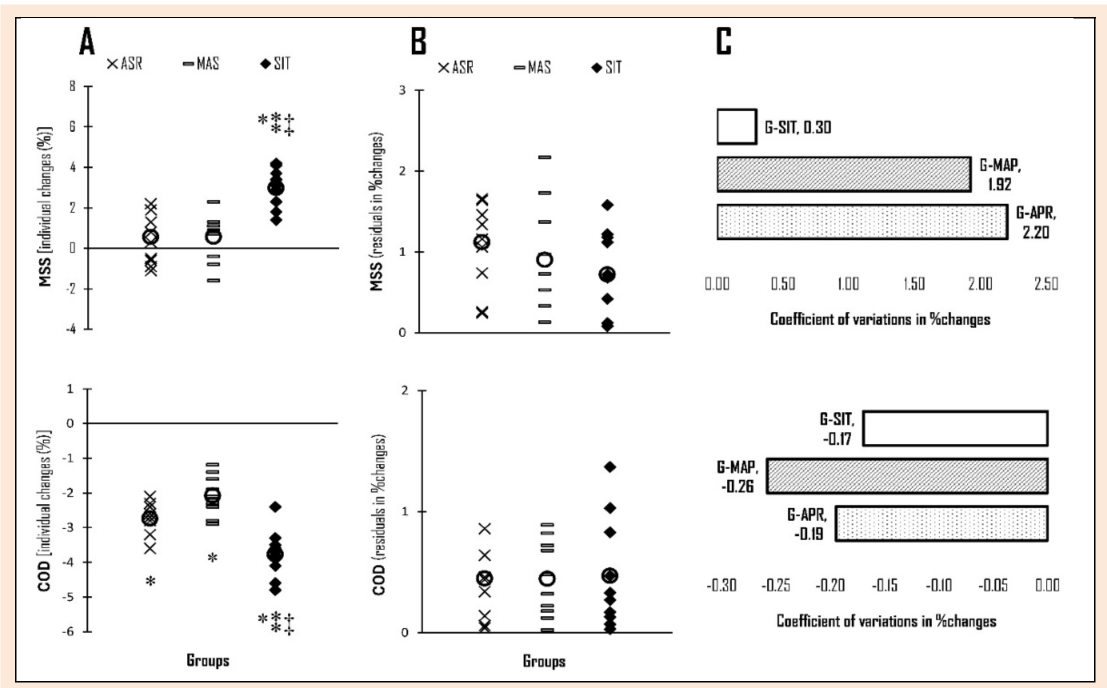

Figure 5. Individual changes (A), residuals in individual changes (B), and (C) coefficient of variations (CV) in mean group changes in maximal sprint speed (MSS) and change of direction (COD) in response to seven weeks of high-intensity interval training prescribed using anaerobic speed reserve (ASR_{HIIT}), maximal aerobic speed (MAS_{HIIT}) and maximal exertion [i.e., sprint interval training (SIT)]. Circles indicate represent the group mean response. * Denotes significant difference *vs.* pre-training ($p \leq 0.05$). † Significantly lower *than* MAS_{HIIT} group ($p \leq 0.05$). ⁑ Significantly greater than $MAS_{HIIT.}$ ‡ Significantly greater than $MAS_{ASR.}$

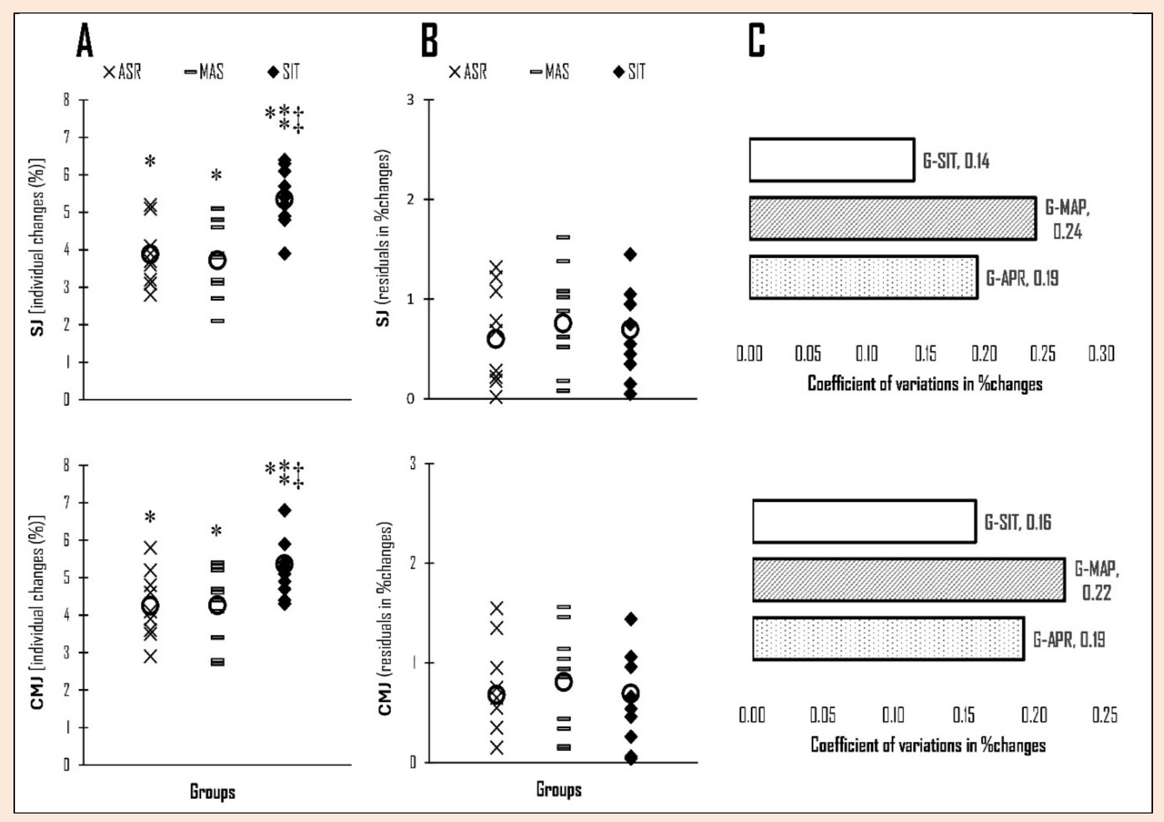

Figure 6. Individual changes (A), residuals in individual changes (B), and (C) coefficient of variations (CV) in mean group changes in vertical jump (VJ) and countermovement jump (CMJ) in response to seven weeks of high-intensity interval training prescribed using anaerobic speed reserve (ASR_{HIIT}), maximal aerobic speed (MAS_{HIIT}) and maximal exertion [i.e., sprint interval training (SIT)]. Circles indicate represent the group mean response. * Denotes significant difference *vs.* pre-training ($p \leq 0.05$). † Significantly lower *than* MAS_{HIIT} group ($p \leq 0.05$). ⁑ Significantly greater than MAS_{HIIT}. ‡ Significantly greater than MAS_{ASR}.

These physiological adaptations underpin the superior bio-motor performance gains seen with load-matched SIT and ASR_{HIIT}, reinforcing the practical value of optimizing interval training intensity to target both anaerobic power and aerobic recovery capacity. Load-matched SIT involves repeated "all-out" efforts performed at maximal or near-maximal intensity. This protocol recruits a greater proportion of fast-twitch muscle fibers and heavily stresses anaerobic energy systems (ATP-PCr and glycolysis) (MacInnis and Gibala., 2017; Gharaat et al., 2020; Forbes and Sheykhlouvand, 2016) compared to the submaximal intensities commonly observed in HIIT prescriptions based on ASR or MAS. The all-out nature of SIT creates very high neuromuscular demand, leading to pronounced improvements in muscle power, rate of force development, and sprint acceleration. Repeated all-out efforts in SIT more closely mimic the demands of soccer, where players must perform multiple maximal or near-maximal sprints interspersed with short recovery times during game play (Bishop et al., 2011). Therefore, SIT's ability to replicate match-intensity efforts likely underlies its superior effectiveness in improving bio-motor abilities critical for soccer performance.

One potential limitation of this study was the inability to account for genetic variations among participants, which are recognized to affect trainability and adaptive response, notably in $\dot{V}O_{2max}$. Moreover, the study did not closely monitor variables such as sleep quality, diet, and psychological factors such as motivation. Strict control over these variables was challenging despite instructing participants to maintain consistency. Lastly, the study's participant group was comprised exclusively of males, thus limiting the generalizability of the findings to female athletes.

Practical applications

The findings of this study offer valuable guidance for coaches, sport scientists, and performance staff working with collegiate and professional soccer players. Implementing interval training protocols based on anaerobic speed reserve or maximal aerobic speed can enhance key physiological adaptations, but load-matched sprint interval training (SIT) appears superior in eliciting both more uniform and greater improvements in aerobic capacity and critical bio-motor abilities such as sprint speed, change of direction, and jumping performance.

Practically, these results suggest that prescribing training intensities using fixed reference points like ASR can reduce variability in adaptive responses, helping coaches better predict and monitor individual progress. However, incorporating load-matched SIT - characterized by maximal all-out efforts - may more effectively promote homogenous and optimized adaptations across a heterogeneous group of players by fully engaging anaerobic and aerobic systems. This approach is particularly beneficial for developing sprint speed, an essential performance attribute in soccer.

Conclusion

In conclusion, this study stands as the first endeavor comparing HIIT individualized using fixed proportions of ASR and MAS with a load-matched SIT in collegiate soccer players. Our results indicated that all three interval interventions adequately stimulate adaptive mechanisms that enhance cardiorespiratory fitness, anaerobic power, jumping ability, and change of direction. Linear sprint speed only enhances in response to SIT. SIT yields significantly greater changes in bio-motor abilities than ASR_{HIIT} and MAS_{HIIT}. The most remarkable finding of this study was that ASR_{HIIT} and SIT result in lower inter-individual variability in the adaptive changes in $\dot{V}O_{2max}$, VT_1, CO_{max}, and SV_{max} than MAS_{HIIT}. Also, CVs in mean group changes following SIT were lower than MAS_{HIIT} and ASR_{HIIT} groups. Our results suggest that optimizing homeostatic stress using load-matched SIT maximizes yielded adaptations to a greater extent than HIIT prescriptions designed per the individual's fixed reference intensities.

Acknowledgements

The author reports no actual or potential conflicts of interest. The datasets generated and analyzed in this study are not publicly available but can be obtained from the corresponding author upon reasonable request, who organized the study. All experimental procedures were conducted in accordance with the relevant legal and ethical standards of the country in which the study was performed.

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Key points

- ASRHIIT and SIT interventions demonstrated significantly lower inter-individual variability in adaptive changes in key physiological parameters such as VO2max, VT1, COmax, and SVmax compared to MASHIIT.
- The load-matched SIT approach led to greater improvements in linear sprint speed, change of direction, and jumping ability compared to ASRHIIT and MASHIIT. Only the SIT group showed enhancements in maximal sprint speed, a critical performance attribute for soccer.
- SIT exhibited lower coefficients of variation in mean group changes for both physiological and performance parameters, highlighting its potential for producing more consistent adaptations across athletes.
- Exercise at higher intensities with load-matched SIT accounted for inter-individual differences in maximal exertion, resulting in more homogenized cardiorespiratory adaptations.

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