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Research article

Adaptations to Optimized Interval Training in Soccer Players: A Comparative Analysis of Standardized Methods for Individualizing Interval Interventions

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Abstract

Accurately prescribing supramaximal interval training facilitates targeting desired physiological adaptations. This study compared the homogeneity of adaptations in cardiorespiratory parameters to supramaximal [i.e., intensities beyond maximal aerobic speed (MAS)] interval interventions prescribed using anaerobic speed reserve (ASR), the speed attained at the end of 30 - 15 Intermittent Fitness Test (V_{IFT}), and MAS. Using repeated-measures factorial design, and during the off-season phase of the athletes' yearly training cycle, thirty national-level soccer players (age = 19 ± 1.6 years; body mass = 78.9 ± 1.6 kg; height = 179 ± 4.7 cm; Body fat = 11 ± 0.9%) were randomized to interventions consisting of 2 sets of 6, 7, 8, 7, 8, and 9-min intervals (from 1st to 6th week), including 15 s running at Δ%20ASR (MAS + 0.2 × ASR), 120%MAS, or 95%V_{IFT} followed by 15 s passive recovery. All ASR, V_{IFT}, and MAS programs sufficiently stimulated adaptive mechanisms, improving relative maximal oxygen uptake [$\dot{V}O_{2max}$ ($p < 0.05$; ES = 1.6, 1.2, and 1.1, respectively)], absolute $\dot{V}O_{2max}$ ($p < 0.05$; ES = 1.5, 1.1, and 0.7), ventilation [$\dot{V}_E$ ($p < 0.05$; ES = 1.6, 1.1, and 1.1)], O_2 pulse [$\dot{V}O_2$/HR ($p < 0.05$; ES = 1.4, 1.1, and 0.6)], first and second ventilatory threshold [VT_1 ($p < 0.05$; ES = 0.7, 0.8, and 0.7) and VT_2 ($p < 0.05$; ES = 1.1, 1.1, and 0.8)], cardiac output [$\dot{Q}_{max}$ (p = 1.5, 1.0, and 0.7)], and stroke volume [SV_{max} ($p < 0.05$; ES = 0.9, 0.7, and 0.5)]. Although there was no between-group difference for the change in the abovementioned variables over time, supramaximal interval training prescribed using ASR and V_{IFT} resulted in a lower coefficient of variation [CV (inter-individual variability)] in physiological adaptations compared to exercise intensity determined as a proportion of MAS. Expressing the intensity of supramaximal interval programs according to the athlete's ASR and V_{IFT} would assist in accurately prescribing interventions and facilitate imposing mechanical and related physiological stimulus according to the athletes' physiological ceiling. Such an approach leads to identical stimulation across athletes with differing profiles and potentially facilitates more homogenized adaptations.

Key words: Intermittent exercise, individualized intervention, cardiac function, maximal oxygen consumption, exercise prescription.

Introduction

Various forms of high-intensity interval training (HIIT) are periodically employed as sport-specific interventions for improving physiological capabilities in soccer players (Wahl et al., 2014; Arazi et al., 2017). HIIT is typically prescribed as short intervals, long intervals, repeated sprints, and small-sided games to target the metabolic oxygen, neuromuscular, and anaerobic systems throughout the season (Laursen and Buchheit, 2019). Opting for a suitable HIIT session for soccer involves considering different factors such as the player's profile, match-play demands, expected long-term adaptations, and training periodization (Faude et al., 2013; Arazi et al., 2017; Laursen and Buchheit, 2019).

When prescribing HIIT, various factors such as duration and intensity of work bouts and recovery between efforts, number of sets or series, number of bouts in series, recovery duration and intensity between series, total work performed, frequency of training sessions and training modality are considered (Tschakert and Hofmann, 2013), and the duration and intensity of the exercise and relief intervals are the key determining factors (Buchheit and Laursen, 2013; Foster et al., 2015; Bonato et al., 2017; Menz et al., 2019; Rasouli mojez et al., 2021; Sayevand et al., 2022). Various forms for HIIT prescribing methods have been developed to help athletes achieve the desired exercise intensity during their training sessions in a controlled and personalized manner. "Procedures may include a rating of perceived exertion (RPE)-based prescription which is considered the universal HIIT practice; the maximal aerobic speed and power-based method, which are thought to be critical prescription components for many sports; the 30-15 intermittent fitness test, that was shown to be an effective means of measuring its capacity for appropriate HIIT prescription in team sports to target specific adaptations; anaerobic speed/power reserve measures, or upper capacity for high-intensity exercise above velocity/power associated with maximal oxygen uptake [$\dot{V}O_{2max}$ ($v/p\dot{V}O_{2max}$)], is an important factor to consider when calibrating supramaximal efforts; heart rate and power meter-based approaches, which has been shown to be the more efficacious method of use across HIIT; and all-out sprint training, the track-and-field or team sport approaches, that may be specific to the sport in general" (Laursen and Buchheit, 2019).

HIIT for maximal intensities is typically prescribed based on the $v/p\dot{V}O_{2max}$, which is also known as maximal aerobic speed/power (MAS/MAP) (Buchheit and Laursen, 2013; Sheykhlouvand et al., 2018). "Since MAP/MAS is theoretically considered the minimal velocity/power at which $\dot{V}O_{2max}$ is elicited (Billat and Koralsztein, 1996), this variable could "represent an ideal reference for training" for improving $\dot{V}O_{2max}$ and related cardiorespiratory parameters (Buchheit and Laursen, 2013). This notion has been justified by the concept that HIIT interventions eliciting $\dot{V}O_{2max}$, or a very high percentage of it, results in the re-

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cruitment of large motor units (Gollnick et al., 1974; Altenburg et al., 2007) and achievement of nearly maximal cardiac output (Buchheit and Laursen, 2013) and may subsequently impose an effective stimulus for improving $\dot{V}O_{2max}$ which is manifested through the enhanced oxygen delivery to active muscles (central component) and increased the capacity of the muscles for utilizing the oxygen (peripheral component) (Midgley and McNaughton, 2006; Laursen and Jenkins, 2002).

In supramaximal intensities (i.e., intensities beyond MAS), both aerobic and anaerobic metabolic systems are involved, and "intuitively, an indirect measure of MAS would not optimally prescribe prescription of a supramaximal intensity requiring anaerobic metabolism" (Collison et al., 2022). In addition, the MAS is method and protocol-dependent (Sandford et al., 2021; Laursen and Buchheit, 2019), and in case of using protocols with longer stage durations for determination of MAS, lower speed values tend to be elicited (Midgley et al., 2006). By contrast, using larger speed increments (shorter tests) could lead to elevated speed values, with the individual's anaerobic capacity potentially being a confounding factor in the assessment (Laursen and Buchheit, 2019). Also, when exercising at supramaximal intensities, optimal responses are related to the proportion of anaerobic speed reserve [ASR; the difference between MAS and maximal sprint speed (MSS)] (Du and Tao, 2023). Athletes with the same MAS may present a different MSS and ASR. Exercise intensity as a proportion of MAS involves a different percentage of ASR across athletes with different profiles, which results in different physiological demands and adaptations (Sandford et al., 2021). Recently, Du and Tao (2023) indicated HIIT prescribed using individualized proportions of MAS results in greater inter-individual variations in physiological adaptations than supramaximal HIIT interventions designed using ASR. In another experiment, Wang and Zhao (2023) indicated the same outcomes when the adaptations to ASR and MAS were compared. At intensities beyond MAS, using ASR normalizes mechanical and related physiological stimulus according to the athletes' ceiling, "ensures similar physiological demand across individuals, and potentially facilitates similar degrees of physiological adaptation" (Collision et al., 2022). Hence, individualizing HIIT at supramaximal intensities using ASR may facilitate homogenized adaptations across individuals with various physiological ceilings (Collison et al., 2022; Du and Tao, 2023).

Although individualizing supramaximal HIIT using ASR may be a more practical approach than MAS, it fails to provide a comprehensive overview of the various physiological factors crucial during team-based specific HIIT sessions (Buchheit and Laursen, 2013). In team sports like soccer, HIIT includes repeated short intervals (Senécal et al., 2021; Douchet et al., 2023) in which coaches should consider factors such as $\dot{V}O_2$ kinetics at the beginning of intervals, physiological capacity of recovery during rest intervals, and change of direction ability in addition to the percentage of ASR involved (Buchheit, 2008a; 2008b). HIIT interventions without considering these factors will result in varying physiological demands, prevent standardizing the training load, and probably limit targeting desired physiological adaptations (Buchheit and Laursen, 2013). It has been purported that the 30-15 Intermittent Fitness Test ($30\text{-}15_{IFT}$) overcomes the above-mentioned limitations as this test has been created to elicit $\dot{V}O_2$ while providing a measure of ASR, repeated running ability, deceleration, accelerations, and change of direction abilities (Buchheit, 2005; 2008a; 2008b; Buchheit and Laursen, 2013). The speed attained at the end of 30-15 Intermittent Fitness Test (V_{IFT}) would be the product of the parameters mentioned above (Buchheit, 2008a; 2008b; Buchheit et al., 2009).

In a recent study, Collison and colleagues (2022) compared the variability of the performance in interval running at supramaximal intensities when prescribed as a proportion of ASR, V_{IFT}, and MAS. They concluded that, compared to intervals performed according to MAS, variability of the time to exhaustion residuals during supramaximal interval running diminished when prescribed according to individual ASR rather than when intervals were performed based on V_{IFT}. The studies mentioned above indicate the potential of such methods in diminishing inter-subject variability in exercise tolerance. However, it is not well elucidated if equalizing the exercise tolerance can also reduce variation in the magnitude of adaptations across individuals with different physiological ceilings over a training period. Accordingly, we aimed to compare the homogeneity of adaptations to HIIT programs designed using ASR, V_{IFT}, and MAS and determine if such an approach will result in more uniform adaptive responses among soccer players with different profiles. Based on the notion that such programming methods equalize mechanical stimulus and physiological demands among athletes with varying profiles (Blondel et al., 2001; Collison et al., 2022), we hypothesized supramaximal HIIT interventions prescribed using ASR and V_{IFT} would decrease inter-individual variability in physiological adaptations.

Methods

Participants

Thirty male soccer players (age = 19 ± 1.6 years; body mass = 78.9 ± 1.6 kg; height = 179 ± 4.7 cm; Body fat = 11 ± 0.9%) signed a written informed consent and voluntarily participated. According to the participants' classification framework provided by McKay and colleagues (2022), our participants are classified as national-level players. Participants with: a) at least 3 years of experience in national-level competitions; b) who were accustomed to maximal testing; c) with no physical limitations and musculoskeletal injuries; and d) who were familiar with different HIIT interventions, were recruited. Using simple randomization method, they were randomly assigned to HIIT groups performing programs prescribed using ASR ($HIIT_{ASR}$), V_{IFT} ($HIITv_{IFT}$), and MAS ($HIIT_{MAS}$), each of 10 (Figure 1). The research ethic committee at the Central South University of Forestry and Technology approved all procedures, and the study conformed to the ethical principles of the World Medical Association.

Experimental design

This study is a repeated-measures factorial design with the allocation ratio of 1:1:1. Figure 2 presents a schematic of the experimental overview. Baseline measurements were conducted during the off-season phase of the athletes' yearly training program, with post-testing after the 6-week HIIT intervention. Before and after the training period, participants performed a progressive exercise test for the evaluation of $\dot{V}O_{2max}$, MAS, O_2 pulse ($\dot{V}O_2$/HR), maximal ventilation ($\dot{V}_E$), and first and second ventilatory threshold [VT_1 and VT_2 (%$\dot{V}O_{2max}$)]. On the second and third occasions, V_{IFT} and MSS were evaluated. Participants completed testing sessions on different days separated with 24 h relief, and they were asked to abstain from alcohol (Barzegar et al., 2021) and avoid intensive physical activity between tests (Gharaat et al., 2020). All tests were carried out in the morning (~9 - 11:30 am) in an ambient temperature of ~22 - 24ºC and a relative humidity of ~55 - 60%. The tests were supervised with specialist blinded to the group assignments. 48 h after finishing the baseline measurements, participants engaged in 3 sessions/week of HIIT, and they underwent the same testing protocol as pre-training, in the same sequence and with similar conditions, 48 h after the last training session. All tests were carried out at the exercise physiology laboratory and training facilities of the Central South University of Forestry and Technology.

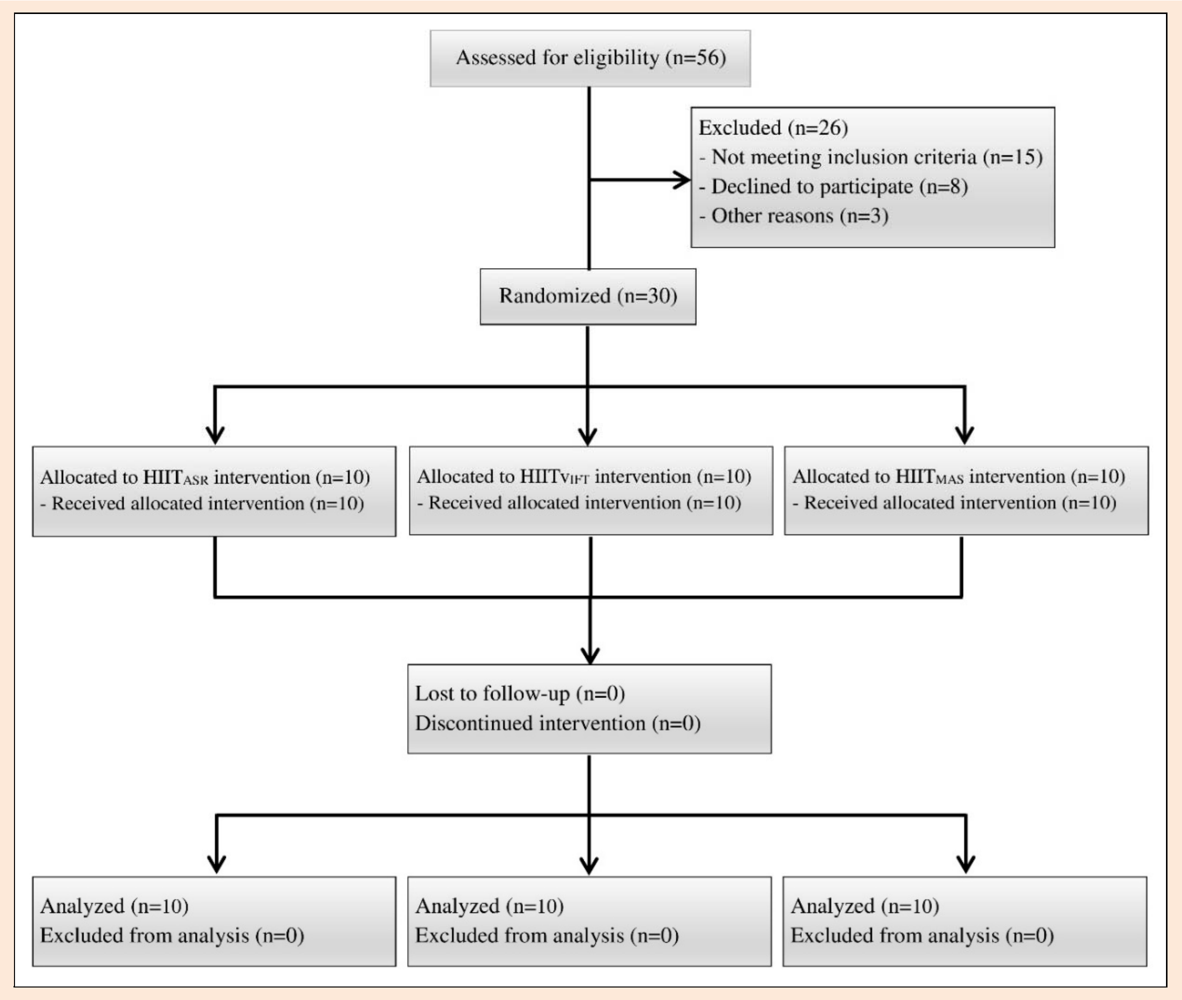

Figure 1. **CONSORT flow diagram.**

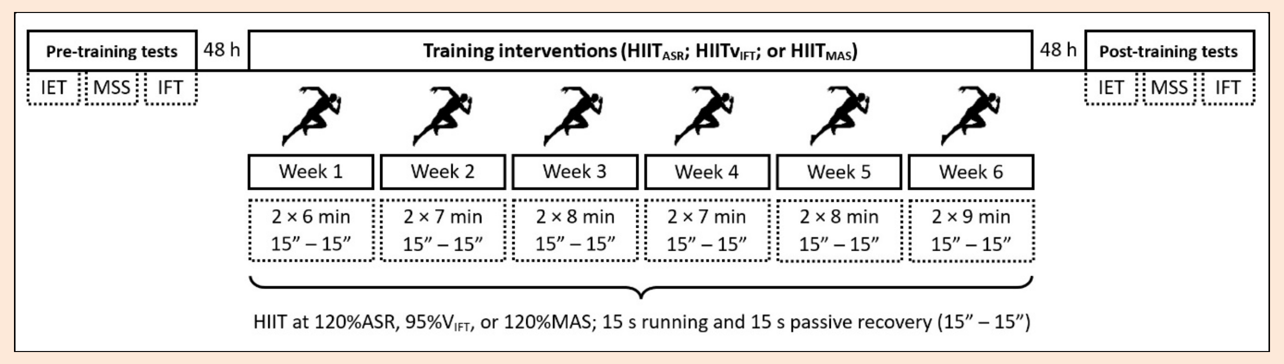

Figure 2. **Overview of the experimental protocol.** IET, incremental exercise test; MSS, maximal sprint speed; IFT, 30-15 incremental fitness test. HIIT$_{ASR}$, high-intensity interval training using anaerobic speed reserve (ASR); HIITv$_{IFT}$, HIIT using finial velocity during 30-15$_{IFT}$ test (V$_{IFT}$); HIIT$_{MAS}$, HIIT using maximal aerobic speed (MAS).

Incremental exercise test using a gas analyzer

Following 10 minutes of warm-up consisting of a 5-min low-to-moderate intensity (50% to 70% of the individual's age-predicted HR_{max}) followed by another 5-min dynamic general stretching (Heyward and Gibson, 2014), athletes performed an incremental running test on a treadmill (Technogym, Cesena, Italy) to evaluate physiological parameters. Participants started to run at the initial velocity of 8 $km{\cdot}h^{-1}$, incrementing by 1 $km{\cdot}h^{-1}$ every 3 min until exhaustion. A 30 s rest interval separated stages to blood sampling from the earlobe for determining blood lactate concentrations $[La^{-}]$ (Lactate Scout+, SensLab, Leipzig, Germany) (Billat et al., 2000; Esfarjani and Laursen, 2007). Physiological parameters were measured using a gas collection system (MetaLyzer 3B-R2, Cortex, Germany) calibrated by an experienced technician before each test. The highest 30 s average of the $\dot{V}O_2$ values was considered as $\dot{V}O_{2max}$. The following criteria confirmed reaching $\dot{V}O_{2max}$: 1) leveling off or a slight drop in $\dot{V}O_2$ despite elevation in running velocity, 2) respiratory exchange ratio > 1.2, 3) HR attained ≥ 90% predicted maximum, 4) $[La^{-}] \geq 8$ mmol l^{-1}, and 5) clear sign of exhaustion (Fereshtian et al., 2017; Sheykhlouvand and Forbes, 2017; Liu and Wang 2023). The point where an increase in the $\dot{V}_E/\dot{V}O_2$ and end-tidal O_2 tension ($P_{ET}O_2$) occurred with no simultaneous elevation in $\dot{V}_E/\dot{V}CO_2$ was considered VT_1. VT_2 identification criterion was the continuous elevation in the $\dot{V}_E/\dot{V}O_2$ and $\dot{V}_E/\dot{V}CO_2$ ratio curves related to the decrease in $P_{ET}O_2$ (Alejo et al., 2022). Maximal cardiac output ($\dot{Q}_{max}$) and maximal stroke volume (SV_{max}) were analyzed using PhysioFlow (Manatec, France) impedance cardiograph device during the incremental exercise test. MAS was established as a minimal velocity that $\dot{V}O_{2max}$ elicited as long as it could be sustained for at least one minute. In the case of reaching $\dot{V}O_{2max}$ during a stage where its speed couldn't be maintained for one minute, the velocity of the previous step was established as MAS.

Maximal sprint speed

Participants completed two consecutive 40-m sprint tests with 10-m splits, and the MSS was established as the fastest 10-m split time (Buchheit et al., 2012). Participants were encouraged to run between electronic timing gates (Freelap Pro Coach BLE 424, Alachua, FL, USA) as fast as possible using a standing position, with their front foot 0.5 m behind the first gate and a self-selected start time, and split times were measured to the nearest 0.01 s. Transmitters were placed on the base according to the manufacturers' instructions (30 cm height) and maximal sprint speed was defined as the running speed attained during $Split_{best}$ (Buchheit et al., 2012). Trials were separated with 2 min relief, and the analysis was done based on the athlete's best performance. Test-retest reliability of the 40-m sprint test was 0.94 (Rimmer and Sleveret, 2000). The test was performed in indoor field with an ambient temperature of ~22 - 24ºC. The condition was almost the same during pre- and post-training. ASR was obtained through MSS minus MAP.

30 - 15 Intermittent Fitness Test

The test comprised 30 s shuttle runs with 15 s passive recovery between efforts. Participants commenced the test with an initial speed set at 8 km h^{-1} thereafter by 0.5 km h^{-1} increment every 45 s. They were instructed to run between two lines, spaced 40-m apart, in a back-and-forth motion. They were guided by a pre-recorded audio file that signaled when they needed to be within a 3-meter area around the target line. During recovery, athletes moved forward to reach the nearest line from where they would commence the next step. Participants were encouraged to complete the maximum number of stages they could. The test ended when they could not sustain a running pace or failed to get the 3-m zone around each line upon hearing the audio signal three times (Buchheit, 2008a). The velocity achieved at the end of $30\text{-}15_{IFT}$ test was considered V_{IFT}.

HIIT programs

Participants commenced HIIT interventions about 48 h after the baseline measurements. Before participating in this experiment, all groups had five sessions per week of moderate-intensity soccer-specific technical and tactical training lasting between 70 - 90 min (~9:30 am). In addition to their regular soccer training, they engaged in 3 sessions per week of HIIT (~4:30 pm) with a 1–2 days gap between sessions (Figure 1). The HIIT training session started with a 10 min warm-up, comprising jogging, dynamic stretching, as well as short sprints with the integration of soccer-specific technical actions. Previous studies have shown that high-intensity running corresponds to 11 - 11.7% of live playing time across matches with up to 105 intensive efforts with short duration (2 - 6 s) (McInnes et al., 1995; Ben et al., 2007; Figueira et al., 2022) every 21-39 seconds (Conte et al., 2015). Accordingly, the duration of intervals was set at 2 sets of 6, 7, 8, 7, 8, and 9 min intervals (from first to sixth week, respectively), including 15 s running at Δ%20ASR (MAS + 0.2 × ASR), 120%MAS, or 95%V_{IFT} followed by 15 s passive recovery. "Since V_{IFT} is 2 - 5 $km{\cdot}h^{-1}$ (15 - 25%) faster than MAS, it is necessary to 'adjust' the percentage of V_{IFT} used when programming" (Buchheit and Laursen, 2013). Hence, we prescribed 95%V_{IFT} for participants of the $HIITv_{IFT}$ group as previously suggested.

Statistical analysis

The analysis was conducted using SPSS software [V 25.0 (IBM Corp., Chicago, IL)]. Sample size was estimated using G*Power software (Faul et al., 2007) and considering the effect size of 0.8, α of 0.05 and β of 0.08, a minimum of six participants was calculated for each group. Nonetheless, anticipating potential participant dropout during the data collection phase, the sample size was subsequently increased to include ten participants in each group. Results were reported as mean ± SD. Levene's and Shapiro-Wilk's tests checked the data's homogeneity of the variance and normality. The difference between changes was analyzed using a group (3 HIIT groups) × time (pre- and post-training) repeated-measure analysis of variance (ANOVA) followed by Tukey's post hoc test. Inter-subject variability was determined by calculating the coefficient of variations (CV) for changes. The α level was set at 0.05.

Results

Levene's test showed that the variances for all measured variables were equal (p > 0.05) and Shapiro-Wilk's tests indicated variables are normally distributed (p > 0.05). There was no difference among groups ($p > 0.05$) for the measured parameters at the baseline. As shown in Table 1, Tble 2 and Figure 2-5, all training interventions significantly improved $\dot{V}O_{2max}$ (mL·kg^{-1}·min^{-1} and L^{-1}·min^{-1}), $\dot{V}O_2$/HR, $\dot{V}_E$, VT_1, VT_2, $\dot{Q}_{max}$, SV_{max}, and MAS over time ($p < 0.05$). Also, ASR significantly decreased in all HIIT groups overtime ($p < 0.05$). There was no between-group difference for the change in the abovementioned variables over time ($p > 0.05$). Lower inter-individual variability (CV) was observed for the percent changes of abovementioned parameters (Figure 4) in response to $HIIT_{ASR}$ and $HIIT_{VIFT}$, when compared to $HIIT_{MAS}$ for relative $\dot{V}O_{2max}$ (0.09 and 0.12 vs. 0.29), absolute $\dot{V}O_{2max}$ (0.11 and 0.14 vs. 0.19), $\dot{V}O_2$/HR (0.20 and 0.23 vs. 0.31), $\dot{V}_E$ (0.16 and 0.23 vs. 0.29), VT_1 (0.09 and 0.11 vs. 0.28), VT_2 (0.14 and 0.17 vs. 0.26), $\dot{Q}_{max}$ (0.11 and 0.14 vs. 0.19), SV_{max} (0.21 and 0.25 vs. 0.32), MAS (0.38 and 0.38 vs. 0.41), and ASR (0.39 and 0.49 vs. 0.63).

Discussion

This study is the first to compare the homogeneity of adaptations to supramaximal HIIT interventions prescribed using ASR, V_{IFT}, and MAS in soccer players. The most striking finding of the present study was that six weeks of supramaximal HIIT using ASR and V_{IFT} resulted in a more uniform adaptive response than HIIT based on MAS across individuals with different profiles. Also, all HIIT interventions sufficiently stimulated adaptive mechanisms promoting physiological parameters associated with the central components of aerobic fitness.

Our findings corroborate propositions from studies indicating ASR (Blondel et al., 2001; Collison et al., 2022; Julio et al., 2022; Du and Tao, 2023) and V_{IFT} (Buchheit, 2005 and 2008; Buchheit and Laursen, 2013) as proper reference intensities for prescribing HIIT. In the first ASR study, Blondel and colleagues (2001) compared exercise tolerance at varying proportions of MAS with the intensity expressed relative to critical velocity and MSS. They concluded that expressing intensity as a proportion of ASR at supramaximal speeds allows for individual anaerobic capacities to be involved, results in a more precise prediction of exercise tolerance, and reduces inter-individual variance in time to exhaustion. However, the extent to which such an approach would result in uniform physiological adaptations remain unclear. Although some studies have tested the homogeneity of performance in response to ASR-based interventions (Julio et al., 2022; Collison et al., 2022),

Table 1. Pre-training *vs.* post-training values for physiological parameters in different HIIT groups. Values are means ± SD.

		Group		
		$HIIT_{ASR}$	**$HIIT_{vIFT}$**	**$HIIT_{MAS}$**
$\dot{V}O_{2max}$ (mL·kg^{-1}·min^{-1})	**Pre**	51.0 ± 2.2	51.6 ± 2.8	51.4 ± 2.0
	Post	54.7 ± 2.4 †	55.0 ± 3.0 †	54.2 ± 2.4 †
	p and Cohen's (d)	0.001 (d = 1.6)	0.001 (d = 1.2)	0.004 (d = 1.1)
$\dot{V}O_{2max}$ (L·min^{-1})	**Pre**	3.95 ± 0.24	4.06 ± 0.16	4.15 ± 0.33
	Post	4.24 ± 0.27 †	4.32 ± 0.17 †	4.39 ± 0.37 †
	p and Cohen's (d)	0.001 (d = 1.5)	0.005 (d = 1.1)	0.001 (d = 0.7)
$\dot{V}O_2$/HR (mL·b^{-1}·min^{-1})	**Pre**	21.6 ± 1.6	21.7 ± 0.9	22.2 ± 1.9
	Post	23.2 ± 1.6 †	23.1 ± 1.0 †	23.5 ± 2.0 †
	p and Cohen's (d)	0.002 (d = 1.4)	0.004 (d = 1.1)	0.005 (d = 0.6)
$\dot{V}_E$ (L·min^{-1})	**Pre**	191.7 ± 14.1	199.5 ± 19.7	195.8 ± 19.3
	Post	214.4 ± 14.6 †	225.3 ± 24.5 †	220.9 ± 25.3 †
	p and Cohen's (d)	0.003 (d = 1.6)	0.002 (d = 1.1)	0.006 (d = 1.1)
VT_1 (%$\dot{V}O_{2max}$)	**Pre**	71.8 ± 6.5	73.2 ± 5.1	74.2 ± 7.0
	Post	76.7 ± 7.0 †	78.0 ± 5.9 †	79.2 ± 5.9 †
	p and Cohen's (d)	0.005 (d = 0.7)	0.001 (d = 0.8)	0.003 (d = 0.7)
VT_2 (%$\dot{V}O_{2max}$)	**Pre**	85.0 ± 5.8	87.3 ± 4.2	87.8 ± 3.1
	Post	89.1 ± 6.3 †	91.9 ± 4.1 †	91.5 ± 3.2 †
	p and Cohen's (d)	0.002 (d = 1.1)	0.006 (d = 1.1)	0.001 (d = 0.8)
$\dot{Q}_{max}$ (L·min^{-1})	**Pre**	24.4 ± 1.5	25.0 ± 1.0	25.6 ± 2.0
	Post	26.1 ± 1.7 †	26.6 ± 1.1 †	27.1 ± 2.3 †
	p and Cohen's (d)	0.005 (d = 1.5)	0.001 (d = 1.0)	0.001 (d = 0.7)
SV_{max} (mL·b^{-1})	**Pre**	133.4 ± 10.2	134.1 ± 15.4	137.1 ± 11.8
	Post	143.1 ± 10.2 †	142.5 ± 16.3 †	144.7 ± 12.5 †
	p and Cohen's (d)	0.002 (d = 0.9)	0.004 (d = 0.7)	0.005 (d = 0.5)
MAS (km·h^{-1})	**Pre**	13.6 ± 0.5	13.6 ± 0.6	13.7 ± 0.7
	Post	14.6 ± 0.4 †	14.7 ± 0.7 †	14.6 ± 0.8 †
	p and Cohen's (d)	0.002 (d = 2.2)	0.001 (d = 1.6)	0.002 (d = 1.2)
MSS (km·h^{-1})	**Pre**	31.3 ± 1.2	30.8 ± 1.6	30.8 ± 1.4
	Post	31.5 ± 1.3	31.0 ± 1.3	31.1 ± 1.3
	p and Cohen's (d)	0.57 (d = 0.1)	0.44 (d = 0.1)	0.14 (d = 0.2)
ASR (km·h^{-1})	**Pre**	17.7 ± 1.2	17.2 ± 1.7	17.1 ± 1.7
	Post	16.8 ± 1.4 †	16.2 ± 1.8 †	16.6 ± 1.6 †
	p and Cohen's (d)	0.006 (d = 0.7)	0.001 (d = 0.6)	0.05 (d = 0.4)

$\dot{V}O_{2max}$, maximum oxygen uptake; $\dot{V}O_2$/HR, O_2 pulse; $\dot{V}_E$, ventilation; VT_1, first ventilatory threshold; VT_2, second ventilatory threshold; $\dot{Q}$, cardiac output; SV, stroke volume; MAS, maximal aerobic speed; MSS, maximal sprint speed; ASR, anaerobic speed reserve. N, 10 for each group. † Significantly greater compared to baseline value ($p < 0.05$).

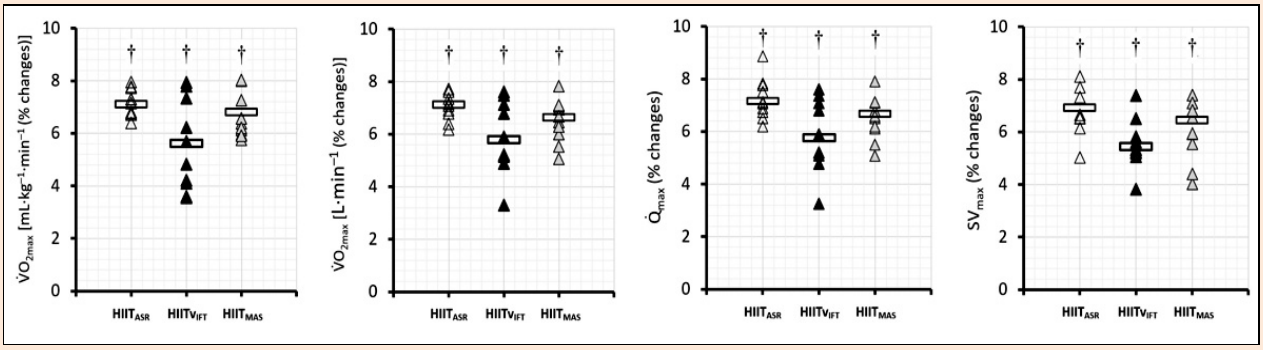

Figure 3. **Adaptive responses of maximal oxygen uptake ($\dot{V}O_{2max}$), cardiac output ($\dot{Q}_{max}$), and stroke volume (SV_{max}) to high-intensity interval training using anaerobic speed reserve ($HIIT_{ASR}$), HIIT using finial velocity during 30-15_{IFT} test ($HIITv_{IFT}$), and HIIT using maximal aerobic speed ($HIIT_{MAS}$).** Triangles indicate individual percent change from baseline (X-axes) and horizontal bars represent mean group response. † Denotes significantly different versus pre-training ($p \le 0.05$).

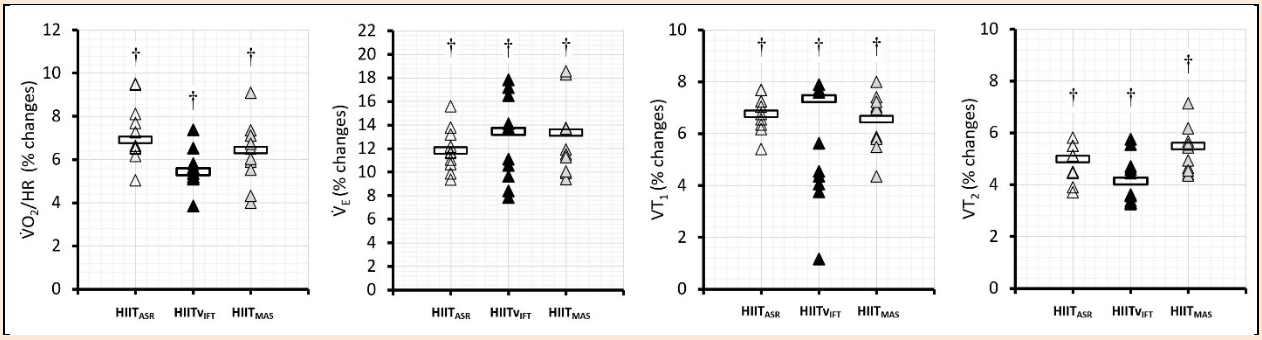

Figure 4. **Adaptive responses of O_2 pulse ($\dot{V}O_2/HR$), ventilation ($\dot{V}_E$), first and second ventilatory threshold (VT_1 and VT_2) to high-intensity interval training using anaerobic speed reserve ($HIIT_{ASR}$), HIIT using finial velocity during 30-15_{IFT} test ($HIITv_{IFT}$), and HIIT using maximal aerobic speed ($HIIT_{MAS}$).** Triangles indicate individual percent change from baseline (X-axes) and horizontal bars represent mean group response. † Denotes significantly different versus pre-training ($p \le 0.05$).

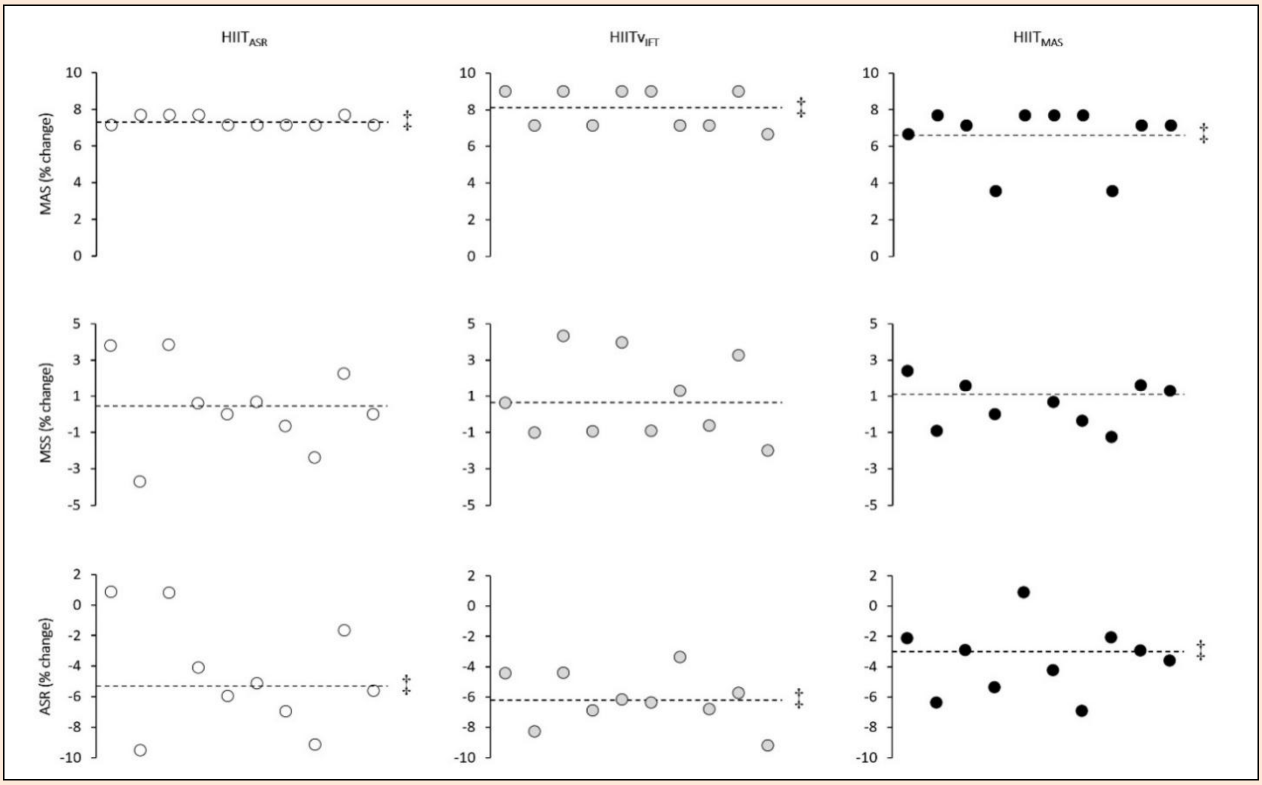

Figure 5. **Adaptive responses of maximal aerobic speed (MAS), maximal sprint speed (MSS), and anaerobic speed reserve (ASR) to high-intensity interval training using anaerobic speed reserve ($HIIT_{ASR}$), HIIT using finial velocity during 30-15_{IFT} test ($HIITv_{IFT}$), and HIIT using maximal aerobic speed ($HIIT_{MAS}$).** Circles indicate individual percent change from baseline and the dashed line represents mean group response. ‡ Denotes significantly different versus pre-training ($p \le 0.05$).

Table 2. Percent changes (%Δ) over time and coefficient of variations (CV) for mean changes in physiological parameters. Values are means ± SD.

	Group					
	$HIIT_{ASR}$		**$HIIT_{VIFT}$**		**$HITT_{MAS}$**	
	%Δ	**CV**	**%Δ**	**CV**	**%Δ**	**CV**
$\dot{V}O_{2max}$ ($mL \cdot kg^{-1} \cdot min^{-1}$)	7.2 ± 0.7	0.09	6.6 ± 0.8	0.12	5.4 ± 1.6	0.29
$\dot{V}O_{2max}$ ($L \cdot min^{-1}$)	7.3 ± 0.8	0.11	6.4 ± 0.9	0.14	5.8 ± 1.1	0.19
$\dot{V}O_2$/HR ($mL \cdot b^{-1} \cdot min^{-1}$)	7.4 ± 1.5	0.20	6.4 ± 1.6	0.25	5.8 ± 1.8	0.31
$\dot{V}_E$ ($L \cdot min^{-1}$)	11.8 ± 1.9	0.16	12.9 ± 3.0	0.23	12.8 ± 3.8	0.29
VT_1 (%$\dot{V}O_{2max}$)	6.8 ± 0.6	0.09	6.5 ± 0.7	0.11	6.7 ± 1.9	0.28
VT_2 (%$\dot{V}O_{2max}$)	4.8 ± 0.7	0.14	5.2 ± 0.9	0.17	4.2 ± 1.1	0.26
$\dot{Q}_{max}$ ($L \cdot min^{-1}$)	6.9 ± 0.8	0.11	6.4 ± 0.9	0.14	5.7 ± 1.1	0.19
SV_{max} ($mL \cdot b^{-1}$)	7.2 ± 1.5	0.21	6.2 ± 1.6	0.25	5.5 ± 1.8	0.32
MAS ($km \cdot h^{-1}$)	7.3 ± 2.8	0.38	8.1 ± 3.1	0.38	6.6 ± 2.7	0.41
ASR ($km \cdot h^{-1}$)	-5.3 ± 2.1	0.39	-6.2 ± 2.7	0.43	-3.0 ± 1.9	0.63

$\dot{V}O_{2max}$, maximum oxygen uptake; $\dot{V}O_2$/HR, O_2 pulse; $\dot{V}_E$, ventilation; VT_1, first ventilatory threshold; VT_2, second ventilatory threshold; $\dot{Q}$, cardiac output; SV, stroke volume; MAS, maximal aerobic speed; MSS, maximal sprint speed; ASR, anaerobic speed reserve. N, 10 for each group.

only one study has investigated the physiological adaptations to interventions prescribed using the ASR approach. Consistent with our findings, Du and Tao (2023) indicated that expressing HIIT intensity as a proportion of the ASR reduces inter-individual variability in subsequent adaptations. Their research was limited in that they compared HIIT interventions performed at supramaximal intensities (Δ20%ASR) with an intervention performed at 100%MAS. However, our results complete the findings of Du and Tao (2023) in this regard. As illustrated in Table 2, the CV values for the change in physiological parameters are significantly lower in response to $HIIT_{ASR}$ compared to the $HIIT_{MAS}$, indicating a positive influence of taking ASR into account when programming HIIT for individuals varying in anaerobic capacity. Employing this approach in designing supramaximal HIIT interventions prevents mismatch between the individual's profile and the training intervention and normalizes physiological and mechanical stress relative to the athlete's ceiling (Sandford et al., 2021; Collison et al., 2022; Du and Tao., 2023).

Per our hypothesis, supramaximal HIIT using V_{IFT} also decreased inter-individual variance in physiological adaptations compared to HIIT prescribed using MAS. Although CV values in the adaptive response to $HIITv_{IFT}$ were lower than $HIIT_{ASR}$, this was not significantly different, indicating a lack of superior effects of ASR-based HIIT to diminish inter-subject variance in adaptive responses compared to HIIT prescribed as a proportion of V_{IFT}. This outcome contradicts Collison and colleagues (2022), who reported that in comparison to prescription using MAS, supramaximal interval running performance variability decreases when prescribing exercise intensity as a percentage of ASR but not when HIIT intervention is defined using V_{IFT}. By contrast, our findings support Buchheit and Laursen (2013), who stated that $30\text{-}15_{IFT}$ not only elicits maximal HR and $\dot{V}O_2$ but additionally provides a measure of ASR, making it a unique tool for individualizing interval training. The mechanism explaining decreased inter-subject variation in the adaptive response to $HIIT_{ASR}$ and $HIITv_{IFT}$ might be because of facilitated involvement of the similar proportions of physiological ceiling across individuals with different profiles (Sandford et el., 2021; Collison et al., 2022). Actually, "exercise intensity beyond MAS is a proportion of ASR rather than a relative intensity in relation to MAS" (Sandford et al., 2021). Using an athlete's MAS to determine the intensity of supramaximal HIIT may impose varying levels of homeostatic stress. This variability could lead to non-uniform stimulus across athletes with differing profiles and, in turn, result in different adaptive responses. Using ASR and V_{IFT} for individualizing HIIT performed at intensities beyond MAS normalizes mechanical and related physiological stimulus according to the athletes' ceiling, "ensures similar physiological demand across individuals, and potentially facilitates similar degrees of physiological adaptation" (Collision et al., 2022).

Another finding of our study was that $\dot{V}O_{2max}$ and related physiological parameters significantly improved in response to all three HIIT interventions over time. Improvements in $\dot{V}O_{2max}$ may occur through an increase in central (i.e., O_2 delivery) and peripheral (i.e., O_2 use by active muscles) components of aerobic fitness (Bayati et al., 2011; Sheykhlouvand et al., 2016; 2022). The mechanism underpinning increased $\dot{V}O_{2max}$ in our participants might be partly because of improved cardiac function, which can be verified by enhanced $\dot{V}O_2$/HR, $\dot{Q}_{max}$, and SV_{max} in all HIIT groups.

A limitation of this study could be the inclusion of only male participants, and our results cannot be applied to women. Also, we could not closely monitor the quality of the participant's sleep and strictly monitor dietary practices. Although the environmental conditions at the baseline measurements and post-test were almost the same, a slight difference in ambient temperature and relative humidity was seen. Our results only apply to the individualized HIIT protocols, and the possibility of such outcomes using higher intensities or training volume is unknown.

Conclusion

In conclusion, the present study indicated that six weeks of supramaximal HIIT using ASR and V_{IFT} resulted in a more uniform adaptive response than HIIT based on MAS across individuals with different profiles. Such individualization decreased inter-subject variability in physiological adaptations to supramaximal HIIT compared to the interventions prescribed based on MAS. Also, HIIT performed using Δ20%ASR, 95%V_{IFT}, and 120%MAS resulted in significant improvements in $\dot{V}O_{2max}$ and physiological parameters associated with the central components of aerobic fitness.

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There is no conflict of interest. The present study complies with the current laws of the country in which it was performed. The datasets generated and analyzed during the current study are not publicly available but are available from the corresponding author, who was an organizer of the study.

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Key points

- Expressing the intensity of supramaximal HIIT according to the athlete's ASR and VIFT resulted in accurately prescribing interventions and normalizes mechanical stimulus according to the athletes' physiological ceiling.
- Such individualization ensures the creation of more identical physiological demands across athletes with different profiles and facilitates the same degrees of physiological adaptations.
- Irrespective of the homogeneity of the adaptations to these HIIT interventions, all three methods sufficiently stimulated adaptive mechanisms and improved cardiorespiratory fitness in well-trained soccer players.

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