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Research article

A Comparative Analysis of High-Intensity Technique-Specific Intervals and Short Sprint Interval Training in Taekwondo Athletes: Effects on Cardiorespiratory Fitness and Anaerobic Power

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Abstract

Technique-specific high-intensity interval training ($HIIT_{TS}$) has been proven to be an effective method to enhance the sport-specific bio-motor abilities of taekwondo athletes. However, studies regarding its effects on comprehensive measures of cardiorespiratory fitness are limited. Furthermore, there is a lack of clarity regarding the extent of individual adaptations to this method compared to HIIT in the form of repeated sprints ($HIIT_{RS}$). This study compared the individual adaptations to $HIIT_{RS}$ and $HIIT_{TS}$ on cardiorespiratory fitness and anaerobic power in trained taekwondo athletes (age = 19.8 ± 1.3 years; body mass = 75.4 ± 9.1 kg; height = 1.73 ± 0.0 .m). All participants completed three sessions per week of a 60-minute regular taekwondo training. Following the 60-minute training, participants completed 3 sets of 10 × 4 s *all-out* $HIIT_{RS}$ or same sets of repeated kicks with both legs ($HIIT_{TS}$) over a 6-week training period. In both groups, rest intervals were set at 15 seconds between efforts and one minute between sets. Before and after the training period, participants underwent a series of lab- and field-based tests to evaluate cardiorespiratory fitness and bio-motor abilities. Both interventions resulted in significant improvements in maximum oxygen uptake ($\dot{V}O_{2max}$), O_2 pulse ($\dot{V}O_2$/HR), first ventilatory threshold (VT_1), second ventilatory threshold (VT_2), cardiac output ($\dot{Q}_{max}$), stroke volume (SV), peak power output (PPO), average power output (APO), squat jump (SJ), and countermovement jump (CMJ). However, linear speed (20-m speed time) and taekwondo-specific agility test (TSAT) only responded to $HIIT_{RS}$. $HIIT_{RS}$ resulted in greater changes in $\dot{V}O_{2max}$, $\dot{V}O_2$/HR, VT_2, and $\dot{Q}_{max}$, and higher percentage of responders in measured parameters than $HIIT_{TS}$. In addition, $HIIT_{RS}$ elicited lower inter-individual variability (CV) in percent changes from pre- to post-training in all measured variables. These results suggest that incorporating 3 sessions per week of $HIIT_{RS}$ into regular taekwondo training results in significantly greater and more homogenized adaptations in cardiorespiratory fitness and bio-motor abilities than $HIIT_{TS}$ among trained taekwondo athletes.

Key words: Combat sports, aerobic power, conditioning, sport-specific training, athletic performance.

Introduction

Taekwondo is an Olympic sport requiring development and maintenance of high levels of physical fitness for a successful competition (O'Sullivan et al., 2009; Kim et al., 2011; Ojeda-Aravena et al., 2021a; 2021b). In its combat modality, taekwondo is characterized as an activity with intermittent bouts of effort and rest, with a typical ratio ranging from 1:2 to 1:7 (da Silva Santos et al., 2020). This dynamic nature of the sport demands high physiological intensity, often exceeding 90% of the maximum heart rate, leading to lactate levels ranging from 5.0 to 14 Mmol·L^{-1} (Bridge et al., 2014; da Silva Santos et al., 2020), with executing rapid, high-speed motor actions, primarily involving the lower limbs (Ojeda-Aravena et al., 2021a; 2021b). Aerobic and anaerobic metabolic systems are considered key determining factors in successful performance in taekwondo (Vasconcelos et al., 2020). During taekwondo competitions, athletes frequently perform high-intensity activities with short recovery periods, which rely on anaerobic metabolic pathways. Improving anaerobic capacity and lactate clearance can significantly enhance their ability to sustain intense activities throughout the competition (Casolino et al., 2012). Anaerobic fitness also plays a pivotal role in sustained prolonged periods of high-intensity movements such as the repetitive execution of punch and kick combinations (Bridge et al., 2014). Elite athletes need high levels of anaerobic capacity (Casolino et al., 2012), a key factor that differentiates competitive levels in taekwondo. On the other hand, during the longer recovery periods, aerobic metabolic pathway prevails. Higher levels of aerobic capacity are necessary to meet the metabolic demands of fighting, accelerate the recovery process (Chaabène et al., 2012; Campos et al., 2012), and support sustained efforts throughout bouts, rounds, and matches (Chaabene et al., 2017).

High-intensity interval training (HIIT) has been shown to efficiently improve sport-specific physiological attributes and elevate athletic performance across a diverse spectrum of sports (Laursen and Buchheit, 2019). HIIT is considered a time efficient strategy to induce skeletal muscle metabolic adaptations, cardiorespiratory fitness, and improve functional exercise capacity, in comparison to more conventional conditioning programs (Parra et al., 2000). HIIT elicits various physiological adaptations resembling traditional continuous training methods, despite a low total exercise volume (Sheykhlouvand et al., 2018a). HIIT also seems to exhibit superior effects on indicators of muscular and cardiac function, as well as markers of metabolic control than moderate-intensity continuous endurance training (Little et al., 2010). The degree and extent of these adaptations vary depending on the features upon which the interventions are designed (Sheykhlouvand et al., 2022). The duration and intensity of training and rest

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intervals play a crucial role in the adaptive responses (Buchheit and Laursen, 2013; Rasouli et al., 2021), which are formally optimized by conforming to the particular competition in which the athlete engages (Wang and Zhao, 2023). Understanding the appropriate training stimuli for optimally prescribing HIIT interventions will optimize the adaptive outcomes (Sandford et al., 2021).

Studies have shown the efficiency of HIIT in improving aerobic capacity and anaerobic power (Laursen and Bauchheit, 2019). Like the nature of HIIT, taekwondo comprises intermittent maximal efforts interspersed by low-to-moderate-intensity activities. Thus, HIIT could be considered a suitable training intervention for taekwondo athletes. Previous studies have introduced several technique-specific HIIT programs [$HIIT_{TS}$ (Aravena Tapia et al., 2020; Ojeda-Aravena et al., 2021a; 2021b)] and running-based HIIT programs [$HIIT_{RS}$ (Monks et al., 2017; Ouergui et al., 2020)] for enhancing athletic performance in taekwondo athletes. Because of the key principle of training specificity and the technical demands of taekwondo, there has been a significant increase in interest in $HIIT_{TS}$. Different taekwondo-specific HIIT interventions have been shown capable of adequately stimulating adaptive mechanisms improving sport-specific performance (Aravena Tapia et al., 2020; Ouergui et al., 2020, 2021; Ojeda-Aravena et al., 2021a; 2021b). Recent studies indicated the efficacy of $HIIT_{TS}$ in enhancing aerobic fitness by ~9-14% (Ouergui et al., 2020; 2021; Ojeda-Aravena and colleagues, 2021a; 2021b). Also, this training approach has been shown effective in improving taekwondo-specific bio-motor abilities comprising vertical jump height [~11% (Ojeda-Aravena et al., 2021b)], taekwondo-specific agility [~8.6% (Ojeda-Aravena et al., 2021a)], and speed of kick [~17% (Aravena Tapia et al., 2020)]. The majority of these studies have focused on sport-specific bio-motor abilities such as different vertical jump tests, multiple frequency speed of kick test ($FSKT_{MULT}$), taekwondo specific agility test (TSAT), linear sprint, kick decrement index (KDI), and total kicks (Aravena Tapia et al., 2020; Ojeda-Aravena et al., 2021a; 2021b). Although some studies have measured the adaptations of aerobic and anaerobic power in response to HIIT in taekwondo athletes (Monks et al., 2017; Ouergui et al., 2020; 2021), the effects of $HIIT_{TS}$ on comprehensive measures of cardiorespiratory fitness need to be unveiled. Moreover, no previous study has directly compared $HIIT_{TS}$ and $HIIT_{RS}$ with respect to aerobic power, cardiac hemodynamics, and Wingate anaerobic power in taekwondo athletes.

In addition to the points mentioned above, inter-subject variation holds paramount significance as a reliability metric for researchers, exerting a profound influence on the precision of estimates of alterations in experimental study variables. This reliability assessment is equally crucial for coaches, scientists, and other professionals who employ tests to oversee the progress of their athletes. Accordingly, this study aimed to compare the effects of six weeks of $HIIT_{TS}$ and $HIIT_{RS}$ on aerobic and anaerobic capacity, and bio-motor abilities in male taekwondo players. We hypothesized both protocols will positively trigger adaptive mechanisms enhancing the mentioned parameters with more significant impact of $HIIT_{RS}$ on cardiorespiratory fitness than $HIIT_{TS}$. The hypothesis is founded on the idea that recruiting more muscle groups by sprint-type HIIT may impose greater mechanical stimulus and higher physiological demands.

Methods

Study design

The baseline measurements were conducted during the off-season phase of the athletes' yearly training program. Three days before the baseline measurements, participants performed familiarization visits to become oriented with testing procedures and the training protocols. Before a 6-week training period, participants underwent a graded exercise test to evaluate cardiorespiratory fitness and cardiac hemodynamics. On other occasions, separated by a 24-hour recovery, they completed an upper-body Wingate test to assess their power output, vertical jump [countermovement jump (CMJ) and squat jump (SJ)], linear sprint, and taekwondo-specific agility test (TSAT). 48 hours after the last testing session, the initial training session commenced, and 48 hours after the last training session, participants completed the same testing under the same order and conditions as a pre-test. Participants were instructed not to consume alcohol and not to engage in strenuous physical activity during the 24 hours leading up to the testing sessions (Gharaat et al., 2020a; Barzegar et al., 2021) (Figure 1).

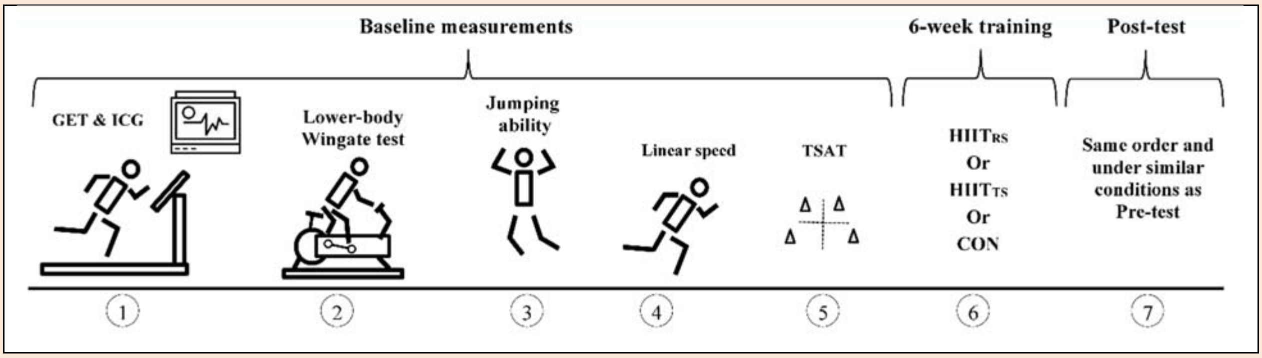

Figure 1. Overview of the experimental protocol. ICG = impedance cardiography; GET = graded exercise test; TSAT = taekwondo-specific agility test; $HIIT_{TS}$ = technique-specific HIIT; $HIIT_{RS}$ = HIIT based on repeated sprint. Numbers in circles denote sequences of testing procedure and training period.

Participants

The sample size was calculated using G*Power software (Faul et al., 2007), and with the assuming effect size of 0.8, β of 0.08, and an alpha level of 0.05 (Liu and Wang., 2023; Dai and Xie, 2023), 10 participants were determined for each group. Thirty provincial-level male taekwondo athletes (age = 19.8 ± 1.3 years; body mass = 75.4 ± 9.1 kg; height = 173 ± 6.1 cm) provided their written informed consent and voluntarily participated in this experiment. Participants were randomly assigned to two experimental groups: $HIIT_{TS}$ (n = 10) and $HIIT_{RS}$ (n = 10), as well as one control group [CON (n = 10)]. The inclusion criteria were having more than five years of taekwondo experience, training at least three sessions per week, and being free of any injury or disorder. All study procedures conformed to the Code of Ethics of the World Medical Association (Declaration of Helsinki), and the ethics committee of the ,University of Guilan reviewed and approved all procedures.

Graded exercise test

Participants completed a maximal incremental test on a treadmill (Technogym, Cesena, Italy) to evaluate aerobic fitness and related physiological parameters. Following a standardized warm-up, the participants commenced the test with the initial velocity of 8 $km \cdot h^{-1}$, incrementally increasing by 1 $km \cdot h^{-1}$ every 3 minutes until exhaustion. Stages were separated by 30 s rest intervals for the determination of blood lactate (Lactate Scout+, SensLab, Leipzig, Germany) through blood sampling from the earlobe. A MetaLyzer breath-by-breath gas collection system (3B-R2, Cortex, Germany) continuously measured physiological parameters, and $\dot{V}O_{2max}$, $\dot{V}O_2$/HR, first and second ventilatory threshold were determined according to the standard criteria (Sheykhlouvand et al., 2015; Fereshtian et al., 2017; Sheykhlouvand and Forbes, 2018; Alejo et al., 2022). $\dot{V}O_{2max}$ was verified if at least three of the following criteria were met: a) plateau or a slight drop in $\dot{V}O_2$ despite increasing workload; B) respiratory exchange ratio (RER) exceeding 1.1; C) attaining ≥ 90% age-predicted heart rate; D) blood lactate concentration reaching 8 mmol/L; E) visible exhaustion. 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 $\dot{V}_E/\dot{V}CO_2$ (Sheykhlouvand and Gharaat, 2024). Also, a transthoracic electrical impedance cardiograph (PhysioFlow®, Manatec, France) evaluated cardiac hemodynamics by assessing stroke volume (SV) and cardiac output ($\dot{Q}_{max}$). Previous research has validated this method as a reliable way to assess cardiac hemodynamics at rest and exercise up to $\dot{V}O_{2max}$ (Charloux et al., 2000; Richard et al., 2001). The procedure involved adhering to the manufacturer's guidelines, positioning two electrodes on the neck, two on the xiphoid sternum, and one on each side of the chest (Charloux et al., 2000). Following a 20-s calibration, cardiac hemodynamics were continuously measured during the graded exercise test, and SV and $\dot{Q}_{max}$ were recorded at the termination of the test, where $\dot{V}O_{2max}$ was obtained.

Lower-body anaerobic Wingate test

A 30-s anaerobic Wingate test on a cycle ergometer (model 894E, Monark, Sweden) evaluated participants' peak power output (PPO) and average power output (APO). PPO was the highest wattage attained during the 30s Wingate and APO was the average of the power output over the 30s duration. At the beginning of the test, the participants were asked to pedal against the inertial resistance of the ergometer as fast as possible. Subsequently, after reaching a threshold of 110/120 RPM a resistance equal to 0.075 kg per every kg of body mass was added, and the electronic revolution counter was initiated. A verbal encouragement was given during the test, and PPO and APO were calculated using the device's software.

Vertical jump

SJ and CMJ tests evaluated vertical jump performance using a Globus electronic contact mat system (Codognè, Italy), determining maximum reach height with a precision of 0.01 m. During the SJ, the participants placed hands on their hips, kept shoulders and feet wide apart, and flexed their knees to about a 90-degree angle for a duration of 3-sec, followed by executing a vertical jump with maximum effort (Ramírez-Campillo et al., 2013). During CMJ, participants were directed to place their hands on hips, stand with their feet and shoulders spaced wide apart, and execute a downward motion (with no limitation on the knee angle achieved) before launching into a maximum-effort vertical jump (Ojeda-Aravena et al., 2021a). Landing in an upright position and bending knees after landing were instructed, and each participant completed three trials of this task, with rest intervals of ~ 60 seconds between each trial. The best-performing trial among the three attempts was selected for subsequent statistical analysis.

Linear speed

After a comprehensive warm-up and two familiarization practice trials at half speed, participants performed two consecutive 20-meter sprint tests on an indoor running track with PolyFlex multipurpose sports flooring. Each sprint was separated by a 3-minute rest period to evaluate linear speed. Participants were encouraged to run between electronic timing gates as fast as possible. A self-selected start time was chosen, and the time was measured to the nearest 0.01 seconds (Freelap BLE 424, USA). The trial that demonstrated the highest level of performance was chosen for the subsequent statistical analysis.

Taekwondo-specific agility test

TSAT was completed according to Chaabene and colleagues (2018) (Figure 2). Briefly, in this test, starting from a guard position with both feet behind a designated line, the participant had a series of tasks to complete as follows:

(a) Move forward while maintaining the guard position, making sure not to cross their feet, and reach the center point as quickly as possible. (b) Once at the center point, turn towards the first partner using a lateral shift and execute a roundhouse kick with their left leg (known as a leading roundhouse kick or "dollyo-chagi"). (c) After kicking the first partner, move towards the second partner and execute another roundhouse kick, this time with their right leg (again, a leading roundhouse kick or "dollyo-chagi"). (d) Return to the center point. (e) Move forward in the guard position and execute a double-roundhouse kick (referred to as "narae-chagi") toward partner 3. (f) Finally, move backward to the start/finish line while maintaining the guard position (Figure 2). During the test, partners 1 and 2 held one kick-target each, while partner 3 held two kick-targets. These targets were to be maintained at torso height. If a participant deviated from these instructions, such as crossing their feet during movement or not delivering a strong kick to the targets, the trial was stopped and restarted after a 3-minute rest period. The time to complete the test was recorded as the performance outcome using an electronic timing system (Chaabene et al., 2018).

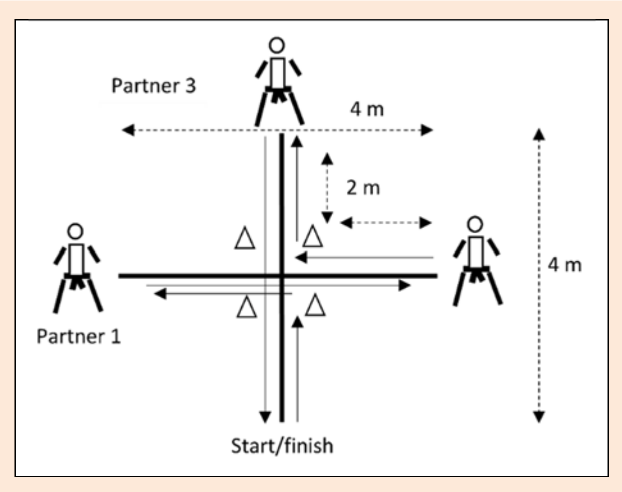

Figure 2. Graphic representation of the taekwondo-specific agility test (TSAT).

HIIT protocols

Forty-eight hours after the baseline measurements, participants commenced the six-week training period comprising only three sessions per week of regular taekwondo training in conjunction with $HIIT_{TS}$ and $HIIT_{RS}$. All groups started their training session with a 10-minute general warm-up consisting of jogging, joint mobility movements, and dynamic flexibility, followed by kicks and blows directed to an impact shield and a low-intensity taekwondo combat simulation. Afterward, athletes worked in pairs for 20 minutes to execute a technical sequence comprising front, spinning, and circular kicks using a speed paddle (Ojeda-Aravena et al., 2021a; Aravena Tapia et al., 2022). During the main part of training, which lasts approximately 30 minutes, the participants completed adapted fights with a focus on technical specifications and tactical guidance, including defense, spatial positioning, technical maneuvers, and offensive and defensive scenarios (Ojeda-Aravena et al., 2021a). Following the 60-minute training, participants of $HIIT_{TS}$ completed 3 sets of 10 × 4 s *all-out* repeated kicks with both legs, with 15 s passive recovery between efforts and one minute rest between sets. $HIIT_{RS}$ completed the same sets and repetitions as $HIIT_{TS}$ but *all-out* running instead of repeated kicks. To monitor the training load, the rating of perceived exertion (RPE) was recorded using the Borg 0-10 RPE Scale (Borg, 1982). During the HIIT training period, which lasted ~ 9 minutes, participants of the CON group continued their regular taekwondo training.

Statistical analyses

The data are presented as mean ± SD. Shapiro-Wilk test examined the normality of distribution, and the homogeneity of variances was assessed using Leven's test. A group ($HIIT_{TS}$, $HIIT_{RS}$, and CON) × time (pre-training vs. post-training) analysis of variance (ANOVA) analyzed the significant interactions or main effect with the Tukey *post-hoc* test when a significant F-ratio was observed. Individual percent changes over time were calculated for each variable, and the coefficient of variations was determined as the ratio of SD to mean group percent changes. In addition, individual residuals in percent changes were calculated as the squared root of the squared difference between the individual percent change and the mean percent change for each tested variable, and a one-way ANOVA compared the group mean residuals for each intervention to determine the effects of HIIT interventions on inter-subject variability in the measured parameters. Effect sizes (ES) were also calculated using Cohen's *d*. The magnitude of the ES was trivial <0.20; small, 0.20-0.50; medium, 0.5-0.80; large, 0.8-1.30; or very large >1.30. Calculation of two-technical error (TE) according to an equation ($TE = SD_{diff} / \sqrt{2}$) established by Hopkins (2000) determined responders (Rs) and non-responders (NRs) to the interventions. According to Hopkins (2000), a change exceeding 2 × TE strongly suggests a substantial likelihood (with odds of 12 to 1) that this response represents a genuine physiological adaptation beyond what could reasonably be attributed to technical or biological fluctuations. NRs were defined as individuals who were unable to demonstrate an increase or decrease (in favor of beneficial changes) in the measured variables that were greater than twice the TE away from zero. TEs were as follows [$\dot{V}O_{2max}$, 0.612 ($ml \cdot kg^{-1} \cdot min^{-1}$) × 2; $\dot{V}O_2$/HR, 0.289 ($ml \cdot b^{-1} \cdot min^{-1}$) × 2; VT_1, 1.489 (%) × 2; VT_2, 1.491 (%) × 2; $\dot{Q}_{max}$, 0.335 ($l \cdot min^{-1}$); SV, 2.564 ($ml \cdot beat^{-1}$) × 2; PPO, 24.633 (W) × 2; MPO, 28.875 (W) × 2; SJ, 0.669 (cm) × 2; CMJ, 0.722 (cm) × 2; 20-m sprint, 0.047 (s) × 2; and TSAT, 0.081 (s) × 2. The Chi-Square test (X^2) was applied to compare groups of participants who fell within the 2 × TE range calculated for each outcome (NRs) or exceeded it by more than two times the TE (Rs). Statistical analyses were carried out using SPSS software, version 25.0 (IBM Corp., Chicago, IL), and the alpha level was set at 0.05.

Results

No between-group differences were noted in the measured variables at baseline. Tables 1 and 2 present mean group changes from pre- to post-training in response to different interventions, and Figures 3 and 4 indicate individual changes and between-group differences in percent changes over time.

Cardiorespiratory fitness measures

Both $HIIT_{RS}$ and $HIIT_{TS}$ significantly enhanced $\dot{V}O_{2max}$ (*d* = 1.16 and 0.67, respectively), $\dot{V}O_2$/HR (*d* = 0.51 and

0.36), VT_1 (d = 2.31 and 1.07), VT_2 (d = 0.93 and 0.78), $\dot{Q}_{max}$ (d = 0.78 & 0.62), and SV (d = 0.89 & 0.60) significantly enhanced in both HIIT groups over time (Table 1). A significant time regimen interaction was found in $\dot{V}O_{2max}$ ($F_{2, 27}$ = 26.9; p = 0.003; η^2 = 0.66), $\dot{V}O_2$/HR ($F_{2, 27}$ = 61.1; p = 0.001; η^2 = 0.82), VT_1 ($F_{2, 27}$ = 12.6; p = 0.007; η^2 = 0.44), VT_2 ($F_{2, 27}$ = 13.7; p = 0.007; η^2 = 0.48), $\dot{Q}_{max}$ ($F_{2, 27}$ = 14.1; p = 0.006; η^2 = 0.51), and SV ($F_{2, 27}$ = 11.6; p = 0.008; η^2 = 0.41). As shown in Table 1 and Figure 3, $HIIT_{RS}$ resulted in greater changes compared to $HIIT_{TS}$ and CON groups in $\dot{V}O_{2max}$ (p = 0.02 and 0.001, respectively), $\dot{V}O_2$/HR (p = 0.008 and 0.003, respectively), VT_2 (p = 0.006 and 0.006, respectively), and $\dot{Q}_{max}$ (p = 0.01 and 0.001, respectively). Also, the change in VT_1 and SV in response to $HIIT_{RS}$ was significantly (p = 0.02 and 0.002, respectively) greater than the CON group.

Bio-motor abilities

After the 6-week training period, both $HIIT_{RS}$ and $HIIT_{TS}$ groups and the CON group showed significantly greater values for PPO (d = 0.54, 0.48, & 0.42, respectively), APO (d = 1.52, 1.21, & 0.58), SJ (d = 1.49, 0.87, & 0.83), and CMJ (d = 1.56, 0.73, & 0.61) than baseline values. However, 20-m sprint speed and TSAT significantly enhanced only in response to $HIIT_{RS}$ (d = 0.72 and 0.58) intervention (Table 2 and Figure 4).

Table 1. Changes in cardiorespiratory fitness in response to $HIIT_{RS}$, $HIIIT_{TS}$, and CON.

	$HIIT_{RS}$		$HIIT_{TS}$		CON	
	Pre	Post	Pre	Post	Pre	Post
$\dot{V}O2max$ (ml·kg^{-1}·min^{-1})	48.8 ± 2.5	† 51.9 ± 2.8	46.4 ± 3.0	† 48.5 ± 3.2	46.6 ± 2.9	47.1 ± 3.2
P-value	0.0004		0.04		0.2	
%Δ	6.4 ‡'§		4.6		1.0	
$\dot{V}O_2$/HR (ml·b^{-1}·min^{-1})	19.9 ± 2.9	† 21.4 ± 3.0	18.3 ± 1.6	† 18.9 ± 1.7	19.7 ± 2.4	19.8 ± 2.2
P-value	0.002		0.03		0.2	
%Δ	7.5 ‡'§		3.2		0.6	
VT1 (%$\dot{V}O_2$max)	69.2 ± 3.0	† 76.2 ± 2.9	71.2 ± 3.9	† 75.4 ± 3.9	70.1 ± 3.2	71.0 ± 2.6
P-value	0.0001		0.02		0.1	
%Δ	10.1 §		5.9		1.2	
VT_2 (%$\dot{V}O_2$max)	86.1 ± 5.2	† 90.8 ± 4.8	81.2 ± 3.6	† 84.1 ± 3.8	82.2 ± 2.7	83.0 ± 3.0
P-value	0.0002		0.001		0.2	
%Δ	5.4 ‡'§		3.6		0.9	
$\dot{Q}$max (l·min^{-1})	23.1 ± 1.8	† 24.6 ± 2.0	21.5 ± 1.5	† 22.5 ± 1.7	22.6 ± 1.9	22.6 ± 1.7
P-value	0.0003		0.03		0.8	
%Δ	6.5 ‡'§		4.6		0.0	
SV (ml·beat^{-1})	131 ± 10.0	† 140 ± 10.1	128 ± 7.7	† 133 ± 9.2	132.9 ± 12.2	135.4 ± 11.8
P-value	0.0001		0.02		0.4	
%Δ	6.8 §		3.9		1.8	

Values are means ± SD. $\dot{V}O_{2max}$, maximum oxygen uptake; $\dot{V}O_2$/HR, O_2 pulse; VT_1, first ventilatory threshold; VT_2, second ventilatory threshold; $\dot{Q}_{max}$, maximal cardiac output; SV, stroke volume. N = 10 for each group.† Significantly greater than pre-training value (P < 0.05). ‡ Significantly greater than $HIIT_{TS}$ group; § Significantly greater than CON group.

Table 2. Changes in bio-motor abilities in response to $HIIT_{RS}$, $HIIIT_{TS}$, and CON.

	$HIIT_{RS}$		$HIIT_{TS}$		CON	
	Pre	Post	Pre	Post	Pre	Post
PPO (W)	911 ± 143	† 995 ± 168	861 ± 119	† 919 ± 122	899 ± 111	† 958 ± 129
P-value	0.0001		0.006		0.02	
%Δ	9.2		6.7		6.5	
APO (W)	590 ± 65	† 680 ± 82	587 ± 44	† 659 ± 50	611 ± 59	† 643 ± 51
P-value	0.0003		0.001		0.01	
%Δ	15.2		12.2		5.2	
SJ (cm)	38.5 ± 1.6	† 41.2 ± 2.0	38.6 ± 2.2	† 40.4 ± 2.1	39.0 ± 1.9	† 40.7 ± 2.0
P-value	0.0009		0.003		0.03	
%Δ	7.0		4.6		4.3	
CMJ (cm)	41.2 ± 1.8	† 44.1 ± 1.9	41.1 ± 2.2	† 42.7 ± 2.4	41.4 ± 2.2	† 43.1 ± 2.4
P-value	0.0003		0.0004		0.001	
%Δ	7.0		3.8		4.1	
20-m sprint (s)	3.20 ± 0.19	† 3.07 ± 0.17	3.16 ± 0.25	3.14 ± 0.24	3.17 ± 0.21	3.13 ± 0.19
P-value	0.0001		0.11		0.55	
%Δ	–4.2		–0.6		–1.2	
TSAT (s)	5.6 ± 0.4	† 5.3 ± 0.3	5.5 ± 0.6	5.3 ± 0.4	5.5 ± 0.5	5.4 ± 0.3
P-value	0.0001		0.09		0.66	
%Δ	–5.6		–3.7		–1.8	

Values are means ± SD. PPO, peak power output; APO, average power output; SJ, squat jump; CMJ, countermovement jump; TSAT, taekwondo-specific agility test. N = 10 for each group.† Significantly greater than pre-training value (P < 0.05).

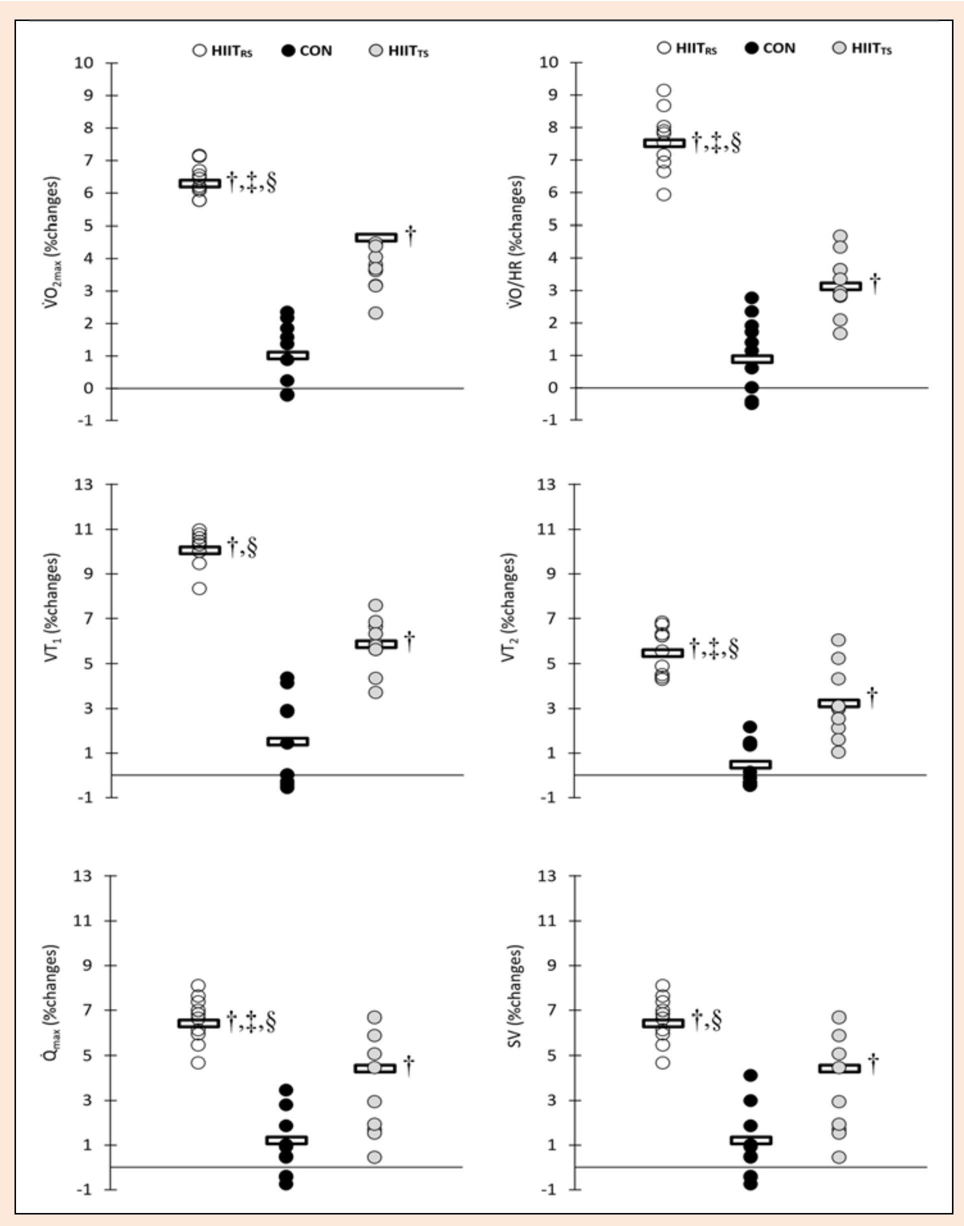

Figure 3. Individual changes in maximum oxygen uptake ($\dot{V}O_{2max}$), O_2 pulse ($\dot{V}O_2/HR$), first ventilatory threshold (VT_1), second ventilatory threshold (VT_2), cardiac output ($\dot{Q}_{max}$), and stroke volume (SV) in response to $HIIT_{RS}$, $HIIT_{TS}$, or CON. The percent changes from baseline (X-axes) are indicated by circles and horizontal bars represent the group mean response. † Significantly greater than pre-training value ($P < 0.05$). ‡ Significantly greater than $HIIT_{TS}$ group; § Significantly greater than CON group.

Inter-individual variability in the adaptations

Figure 5 illustrates individual and the percent of group non-responders in measured variables to the training interventions. Overall, the $HIIT_{RS}$ group showed only 30 % non-responders in PPO. By contrast, all measured variables consisted of non-responders to $HIIT_{TS}$, ranging between 20-100% (Figure 5). X^2 test indicated more responders to $HIIT_{RS}$ than $HIIT_{TS}$ in $\dot{V}O_{2max}$ ($p = 0.05$), $\dot{V}O_2/HR$ ($p = 0.01$), VT_2 ($p = 0.02$), $\dot{Q}_{max}$ ($p = 0.02$), SV ($p = 0.02$), APO ($p = 0.05$), SJ ($p = 0.01$), CMJ ($p = 0.02$), 20m-sprint ($p = 0.008$), and TSAT ($p = 0.05$).

No significant time-regimen interaction was observed for the residuals in measured variables. However, inter-individual variability (CV) for the changes in measured variables following $HIIT_{RS}$ was lower than $HIIT_{TS}$ (Figure 6).

Rate of perceived exertion (RPE)

RPE over the training sessions for $HIIT_{RS}$ (9.11 ± 0.54) and $HIIT_{TS}$ (8.95 ± 0.75) indicated both groups completed the interventions at maximal intensity.

Discussion

This study compared the individual adaptive responses to running-based sprint-type HIIT ($HIIT_{RS}$) with taekwondo-specific HIIT ($HIIT_{TS}$) on measures of cardiorespiratory fitness and anaerobic power in trained taekwondo athletes. The most remarkable findings of the present study were that both $HIIT_{RS}$ and $HIIT_{TS}$ interventions significantly enhanced aerobic and anaerobic power. However, $HIIT_{RS}$ resulted in significantly greater improvements in cardiorespiratory fitness adaptations, more individual responders, and lower inter-individual variability across the participants, than $HIIT_{TS}$.

Previous studies have indicated the predominance of cardiorespiratory fitness in taekwondo performance (Chaabène et al., 2012; Campos et al., 2012; Chaabene et al., 2017) and its vital effects on the restoration of required substrates for intensive actions [particularly storage of creatine phosphate (Campos et al., 2012)]. Elevated levels of the first and second ventilatory thresholds (VT_1 and VT_2) also facilitates maintaining higher proportions of $\dot{V}O_{2max}$ over extended durations, aiding athletes in postponing fatigue (Stolen et al., 2005; Forbes and Sheykhlouvand, 2016; Dolci et al., 2020; Laursen and Buchheit, 2019). Six weeks of $HIIT_{RS}$ and $HIIT_{TS}$ significantly enhanced $\dot{V}O_{2max}$ and first and second ventilatory thresholds. An increase in both the delivery of oxygen [central (Sheykhlouvand et al., 2016a; 2016b; 2018a) and the use of oxygen by active muscles (peripheral) can lead to improvements in cardiorespiratory fitness (Sheykhlouvand et al., 2022; Sayevand et al., 2022; Liu and Wang, 2023; Dai and Xie, 2023; Gharaat et al., 2020b). One potential explanation for the rise in aerobic fitness in our study's participants may be their improved cardiac function explaining enhanced central component of aerobic fitness. This improvement can be corroborated by the enhanced $\dot{V}O_2$/HR, $\dot{Q}_{max}$, and SV_{max} observed in the HIIT groups (Sheykhlouvand et al., 2024; Gharaat et al., 2024). As we hypothesized, more significant changes in aerobic fitness and cardiac hemodynamics ($\dot{Q}_{max}$, and SV_{max}) in response to $HIIT_{RS}$ than $HIIT_{TS}$ could be attributed to higher mechanical stress, work rate, and physiological demands imposed by sprint-type HIIT.

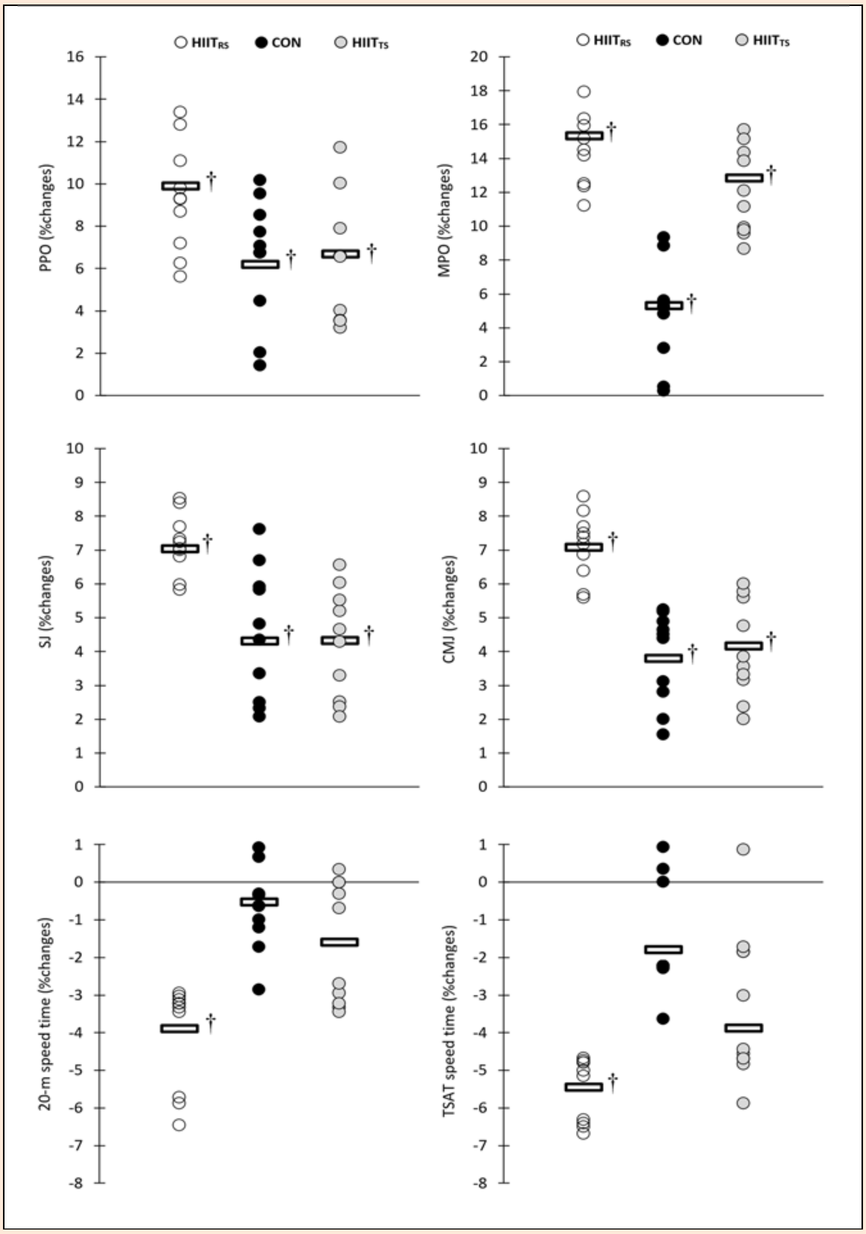

Figure 4. Individual changes in peak power output (PPO), average power output (APO), squat jump (SJ), countermovement jump (CMJ), linear speed (20-m speed time), and taekwondo-specific agility test (TSAT) in response to $HIIT_{RS}$, $HIIT_{TS}$, or CON. The percent changes from baseline (X-axes) are indicated by circles and horizontal bars represent the group mean response. † Significantly greater than pre-training value ($P < 0.05$).

A

HIIT$_{RS}$	Individual response										
	1	2	3	4	5	6	7	8	9	10	NR (%)
$\dot{V}O_{2max}$ (ml·kg^{-1}·min^{-1})	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	0
$\dot{V}O_2$/HR (ml·b^{-1}·min^{-1})	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	0
VT_1 (%)	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	0
VT_2 (%)	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	0
$\dot{Q}_{max}$ (l·min^{-1})	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	0
SV (ml·b^{-1})	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	0
PPO (W)	↑	↑	↑	↑	↑	→	→	↑	↑	→	**30 %**
MPO (W)	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	0
SJ (cm)	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	0
CMJ (cm)	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	0
Speed (s)	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	0
TSAT (s)	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	0

B

HIIT$_{TS}$	Individual response										
	1	2	3	4	5	6	7	8	9	10	NR (%)
$\dot{V}O_{2max}$ (ml·kg^{-1}·min^{-1})	→	↑	↑	→	↑	→	↑	↑	→	↑	**40 %**
$\dot{V}O_2$/HR (ml·b^{-1}·min^{-1})	→	↑	↑	→	↑	↑	↑	→	↑	↑	**30 %**
VT_1 (%)	↑	↑	→	↑	↑	↑	→	↑	↑	↑	**20 %**
VT_2 (%)	→	→	→	↑	↑	↑	↑	↑	↑	→	**40 %**
$\dot{Q}_{max}$ (l·min^{-1})	→	↑	↑	→	↑	↑	↑	↑	→	→	**40 %**
SV (ml·b^{-1})	↑	→	↑	→	↑	↑	→	→	↑	↑	**40 %**
PPO (W)	↑	↑	→	→	↑	↑	→	↑	↑	→	**40 %**
MPO (W)	→	↑	→	↑	↑	↑	↑	↑	→	↑	**30 %**
SJ (cm)	→	↑	↑	→	↑	→	↑	↑	→	↑	**40 %**
CMJ (cm)	→	↑	↑	→	→	↑	↑	↑	→	↑	**40 %**
Speed (s)	→	→	↓	→	→	→	→	→	→	↓	**100 %**
TSAT (s)	→	↑	↑	↑	↑	↑	↑	→	↑	→	**30 %**

C

CON	Individual response										
	1	2	3	4	5	6	7	8	9	10	NR (%)
$\dot{V}O_{2max}$ (ml·kg^{-1}·min^{-1})	↑	↓	→	→	→	→	↓	→	→	↓	**90 %**
$\dot{V}O_2$/HR (ml·b^{-1}·min^{-1})	→	↓	→	→	→	→	↓	→	→	↑	**90 %**
VT_1 (%)	→	→	→	→	→	→	↓	↓	→	↓	**100 %**
VT_2 (%)	↓	→	↓	→	→	↓	↓	↑	→	↑	**80 %**
PPO (W)	↑	↑	→	↑	↑	↓	↓	↑	↑	↑	**30 %**
MPO (W)	↑	→	→	→	↓	→	↑	→	↓	→	**80 %**
Speed (s)	→	↑	↑	→	↑	→	↑	↑	↑	↑	**30 %**
COD (s)	→	↑	↑	→	↑	→	↑	↑	→	↑	**40 %**
SJ (cm)	↓	→	→	→	→	→	→	→	→	→	**100 %**
CMJ (cm)	→	↓	→	↓	↓	↓	→	↓	↓	→	**100 %**

Figure 5. Individual patterns of response to HIIT$_{RS}$, HIIT$_{TS}$, or CON. ↑ denote responders (white boxes); → denote non-responders (grey boxes), and ↓ indicate adverse responses (black boxes). The percentage of participants demonstrate non-responders including both non- and adverse responses.

Anaerobic fitness is also an important feature for developing taekwondo performance because kicks and punches are applied with high-intensity movement (da Silva Santos et al., 2018). Our results indicated the effectiveness of HIIT interventions and typical taekwondo training in improving Wingate anaerobic power and vertical jump, with the latter representing muscular power. Our findings corroborate previous studies indicating the effectiveness of repeated sprint HIIT (Ojeda-Aravena et al., 2021b; Monks et al., 2017) and taekwondo-specific HIIT (Ouergui et al., 2020; Ojeda-Aravena et al., 2021a) on these parameters. However, linear speed and TSAT only improved in response to HIIT$_{RS}$, which could be attributed to the repeated generation of sprints during this intervention. Exercising at all-out intensities requires the maximal contribution of the anaerobic metabolic pathway and stimulates mechanisms involved in enhancing this metabolic pathway. On the other hand, mechanical stress imposed on the body contributes to elevated anaerobic performance (Dolci et al., 2020; Hoffmann et al., 2020; Sheykhlouvand et al., 2018b). Possible explanations for enhanced anaerobic power could be elevated discharge rate and recruitment of high-threshold motor units (Dolci et al., 2020), increased total creatine content of active muscles (Hoffmann et al., 2020), and enhanced buffering capacity of muscles (Sheykhlouvand et al., 2018b).

Another important finding of this study was lower inter-individual variability in adaptive responses to HIIT$_{RS}$ than HIIT$_{TS}$. HIIT$_{RS}$ resulted in a lower coefficient of variation in mean percent change in all measured variables than HIIT$_{TS}$ (Figure 6). Also, the percentage of responders to HIIT$_{RS}$ was higher than HIIT$_{TS}$ (Figure 3). In terms of CV, studies have indicated creating consistent levels of mechanical stress through precisely designed interventions according to the athlete's ceilings ensures the same degrees of physiological demands and more uniform adaptations across athletes with varying profiles (Sandford et al., 2021; Du and Tao, 2023; Wang and Zhao, 2023). According to our outcomes, we can speculate performing running-based HIIT with *all-out* intensity engages almost the total physiological capacity (100%) of individuals and facilitates the same levels of adaptations among athletes with different ceilings. Repeated kicks recruit different proportions of physiological capacities and metabolic demands and cause greater inter-individual variability in physiological adaptations. In other words, despite the same training time and frequency, protocols with different metabolic demands may result in varied individual adaptations. Consistent with previous studies indicating heterogeneity in the individual response to $HIIT_{TS}$ (Ojeda-Aravena et al., 2021a; 2021b) we observed significant rates of non-responders to such intervention. These results validate the idea that individuals who do not respond to a particular exercise regimen may undergo adaptation when exposed to a different protocol (Bouchard et al., 2012), potentially due to different sensitivities to training volume (Sisson et al., 2009) and/or intensity (Ross et al., 2015). It reinforces the idea of incorporating various training protocols when designing exercise plans and suggest if someone initially does not respond to a specific exercise prescription, they might experience a more positive response if an alternative training method is recommended (Bonafiglia et al., 2016).

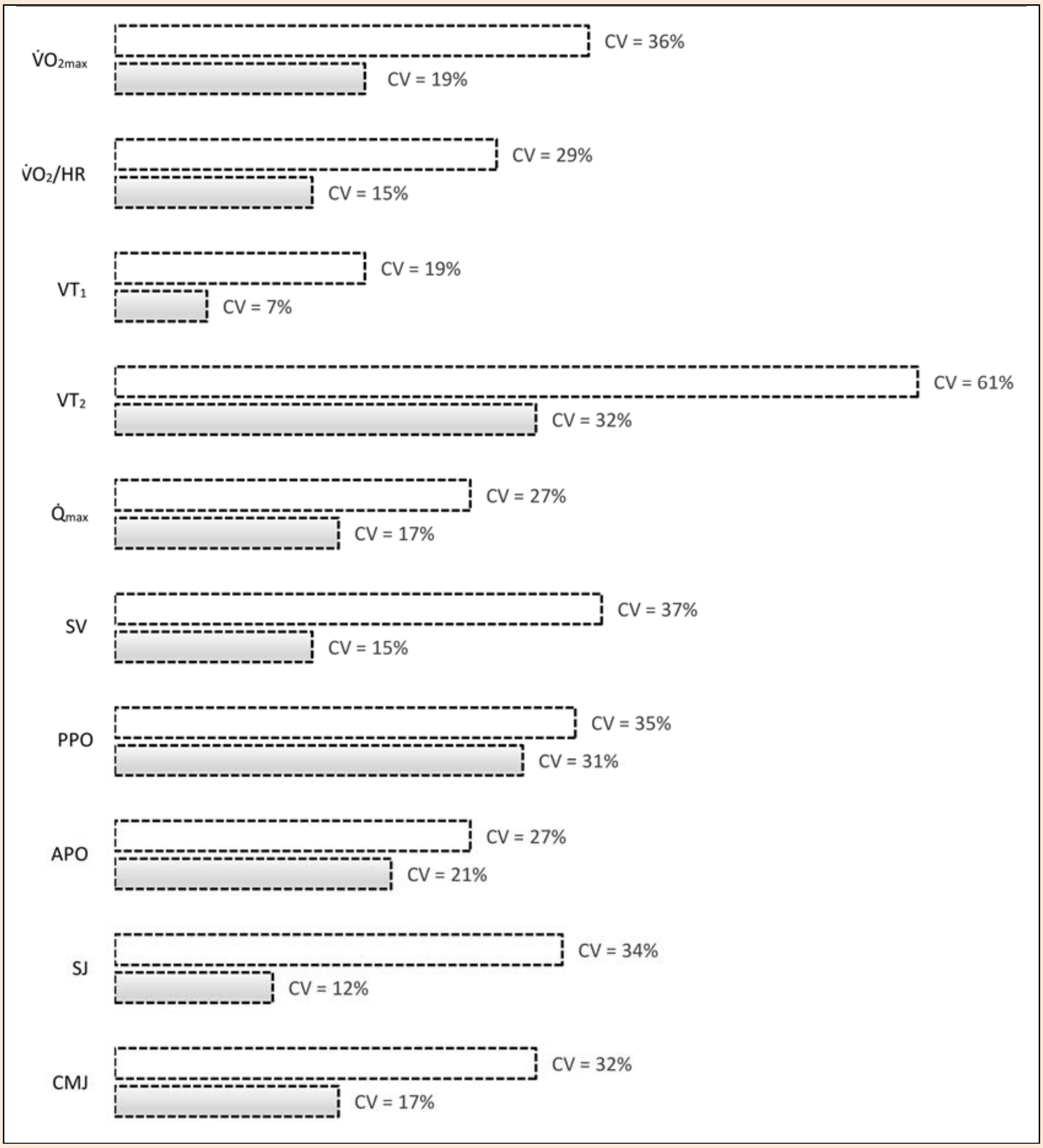

Figure 6. The inter-individual variation (CV) of percent changes in maximum oxygen uptake ($\dot{V}O_{2max}$), O_2 pulse ($\dot{V}O_2$/HR), first ventilatory threshold (VT_1), second ventilatory threshold (VT_2), cardiac output ($\dot{Q}_{max}$), and stroke volume (SV), peak power output (PPO), average power output (APO), squat jump (SJ), and countermovement jump (CMJ) in response to $HIIT_{RS}$ (gray bars) and $HIIT_{TS}$ (white bars).

A limitation of this study was the difficulty in rigorously overseeing the dietary practices of athletes during training. Furthermore, our participant cohort was comprised solely of men, preventing the extension of our results to women involved in taekwondo. It's important to note that our results are specific to the particular HIIT protocols employed in our study, and we cannot ascertain whether comparable adaptations would manifest with different volumes of HIIT, whether higher or lower. It is recommended that future research endeavors explore protocols with diverse training loads and intensities to enhance our understanding of the subject matter further. Additionally, extending the study to encompass various age categories and genders would contribute valuable insights, allowing for a more comprehensive evaluation of the implications. Furthermore, it is suggested that future investigations consider measuring other parameters, such as different hormonal adaptations, to provide a more holistic perspective on the physiological responses to the varied aspects of training.

Conclusion

In conclusion, the current study compared the effects of $HIIT_{RS}$ and $HIIT_{TS}$ interventions on cardiorespiratory fitness and anaerobic power, as well as individual responses to these protocols performed over six weeks. While both training protocols significantly improved aerobic and anaerobic power, $HIIT_{RS}$ resulted in significantly greater improvements in cardiorespiratory fitness compared to $HIIT_{TS}$. Also, noticeable variation was observed in the individual responses and adaptations following $HIIT_{TS}$, including the percentage of non-responders. Additionally, $HIIT_{RS}$ elicited lower inter-individual variability (CV) in percent changes from pre- to post-training.

Acknowledgements

The experiments comply with the current laws of the country in which they were performed. The authors have no conflict of interest to declare. The datasets generated during and/or 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

- High-intensity technique-specific interval intervention sufficiently stimulates adaptive mechanisms responsible for enhancing aerobic and anaerobic power in taekwondo athletes.
- However, engaging in HIITRS leads to significantly greater improvements in cardiorespiratory fitness compared to technique-specific HIIT.
- HIITRS results in more consistent adaptations than HIITTS across individuals.

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