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Research article

Sequencing Effects of Concurrent Resistance and Short Sprint Interval Training on Physical Fitness, and Aerobic and Anaerobic Performance of Karate Athletes

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Abstract

This study aimed to evaluate the effects of an 8-week concurrent training (CT) program that combined short sprint interval training (sSIT) and resistance training (RT) in alternating sequences (i.e., sSIT + RT or RT + sSIT) on the physical fitness, aerobic capacity, and anaerobic performance of male karate athletes, in comparison to each training intervention conducted independently. Forty national-level young male athletes volunteered to participate in this study and were divided into sSIT, RT, sSIT + RT, RT + sSIT, and active control (CG) groups, each group consisted of eight athletes and performed 3 days of weekly training intervention including 4 sets of 5 repetitions of 5 seconds of all-out running for sSIT program and also back squats, leg presses, seated knee flexions, and calf raises for 3 sets of 6 - 12 repetition maximum for the RT intervention. After the intervention, the sSIT, RT, sSIT + RT and RT + sSIT groups demonstrated improvements in the counter-movement vertical jump (CMVJ) (effect size [ES] = 0.64, 0.88, 1.58, 1.55), 20-m sprint (ES = -0.82, -0.62, -1.10, -1.16), 4 × 9-m shuttle run (ES = -0.62, -0.35, -1.15, -0.89), strength (ES = 0.19, 0.44, 0.34, 0.43), peak (ES = 1.27, 0.73, 1.80, 1.53), and mean power output (ES = 0.87, 0.54, 1.37, 1.11), as well as in comparison to the CG ($p < 0.05$), respectively. Additionally, improvements in aerobic performance were observed in the sSIT, sSIT + RT, and RT + sSIT groups (ES = 0.75, 0.92, 0.62) after the training intervention, and in comparison to CG ($p < 0.05$), while the RT group did not show significant changes post-training. By comparing the CT groups, no sequencing effects were observed in the adaptations of variables between the sSIT + RT vs. RT + sSIT groups. In conclusion, this study's findings demonstrate that sSIT, RT, and CT with different orders have a positive impact on inducing adaptations in physical fitness, aerobic and anaerobic performance. Additionally, combining sSIT and RT resulted in further adaptations in karate athletes without any differences between CT groups.

Key words: Strength training, explosive and anaerobic power, combat sport.

Introduction

Karate is a martial art and combat sport which divided into two main components: Kata and Kumite (Chaabene et al., 2019). Kumite, the competitive aspect of karate, involves sparring between two opponents with the goal of scoring points by striking specific areas of the body (i.e., IPPON, WASSARI, and YUKO) (Arazi and Izadi, 2017). This type of karate requires both technical skills and physical fitness such as muscular strength and power (Ojeda-Aravena et al., 2021). Additionally, aerobic power, including maximum oxygen consumption ($\dot{V}O_{2max}$), plays a vital role in karate performance by preventing fatigue during training as well as facilitating proper recovery between combats (Chaabene et al., 2019). Furthermore, anaerobic performance is a crucial factor in a karateka's ability to perform at a high-level explosive actions, in addition to physical fitness and aerobic performance (Ioannides et al., 2020). According to the World Karate Federation guidelines, the main goal of a karate athlete is to score points through physical contact with the opponent, requiring the execution of high-intensity techniques (Chaabene et al., 2012).

In Kumite competitions, athletes participate in multiple matches with short breaks, involving two 3-minute rounds of intense defensive and offensive movements (Chaabene et al., 2012). To produce maximal performance in karate competitions, athletes must focus on improving physical fitness, aerobic and anaerobic performance to enhance specific kinetic patterns necessary for success (Imamura et al., 1998). Therefore, karate athletes (i.e., Kumite) need to follow a well-designed training program that targets physical fitness, aerobic and anaerobic performance to optimize their ability in combats (Chaabene et al., 2019).

Resistance training (RT) has been recognized as a valuable method for enhancing muscular strength and power performance (i.e., vertical jump) (Kraemer et al., 2002), while endurance training (ET) is beneficial for improving aerobic metabolic pathways (Jones and Carter, 2000). However, the limited training time in today's sports environment poses a challenge, as scheduling separate RT and ET can be difficult. To address this issue, strength and conditioning professionals are seeking ways to make training more time-efficient without compromising its quality (Gao and Yu, 2023). Consequently, many athletes now incorporate both RT and ET in the same session to enhance their physical fitness and optimize aerobic and anaerobic metabolic conditioning (Da Silva et al., 2020; Pito et al., 2022). This approach, known as concurrent training (CT), allows athletes to maximize their training time and effectiveness (Petré et al., 2018). Studies suggest that CT may provide greater advantages than concentrating exclusively on RT or ET (Cadore et al., 2012; 2013). Nevertheless, participation in CT can lead to an interference effect on strength and power adaptations, potentially impacting performance in physical fitness assessments (Cadore et al., 2012; 2013; Petré et al., 2018; Lee et al., 2020). Specifically, it seems that engaging in ET either before or after RT can adversely affect adaptations in strength, jump performance, and power output (Petré et al., 2018; Lee et al., 2020).

In order to minimize interference effects, it is recommended to adjust the sequence and type of exercises during CT (Fyfe et al., 2016). Previous research has shown that a 3-hour interval between RT and ET can help reduce

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interference effects on strength performance (Lee et al., 2020). However, modifying training variables (i.e., incorporation of sprint interval training [SIT] instead of continues ET) is also a viable option for reducing interference effects (Magill et al., 1990; Petré et al., 2018). On the other hand, incorporating SIT as a method of ET could prove to be an appropriate regimen for promoting adaptations in physical fitness, aerobic and anaerobic performance (Gist et al., 2014). More importantly, Boullosa et al., (2022) highlighted that engaging in short SIT (sSIT) with maximal effort or *all-out* condition may lead to greater improvements in physical performance and aerobic performance, making it an effective training method. Therefore, incorporating running based sSIT with all-out conditions compared with continuous running or other forms of ET (i.e., cycling) may help counteract negative effects on resistance exercise outcomes observed in previous research (Cadore et al., 2012; 2013; Fyfe et al., 2016; Petré et al., 2018; Lee et al., 2020).

The combination of sSIT and RT, known as sSIT + RT, is suggested as an effective strategy for improving physical fitness, aerobic and anaerobic performance, particularly beneficial for karate athletes aiming to enhance various aspects of performance during combats (Ojeda-Aravena et al., 2021; Cid-Calfucura et al., 2023). However, further research is needed to determine the most effective sequencing effects of sSIT and RT for optimizing adaptations in the physical fitness, aerobic and anaerobic performance among karate athletes. It remains unclear for karate athletes which combination of sSIT and RT (i.e., sSIT + RT or RT + sSIT) is suitable for optimizing adaptations in physical fitness, aerobic and anaerobic performance.

Apart from the potential influence of sequencing effects of sSIT and RT on performance adaptations, it is essential to monitor individual responses to training when incorporating a training program (Ojeda-Aravena et al., 2021). Previous studies that incorporated different forms and sequences of CT typically focused on reporting the average values of the groups (Da Silva et al., 2020; Pito et al., 2022; Gao and Yu, 2023), neglecting the individual responses to training. Conversely, it is important to consider the variability among subjects in their adaptive responses to training when recommending a training program. Therefore, it is crucial to ascertain the individual response to training in order to optimize adaptations to the training program. Unfortunately, there is a lack of research available on this subject, specifically analyzing inter-individualized responses to the combination of sSIT and RT following an 8-week training program. Moreover, there is a lack of certainty regarding whether the combination of sSIT and RT can effectively enhance the physical fitness, aerobic and anaerobic performance of karate athletes when compared to utilizing sSIT or RT alone (Tack, 2013; Yudhistira, 2023). Additionally, the optimal sequence for combining sSIT and RT remains unknown. It is crucial to address these gaps in knowledge in order to develop a more comprehensive understanding of the potential benefits and individualized responses associated with integrating sSIT and RT in the context of karate athletes. Therefore, the aim of this study was to assess the influence of an 8-week intervention involving sSIT, RT, and their combination (sSIT + RT or RT + sSIT) on the physical fitness, aerobic and anaerobic performance of male karate athletes.

Methods

Participants

A total of forty male karate athletes, competing at the national level in Kumite, and having a minimum of two years of experience in national competitions volunteered to participate in this study. They were matched based on their weight divisions and then randomly assigned to five groups: sSIT (n = 8), RT (n = 8), sSIT + RT (n = 8), RT + sSIT (n = 8), and an active control group (CG, n = 8) (Table 1). The athletes had prior knowledge of RT and various types of ET, such as continuous running and SIT, but did not engage in these activities for a minimum of 3 months prior to their involvement in the study. The athletes met the inclusion criteria by meeting the following conditions: (1) having over 5 years of karate training and 2 years of competitive experience; (2) engaging in continuous karate training for the past 2 years without any musculoskeletal injuries in the last 6 months; (3) no recent experience with RT and ET in the past 3 months; (4) not participating in competitive karate during the intervention period; (5) absence of potential musculoskeletal, neurological, or orthopedic conditions that could have affected their ability to engage in such training (Gharaat et al., 2025). Prior to the commencement of the study, all participants were extensively briefed on the research procedures, requirements, benefits, and risks, and they provided written consent after being fully informed. The study design obtained approval from the Ethics Committee of Nantong University and adhered to the ethical guidelines outlined in the Declaration of Helsinki for research involving human subjects. In order to investigate the effects of training intervention on the physical fitness adaptations of karate athletes, a sample size calculation was executed with G*Power software (Version 3.1.9.2, University of Kiel, Germany). The study primarily aimed to assess variations in physical fitness parameters, specifically the countermovement vertical jump as noted by Ojeda-Aravena et al. (2021). The data were analyzed using a two-way mixed-design ANOVA, with an effect size of 0.8, a power of 0.8, and a p-value threshold of 0.05. This calculation indicated an 80% likelihood of detecting the expected effect size, which required a minimum of eight participants per group to thoroughly evaluate the changes in the physical fitness of karate athletes.

Table 1. Subjects' characteristics (mean ± SD).

	sSIT	RT	sSIT+RT	RT+sSIT	CG
Age (y)	21.4 ± 2.2	21.7 ± 2.4	21.5 ± 2.8	21.6 ± 2.1	21.2 ± 2.4
Height (cm)	179.6 ± 6.1	180.1 ± 6.6	179.9 ± 5.7	181.2 ± 6.5	179.7 ± 5.8
Body mass (kg)	81.6 ± 12.3	82.5 ± 12.8	81.8 ± 11.9	80.7 ± 12.1	82.2 ± 13.7
Training age (y)	7.2 ± 2.6	7.6 ± 1.9	6.9 ± 1.5	7.2 ± 1.4	7.4 ± 1.8

sSIT = short sprint interval training, RT = resistance training, CG = concurrent training.

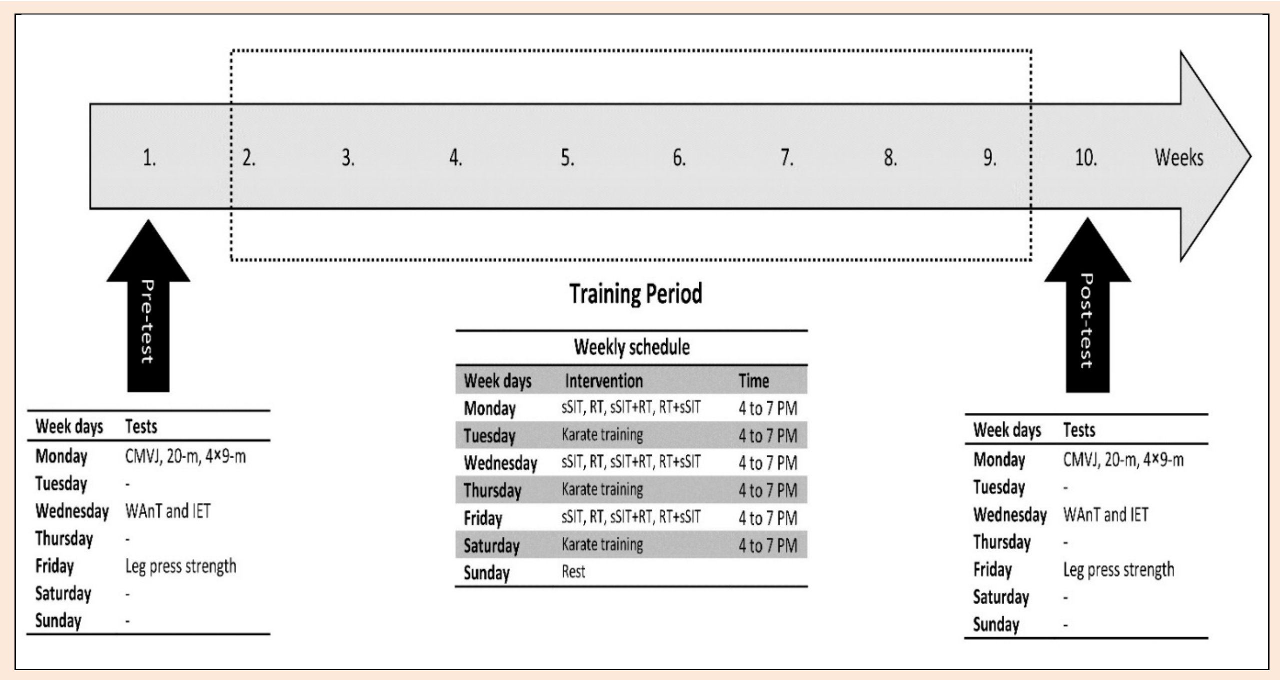

Figure 1. Experimental design. WAnT = Wingate anaerobic power test, IET = incremental exercise test, CMVJ= countermovement vertical jump, RT = resistance training, CG = concurrent training.

Experimental design

Utilizing a longitudinal study design, a comprehensive investigation was carried out over a 10-week period, encompassing pre-test and post-test assessments (Figure 1). This included 1 week of pre-intervention testing, an 8-week training program, and 1 week of post-intervention testing. The main objective was to evaluate inter-individual variability in adaptive responses and distinguish differences in RT, sSIT, sSIT + RT, and RT + sSIT programs. The study was structured as a randomized controlled trial, with group allocation based on computer-generated random numbers through R software (version 2.14, Foundation for Statistical Computing). Subjects were enlisted for three separate afternoon sessions (i.e., 4 to 7 PM), with a 48-hour recovery period, to measure countermovement vertical jump (CMVJ), 20-m sprint, 4×9-m shuttle run, leg press strength, Wingate anaerobic power test (WAnT), and incremental exercise test (IET).

Anthropometry

During the initial testing session on day 1, prior to conducting the CMVJ test, the subjects' height was determined using a stadiometer (Seca 222, Terre Haute, IN) fixed to the wall, which offered a precision of 0.5 cm. To evaluate the body mass of the subjects, a digital scale (Tanita, BC-418MA, Tokyo, Japan) with a precision of 0.1 kg was utilized. To ensure precise measurements, each assessment was carried out twice to minimize any potential errors.

Countermovement vertical jump

The role of explosive muscular power is essential in the context of karate performance, particularly in Kumite (Roschel et al., 2009). The assessment of lower body explosive power in karate athletes was conducted using the CMVJ. After a 15-minute warm-up routine, which included 5 minutes of running and 10 minutes of stretching and ballistic movements, the subjects were asked to perform 3 trials of CMVJ in order to become familiar with the exercise. Following this, the CMVJ was measured using the VERTEC device (Wall-mounted version, Power System, USA). To ensure accuracy, the VERTEC was adjusted to match the height of each subject by having them stand with their dominant side facing the base of the device. The dominant hand was raised, and the VERTEC was adjusted so that the hand was at the appropriate distance from the marker on the device. When given the verbal command "GO," the subjects flexed their knee joints to approximately 90° (i.e., a band placed parallel to the ground) and jumped as high as possible. The difference between the initial value and the maximum jump height was calculated to determine the CMVJ height. The highest measurement out of the three attempts, with a 30-second break in between, was selected for analysis (Ioannides et al., 2020). The reliability coefficient (ICC) for CMVJ was 0.95 ± 0.11.

20-m sprint

Sprinting speed represents the physical ability of karate athletes to execute swift movements, which is essential for facilitating their mobility and ultimately aiding in their competitive success (Kabadayi et al., 2022). In this study, an indoor track was utilized for the sprint running test. This test comprised three sprints covering a distance of 20-m, with each sprint performed at maximum effort. A rest period of 180 seconds was provided between each sprint. To accurately measure the running time, photocell gates (JBL Systems, Norway) were employed. These gates had a precision of 0.001 seconds and were positioned approximately 0.7 meters above the floor to capture trunk movement while minimizing false triggers caused by limb activity. The starting position was standardized, with the preferred foot's toe placed forward and positioned 0.5-m behind the starting line. Following a warm-up consisting of three trials, each subject executed the 20-m sprint as fast as possible upon receiving a "GO" command. The fastest time achieved from the trials was utilized for subsequent analysis, in accordance with the methodology outlined by Rimmer and Sleivert (2000). The ICC for the 20-m sprint was determined to be 0.94 ± 0.24.

4×9-m shuttle run

The majority of motion in karate consists of forward and backward movements. To achieve success in this discipline, a high level of change of direction abilities are essential (Arazi and Izadi, 2017). The shuttle run test was employed to assess the capability for sprinting and directional changes. In the 4×9-m shuttle run, subjects commenced from behind the starting line and, upon instruction, sprinted the 9-m distance. Upon completion of each 9-m section, subjects were instructed to halt with one foot beyond a designated marker, then quickly reverse their running direction and sprint back to the starting point. This sequence was repeated for a total of four 9-m sections, with the photocell gates (JBL Systems, Norway) recording the time once subjects crossed the finish line. The best scores from the three attempts, with a 180-second break in between, were selected for analysis (Arazi and Izadi, 2017). The ICC for the 4×9-m shuttle run was 0.97 ± 0.14.

Muscular strength

It is commonly acknowledged that the performance of karate athletes is closely associated with their lower body strength performance (Ben Hassen et al., 2022). In the current study, the lower body maximal strength (one repetition maximum [1RM]) was measured using a bilateral leg press device (Body Solid, GLPH 1100, USA) following the guidelines recommended by Kraemer and Fry (1995). After a 15-minute general warm up, each subject completed a specific warm-up series that included 8-10 repetitions at a light weight (about 50% of 1RM). This was followed by a second warm-up set of 3-5 repetitions with a moderate weight (roughly 75% of 1RM), and a third warm-up set with 1-3 repetitions at a heavy weight (around 90% of 1RM). Subsequent to the warm-up, each subject underwent a 1RM assessment by progressively increasing the load until they could no longer perform a proper lift with full range of motion and correct technique. The 1RM test was conducted through approximately 5 sets of one repetition, with 3 to 5 minutes of rest between trials. Spotters were on hand to provide verbal encouragement and ensure the safety of the subjects. The ICC for the $1RM_{LP}$ was determined to be 0.93 ± 0.22.

Wingate anaerobic power

Considering the intermittent nature of karate, it is crucial to evaluate anaerobic power performance when determining an athlete's fitness level (Nema et al., 2024). In fact, anaerobic power performance is essential for the effective execution of techniques during high-intensity attacking or defensive actions that result in points during a match (Nema et al., 2024). Furthermore, previous research conducted in this area has utilized the WAnT to evaluate the anaerobic performance of karate athletes (Doria et al., 2009). In this study, the WAnT was carried out on a cycle ergometer (Ergomedics 874, Monark, Sweden) to assess anaerobic power of athletes (Nikookheslat et al., 2016). After a 10-minute warm-up cycling period, the subjects were instructed to pedal as fast as possible for 30 seconds against a resistance determined by multiplying their body mass in kilograms by 0.075. Peak power was estimated as the average power output over a 5-second period with the highest performance, typically occurring within the first 5 seconds of the test. Mean power was calculated as the average power output throughout the 30-second duration. Throughout the test, subjects were verbally motivated to give their best effort during the WAnT (Ning and Sheykhlouvand, 2025).

Incremental exercise test

Given that karate consists of high-intensity intermittent activities with brief rest intervals, the metabolic profile of a karate athlete is primarily aerobic (Chaabene et al., 2012). Therefore, evaluating cardiorespiratory fitness is essential for monitoring the effectiveness of the training regimen for karate athletes. Following a 10-minute warm-up involving walking, the subjects proceeded to undertake the IET on a treadmill. The test commenced at an initial intensity of 8 $km \cdot h^{-1}$, with the velocity gradually increasing by 1 $km \cdot h^{-1}$ every 3 minutes. Each stage was separated by a 30-second relief interval, during which the concentration of blood lactate was measured via earlobe blood sampling (Gharaat et al., 2020). Throughout the test, a breath-by-breath gas collection system (MetaLyzer, Cortex, Germany) was used. To confirm the achievement of $\dot{V}O_{2max}$, a minimum of three of the following criteria had to be met: a) a plateau or a slight decline in $\dot{V}O_{2max}$ despite an increase in workload; b) a respiratory exchange ratio exceeding 1.10; c) reaching or surpassing 90% of the age-predicted maximum heart rate (Song and Sheykhlouvand, 2024; Tao et al., 2024).

Training intervention

All subjects engaged in karate practice sessions on Tuesdays, Thursdays and Saturdays in the afternoon from 4:00 to 7:00 P.M for 90 to 100 minutes. The sSIT, RT, sSIT + RT, and RT + sSIT groups completed their training on Mondays, Wednesdays, and Fridays in the afternoon. The sSIT program included 4 sets of 5 repetitions of 5 seconds of all-out running, with a recovery period of 1:3 ratios (i.e., 5 seconds of run: 15 seconds of rest) between efforts and three minutes of recovery between sets which the number of trials increasing by 1 repetition biweekly (Boullosa et al., 2022). The RT program consisted of back squats, leg presses, seated knee flexions, and calf raises for 3 sets of 6-12 repetition maximum (RM), performed in a circuit fashion with 30-second rests between trials and 90-second rests between circuits (Glowacki et al., 2004) (Table 2). In line with the study's objective to investigate the sequence effects of combining sSIT and RT, the two groups of karate athletes performed sSIT and RT in alternate orders with a 10-minute interval (Fyfe et al., 2016): sSIT+RT and RT + sSIT. Each training session began with a 15-minute warm-up routine. The athletes were closely monitored by a specialized strength and conditioning coach during the sessions to guarantee the accurate implementation of training techniques, maintaining a ratio of 1 coach to 4 athletes.

Table 2. Training intervention.

Type of Exercise	Week 1 & 2	Week 3 & 4	Week 5 & 6	Week 7 & 8
sSIT	4 × 5 reps, 5 sec all-out running	4 × 6 reps, 5 sec all-out running	4 × 7 reps, 5 sec all-out running	4 × 8 reps, 5 sec all-out running
RT*	3 × 12 RM, ~ 70%	3 × 10 RM, ~ 75%	3 × 8 RM, ~ 80%	3 × 6 RM, ~85%

*back squat, leg press, seated knee flexion and calf rise. sSIT = short sprint interval training, RT = resistance training.

Statistical analysis

The mean ± standard deviation (SD) was used to present the data. The Shapiro-Wilk test was utilized to assess the normality of the data for both pre and post-test values, while Levene's test was employed to evaluate the homogeneity of variances. An ANOVA with a two-factor design (time [2] × group [5]) was conducted to analyze repeated measures. Following the attainment of significant F values, pairwise comparisons were carried out in combination with a Bonferroni post hoc procedure to identify specific points of significant difference while maintaining control over type I errors. The effect size (ES) with a 95% confidence interval (CI) was used to assess the training effects' magnitude. Hedge's g was used to calculate the ES for all measures. According to Hopkins et al. (2009), an ES of < 0.2 was considered trivial, 0.2 - 0.6 was small, 0.6 - 1.2 was moderate, 1.2 - 2.0 was large, 2.0 - 4.0 was very large, and > 4.0 was nearly perfect. The significance level was set at 0.05. The coefficient of variation (CV) was calculated to evaluate inter-individual variability in adaptations over time. Individual percent changes from pre-training to post-training were computed for each variable, and the mean ± SD of these changes was determined (Δ% = (post – pre) / pre × 100) and analyzed with the one-way ANOVA and Bonferroni post hoc procedure. The CV (ratio of SD to the mean) of percent changes was then calculated for each variable. Additionally, individual residuals (Rs) in changes were computed as the square root of the squared difference between individual change and mean group change for each tested variable. Ultimately, the inter-subject variability in adaptive responses to interventions was evaluated by comparing between-group mean residuals for each variable (Ojeda-Aravena et al., 2021).

Results

Every player exhibited unwavering adherence, leading to a 100% success rate. Furthermore, there were no reported instances of injuries associated with the training and testing interventions. Additionally, no statistically significant differences ($p > 0.05$) were observed among the groups at the baseline.

The analysis revealed a significant main effect of time ($p = 0.001$) in the training groups (i.e., sSIT, RT, sSIT + RT, and RT + sSIT) following the intervention period for the CMVJ, 20-m sprint, 4 × 9-m shuttle run, $1RM_{LP}$, peak and mean power, as well as $\dot{V}O_{2max}$ (except in $\dot{V}O_{2max}$ for the RT group) with trivial to large ESs (Table 3 and Table 4). Moreover, there was a significant group × time interaction ($p = 0.001$), which reveals that the training groups showed more pronounced adaptive responses in the physical fitness, aerobic and anaerobic performance compared to the CG ($p = 0.001$), except RT vs. CG in the $\dot{V}O_{2max}$ (Table 3 and Table 4).

Following the 8-week training intervention, the sSIT + RT and RT + sSIT groups indicated more adaptations (interaction effect; $p = 0.001$) than the sSIT and RT groups in the CMVJ (sSIT + RT = 12.1% ± 1.8%, and RT + sSIT = 12.1% ± 1.9% vs. sSIT = 5.6% ± 2.1%, $p = 0.002$, and RT = 7.9% ± 1.7%, $p = 0.011$) peak (sSIT + RT = 12.3% ± 2.8%, and RT + sSIT = 12.5% ± 2.9% vs. sSIT = 7.7% ± 1.5%, $p = 0.013$, and RT = 5.3% ± 2.0%, $p = 0.022$) and mean power output (sSIT + RT = 10.6% ± 2.1%, and sRT + SIT = 10.5% ± 1.9% vs. sSIT = 6.8% ± 0.9%, $p = 0.001$, and RT = 4.8% ± 1.3%, $p = 0.001$) (Figure 2A, Figure 3A and B, Table 5).

There was a significant group × time interaction ($p = 0.001$) in the 20-m sprint, which indicating more adaptations for the sSIT+RT (-7.1% ± -1.6%, $p = 0.048$) and sRT+SIT (-7.1% ± -2.1%, $p = 0.05$) groups than the RT (-4.3% ± -2.1%) group, without any significant differences compared with the sSIT group (-5.5% ± -1.9%, $p = 0.374$) (Figure 2B).

There was a significant group × time interaction ($p = 0.001$) in 4 × 9-m shuttle run, which indicating greater adaptations for the sSIT+RT (-5.2% ± -1.0%) group compared with the sSIT (-3.2% ± -0.7%, $p = 0.027$) and RT (-2.0% ± -0.9%, $p = 0.039$) groups, while the gains in the RT+sSIT (-4.2% ± -1.1%) group was only greater when compared to RT (-2.0% ± -0.9%, $p = 0.009$) alone (Figure 3C).

Lower adaptation in the $1RM_{LP}$ was observed for the sSIT group than the other training groups (interaction effect; $p = 0.001$) (sSIT = 4.0% ± 2.5% vs. RT = 9.4% ± 2.5%, $p = 0.001$, sSIT + RT = 7.7% ± 2.1%, $p = 0.019$, RT + sSIT = 9.4% ± 1.8%, $p = 0.001$) (Figure 2D).

In contrast, lower adaptation in the $\dot{V}O_{2max}$ was displayed for the RT group in comparison to other training groups following the training intervention (interaction effect; $p = 0.001$) (RT = 0.46% ± 0.47% vs. sSIT = 5.4% ± 1.3%, $p = 0.001$, sSIT + RT = 5.4% ± 1.3%, $p = 0.001$, RT + sSIT = 3.8% ± 1.6%, $p = 0.001$) (Figure 3C).

Neither the interference effect nor the order effect was observed in the physical and physiological performance of karate athletes following the training period (Table 5). Additionally, significant differences between sSIT and RT were demonstrated after the training intervention only in the $1RM_{LP}$ (RT = 9.4% ± 2.5% vs. sSIT = 4.0% ± 2.5%, $p = 0.001$) and $\dot{V}O_{2max}$ (sSIT = 5.4 % ± 1.3% vs. 0.46% ± 0.47%, $p = 0.001$). Although the individual Rs in percent change did not differ between the groups, the SIT group indicated lower inter-subject variability than the RT group in the 20-m sprint, 4 × 9-m shuttle run, peak and mean power output, as well as $\dot{V}O_{2max}$ (Table 6). In contrast, the RT group indicated lower CVs than the sSIT group in the CMVJ and $1RM_{LP}$. When comparing the sSIT + RT vs. the RT + sSIT group, lower CVs were observed in the $\dot{V}O_{2max}$, 4 × 9-m shuttle run, and 20-m sprint for the sSIT+RT group, while lower CVs were demonstrated for the RT + sSIT group in the CMVJ, and $1RM_{LP}$.

Table 3. Physical performance changes from pre- to post-intervention (mean ± SD).

Variables	Groups	Pre-intervention	Post-intervention	Significant	Hedge's g (95% CI)
CMVJ (cm)	sSIT	33.8 ± 2.9	35.7 ± 2.7*	Time Effect	0.64 (-0.36 to 1.65) Moderate ↑
	RT	34.3 ± 2.8	37.1 ± 3.2*	0.001	0.88 (-0.15 to 1.91) Moderate ↑
	sSIT+RT	34.2 ± 2.4	38.3 ± 2.5*	Group × Time Effect	1.58 (0.46 to 2.70) Large ↑
	RT+sSIT	34.6 ± 2.6	38.7 ± 2.4*	0.001	1.55 (0.43 to 2.67) Large ↑
	CG	34.5 ± 2.6	34.8 ± 2.2		-
20-m sprint (sec)	sSIT	3.41 ± 0.24	3.21 ± 0.22*	Time Effect	-0.82 (-1.84 to 0.20) Moderate ↓
	RT	3.42 ± 0.22	3.27 ± 0.24*	0.001	-0.62 (-1.62 to 0.39) Moderate ↓
	sSIT+RT	3.43 ± 0.22	3.19 ± 0.19*	Group × Time Effect	-1.10 (-2.16 to -0.05) Moderate ↓
	RT+sSIT	3.39 ± 0.21	3.15 ± 0.18*	0.001	-1.16 (-2.22 to -0.10) Moderate ↓
	CG	3.44 ± 0.19	3.43 ± 0.19		-
4 × 9-m shuttle run (sec)	sSIT	9.45 ± 0.47	9.14 ± 0.48*	Time Effect	-0.62 (-1.62 to 0.39) Moderate ↓
	RT	9.43 ± 0.50	9.24 ± 0.52*	0.001	-0.35 (-1.34 to 0.64) Small ↓
	sSIT+RT	9.47 ± 0.45	8.97 ± 0.37*	Group × Time Effect	-1.15 (-2.20 to -0.09) Moderate ↓
	RT+sSIT	9.49 ± 0.44	9.09 ± 0.41*	0.001	-0.89 (-1.92 to -0.14) Moderate ↓
	CG	9.42 ± 0.43	9.41 ± 0.41		-
$1RM_{LP}$ (kg)	sSIT	211.2 ± 40.2	219.3 ± 39.6*	Time Effect	0.19 (-0.79 to 1.17) Trivial ↑
	RT	211.8 ± 41.9	231.2 ± 42.0*	0.001	0.44 (-0.55 to 1.43) Small ↑
	sSIT+RT	210.0 ± 43.5	226.2 ± 46.7*	Group × Time Effect	0.34 (-0.65 to 1.33) Small ↑
	RT+sSIT	211.8 ± 42.2	231.5 ± 43.6*	0.001	0.43 (-0.56 to 1.43) Small ↑
	CG	214.3 ± 37.1	215.6 ± 35.3		-

*denotes significant differences in training groups compared with the pre-intervention value and compared with CG at post-intervention ($p < 0.05$). CMVJ = countermovement vertical jump, $1RM_{LP}$ = one repetition maximum leg press, sSIT = short sprint interval training, RT = resistance training, CG = concurrent training.

Table 4. Physiological performance changes from pre- to post-intervention (mean ± SD).

Variables	Groups	Pre-intervention	Post-intervention	Significant	Hedge's g (95% CI)
Peak power output (W)	sSIT	811.1 ± 41.2	874.6 ± 52.4*	Time Effect	1.27 (0.20 to 2.35) Large ↑
	RT	824.0 ± 54.2	868.0 ± 59.1*	0.001	0.73 (-0.28 to 1.75) Moderate ↑
	sSIT+RT	808.3 ± 43.8	908.6 ± 60.3*	Group × Time Effect	1.80 (0.64 to 2.96) Large ↑
	RT+sSIT	815.1 ± 64.8	916.5 ± 60.4*	0.001	1.53 (0.42 to 2.64) Large ↑
	CG	815.8 ± 40.7	816.7 ± 41.1		-
Mean power output (W)	sSIT	472.6 ± 34.6	504.8 ± 35.5*	Time Effect	0.87 (-0.16 to 1.89) Moderate ↑
	RT	468.8 ± 39.3	491.7 ± 41.1*	0.001	0.54 (-0.46 to 1.54) Small ↑
	sSIT+RT	476.5 ± 31.3	527.5 ± 38.5*	Group × Time Effect	1.37 (0.28 to 2.46) Large ↑
	RT+sSIT	474.6 ± 38.2	524.8 ± 47.0*	0.001	1.11 (0.42 to 2.64) Moderate ↑
	CG	469.5 ± 45.7	470.8 ± 48.3		-
$\dot{V}O_{2max}$ ($ml.kg^{-1}.min^{-1}$)	sSIT	42.3 ± 2.8	44.6 ± 3.0*	Time Effect	0.75 (-0.26 to 1.76) Moderate ↑
	RT	41.9 ± 2.7	42.1 ± 2.6	0.001	0.08 (-0.91 to 1.05) Trivial ↑
	sSIT+RT	41.6 ± 2.3	43.9 ± 2.4*	Group × Time Effect	0.92 (-0.11 to 1.96) Moderate ↑
	RT+sSIT	41.4 ± 2.5	43.0 ± 2.4*	0.001	0.62 (-0.39 to 1.62) Moderate ↑
	CG	41.8 ± 2.6	41.9 ± 2.5		-

*denotes significant differences in training groups compared with the pre-intervention value and compared with CG at post-intervention ($p < 0.05$). sSIT = short sprint interval training, RT = resistance training, CG = concurrent training.

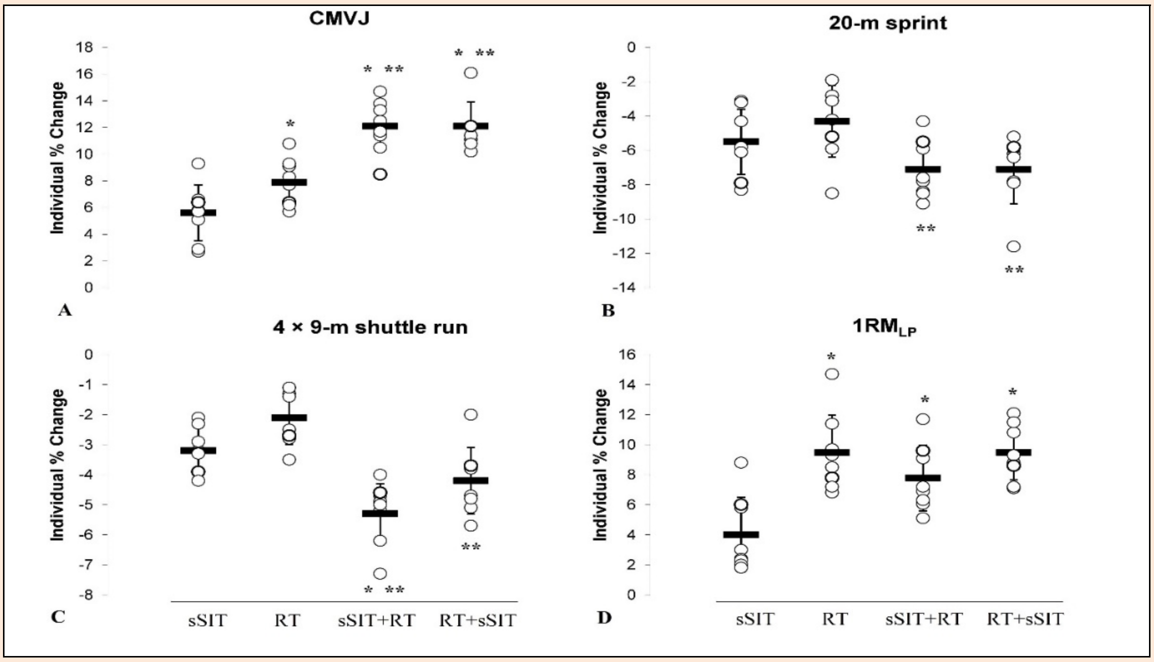

Figure 2. Individual % change in CMVJ (A), 20-m sprint (B), 4 × 9-m shuttle run (C) and 1RM$_{LP}$ (D) following the 8-week training (mean ± SD). CMVJ = countermovement vertical jump, 1RM$_{LP}$ = one repetition maximum leg press, sSIT = short sprint interval training, RT = resistance training. * Compared to sSIT, ** Compared to RT.

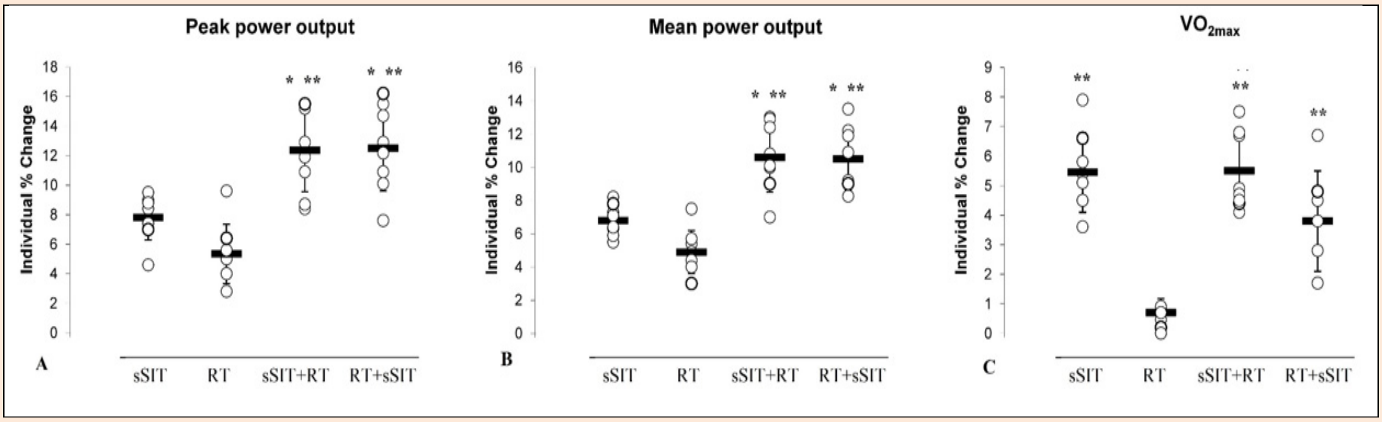

Figure 3. Individual % change in peak power output (A), mean power output (B), and $\dot{V}O_2max$ (C) following the 8-week training (mean ± SD). CMVJ = countermovement vertical jump, 1RM$_{LP}$ = one repetition maximum leg press, sSIT = short sprint interval training, RT = resistance training. * Compared to sSIT, ** Compared to RT.

Table 5. Between-group comparisons of changes in all performance measures from pre- to post-intervention. Data are standard mean difference (SMD) and 95 % CI.

Variable	Interference effect				Order effect
	sSIT vs. sSIT+RT	sSIT vs. RT+sSIT	RT vs. sSIT+RT	RT vs. RT+sSIT	sSIT+RT vs. RT+sSIT
CMVJ (cm)	-1.00 (-1.98 to 0.09) Moderate difference	-1.17 (-2.16 to -0.06) Moderate difference	-0.42 (-1.38 to 0.59) Small difference	-0.53 (-1.53 to 0.46) Small difference	-0.16 (-1.14 to 0.83) Trivial difference
20-m sprint (sec)	-0.10 (-1.07 to 0.89) Trivial difference	-0.30 (-1.27 to 0.70) Small difference	-0.37 (-134 to 0.64) Small difference	-0.57 (-1.53 to 0.46) Small difference	-0.22 (-1.19 to 0.78) Small difference
4 × 9-m shuttle run (sec)	0.40 (-0.61 to 1.36) Small difference	0.11 (-0.87 to 1.09) Trivial difference	0.60 (-0.43 to 1.56) Moderate difference	0.32 (-0.68 to 1.29) Small difference	-0.31 (-1.28 to 0.69) Small difference
1RM$_{LP}$ (kg)	-0.15 (-1.13 to 0.83) Trivial difference	-0.28 (-1.26 to 0.71) Small difference	0.11 (-0.87 to 1.09) Trivial difference	-0.01 (-0.99 to 0.97) Trivial difference	-0.12 (-1.09 to 0.87) Trivial difference
Peak power output (W)	-0.60 (-1.57 to 0.43) Moderate difference	-0.73 (-1.70 to 0.32) Moderate difference	-0.68 (-1.65 to 0.36) Moderate difference	-0.80 (-1.78 to 0.25) Moderate difference	-0.12 (-1.10 to 0.86) Trivial difference
Mean power output (W)	-0.61 (-1.58 to 0.42) Moderate difference	-0.48 (-1.70 to 0.32) Small difference	-0.90 (-1.87 to 0.17) Moderate difference	-0.75 (-1.72 to 0.30) Moderate difference	0.6 (-0.92 to 1.04) Moderate difference
$\dot{V}O_{2max}$ (ml.kg^{-1}.min^{-1})	0.26 (-0.74 to 1.23) Small difference	0.59 (-0.44 to 1.56) Small difference	-0.79 (-1.69 to 0.33) Moderate difference	-0.36 (-1.33 to 0.65) Small difference	0.37 (-0.63 to 1.34) Small difference

CMVJ = countermovement vertical jump, 1RM$_{LP}$ = one repetition maximum leg press, sSIT = short sprint interval training, RT = resistance training.

Table 6. Individual residuals (Rs) in percent change and inter-subject variability (CV) in response to training.

Variable	Variables	sSIT	RT	sSIT+RT	RT+sSIT
CMVJ (cm)	Rs	1.50	1.43	1.51	1.11
	CV (%)	37.7	22.1	16.2	14.9
20-m sprint (sec)	Rs	1.51	1.64	1.42	1.50
	CV (%)	-35.0	-48.6	-23.5	-28.6
4 × 9-m shuttle run (sec)	Rs	0.59	0.81	0.75	0.86
	CV (%)	-23.1	-44.2	-19.6	-26.5
$1RM_{LP}$ (kg)	Rs	2.14	1.87	1.77	1.52
	CV (%)	62.9	27.3	28.2	19.7
Peak power output (W)	Rs	1.15	1.42	2.37	2.34
	CV (%)	19.8	38.4	23.3	23.6
Mean power output (W)	Rs	0.77	1.00	1.64	1.64
	CV (%)	13.6	27.6	19.7	19.28
VO_2max ($ml.kg^{-1}.min^{-1}$)	Rs	1.00	0.39	1.17	1.30
	CV (%)	24.7	103.9	24.3	44.13

CMVJ = countermovement vertical jump, $1RM_{LP}$ = one repetition maximum leg press, sSIT = short sprint interval training, RT = resistance training.

Discussion

The aim of the current study was to examine the effects of an 8-week intervention involving sSIT, RT, and CT (sSIT + RT or RT + sSIT) on the physical fitness, aerobic and anaerobic performance of male karate athletes. Results indicated improvements in the CMVJ, 20-m sprint, 4 × 9-m shuttle run, $1RM_{LP}$, peak and mean power, as well as $\dot{V}O_{2max}$ for the training groups following the training period (except in $\dot{V}O_{2max}$ for the RT group). Both the sSIT + RT and RT+sSIT groups indicated more adaptations than the RT or sSIT in the CMVJ, 4 × 9-m shuttle run, peak and mean power output as well as $\dot{V}O_{2max}$. No sequencing effects were displayed following the 8-week sSIT and RT in the physical fitness, aerobic and anaerobic performance adaptations. However, the RT group showed greater gains in $1RM_{LP}$ than the sSIT group, and the sSIT group demonstrated more adaptation in $\dot{V}O_{2max}$ than the RT group following the training period.

The present study revealed that there were no significant alterations in the physical fitness, aerobic and anaerobic performance of karate athletes who did not participate in any intervention program (i.e., CG). Conversely, all athletes engaged in the same karate training prior to and throughout the duration of the study, with the CG solely involved in karate practice, showing no changes in their performance. These results highlight the importance for athletes and coaches to recognize that relying solely on karate training may not be an effective strategy for achieving performance adaptations. To facilitate such adaptations, it is essential to incorporate additional training regimens, such as RT, sSIT, or a combination of both (i.e., CT). While the inclusion of RT, sSIT or CT alongside karate training may increase the overall training load, it is evident that karate training alone is insufficient to elicit adaptive responses in athletes.

An 8-week training intervention induced moderate training effects for the single training groups (i.e., sSIT and RT) and large training effects for the CT (i.e., sSIT+RT and RT+sSIT). The improvements in the CMVJ could be due to enhancements in neuromuscular adaptations such as enhancing the rate of force development and firing rate induced by sSIT (Arazi et al., 2017; Song and Deng, 2023) and RT (Aagaard et al., 2002; Vissing et al., 2008; Cid-Calfucura et al., 2023). Although when comparing the sSIT and RT groups, more adaptations in the CMVJ were observed for the RT group (7.9% vs. 5.6%), these differences did not reach significance and it could be stated that sSIT is also an effective training modality for enhancing jumping ability similar to RT. However, combining sSIT and RT induced further training benefits than sSIT and RT alone. Neither interference nor order effects in adaptations were observed following the training, which is in contrast to previous studies that used concurrent (RT + ET) training and found a reduction in jump height and power following this training approach (Hennessy and Watson, 1994; Rønnestad et al., 2012; Fyfe et al., 2016; Lee et al., 2020). These findings could be explained by a mechanism linked to the structure of the training program. Prior studies commonly utilized aerobic continuous running or cycling exercises of moderate intensity before or after RT (Hennessy and Watson, 1994; Rønnestad et al., 2012; Fyfe et al., 2016; Lee et al., 2020). Moreover, non-all-out interventions were integrated during interval training, leading to reduced activation of fast-twitch muscle fibers and resulting in localized fatigue and exhaustion (Lee et al.,2020).

As a consequence, the utilization of short duration (i.e., 5 seconds) and all-out sSIT not only brought about adaptations in the CMVJ but also yielded even greater adaptations when combined with RT in both training sequences. The similar adaptations observed in the CMVJ following the combined sSIT + RT and RT + sSIT (12.1%) emphasize the superiority of concurrent sSIT and RT in inducing greater gains compared to a single training method without any interference effect.

The 8-week sSIT, RT, and combined training programs resulted in significant decreases in sprint and shuttle run times. These improvements in sprint and change of direction ability indicate the positive effects of sSIT and RT on locomotor ability by involving fast-twitch muscle fibers and also improvements in stride length (Rimmer and Sleivert, 2000; Arazi et al., 2017; Song and Deng, 2023; Seitz et al., 2014). The combination of sSIT and RT induced similar adaptations in sprint performance, with significant differences compared to RT alone. The sSIT + RT group showed more gains in change of direction ability compared to RT and sSIT alone. These findings support the use of sSIT for adaptations in sprint and change of direction, especially when combined with RT. Incorporating sSIT sessions during CT programs can eliminate interference effects on sprint and change of direction ability (Buchheit and Laursen, 2013; Laursen and Buchheit, 2019). Overall, the sSIT is recommended for improving sprint and change of direction ability when the athletes want to train in one type of training, while the order of sSIT + RT is suitable for athletes who want to incorporate both types of training in a single session.

The strength performance of karate athletes significantly improved after an 8-week training program that included RT, sSIT + RT, and RT + sSIT. These findings suggest that RT is the primary training approach for enhancing strength gains (Aagaard et al., 2002; Vissing et al., 2008), and in comparison to previous research that utilized sSIT alone, different forms of sSIT have minimal effects on strength performance (Song and Deng, 2023). The similar strength gains observed in the RT, sSIT + RT, and RT + sSIT groups indicate that the addition of sSIT before or after RT does not interfere with the training effects, and the sequencing of sSIT and RT has similar outcomes. The strength gains induced by RT can be attributed to two mechanisms: a) neuromuscular adaptations, such as improved muscular coordination, inhibition of antagonist muscles, and activation and contraction of synergistic muscles and motor units, which align with previous research and are the primary factors behind the strength gains induced by RT (Aagaard et al., 2002; Vissing et al., 2008), and b) RT-induced increases in muscle hypertrophy, characterized by increases in myofilaments, actin and myosin filaments, sarcoplasm, and connective tissue, which are consistent with previous studies (Schoenfeld, 2010). Therefore, it can be concluded that RT is the main training modality for enhancing strength gains, and incorporating RT before and after training can lead to similar adaptations, which is beneficial for karate athletes. Interval training involving short-term trials (e.g., 5 seconds) performed with all-out effort has shown no adverse effects on strength gains. In fact, sSIT not only do not inhibit strength development, but they also prove to be an effective way to generate consistent adaptations in athletes. Incorporating sSIT sessions before and after RT may enhance muscle fiber activation under all-out conditions, potentially resulting in increased strength gains.

The aerobic power and anaerobic performance, such as $\dot{V}O_{2max}$ as well as peak and mean power output, showed improvement in karate athletes after an 8-week training period for all groups, except for the RT group in terms of $\dot{V}O_{2max}$. Previous studies have reported that combination of RT and various forms of ET can enhance both aerobic and anaerobic metabolic pathways (Gao and Yu, 2023; Leveritt et al., 2003). While RT did lead to an increase in peak and mean power output, these gains were lower compared to the other groups. Similarly, RT did not result in any changes in $\dot{V}O_{2max}$, which is consistent with previous research (Aagaard et al., 2011). However, when RT was combined with sSIT before and after training, significant adaptations were observed, resulting in greater gains compared to RT alone. Furthermore, the combination of RT and sSIT in different orders eliminated the lesser effects of RT on aerobic and anaerobic performance. Additionally, the sSIT group demonstrated greater adaptations in $\dot{V}O_{2max}$ compared to the RT group, highlighting the superiority of sSIT in enhancing aerobic performance. Our findings indicate that sSIT is the primary training approach for inducing adaptations in both central (enhancing oxygen delivery, mitochondrial biogenesis, and cardiac output) and peripheral (enhancing oxygen extraction and utilization by active muscles) parameters in karate athletes (Ojeda-Aravena et al., 2021). The improved aerobic performance in our participants may be attributed to elevated O2pulse ($\dot{V}O_2$/HR), increased discharge rate and recruitment of high-threshold motor units, augmented total creatine content in active muscles, and enhanced muscle buffering capacity, all of which play crucial roles in power output development (Laursen and Buchheit, 2019; Boullosa et al., 2022; Gao and Yu, 2023; Sheykhlouvand and Gharaat, 2024; Gharaat et al., 2024).

Based on our findings, it can be stated that sSIT is an effective training method for inducing adaptations in aerobic and anaerobic performance. When combined with RT, both before and after, sSIT can lead to even greater adaptations without any interference effects. Specifically, the addition of sSIT to RT resulted in increased gains in peak and mean power output, indicating enhanced involvement of muscle fibers, ATP-PCr, and glycolytic pathways (Boullosa et al., 2022; Forbes and Sheykhlouvand, 2016). However, no significant differences were observed in $\dot{V}O_{2max}$ by RT alone. It appears that sSIT is the primary training approach for improving aerobic performance, as the groups that engaged in sSIT or sSIT+RT demonstrated slightly greater gains compared to the group that performed sSIT after RT. However, these differences were not statistically significant.

Overall, the findings of the present study demonstrate that sSIT, RT, and a combination of RT and sSIT with different orders have a positive effect on inducing such adaptations in the physical fitness, aerobic and anaerobic performance in karate athletes. In addition, no interference effect or order effect was detected in the physical fitness, aerobic and anaerobic performance of karate athletes after the training period. However, the strength gains were greater for the RT group than the sSIT group, while the sSIT group showed more adaptations in aerobic performance than the RT group.

Regarding inter-subject variability after the training intervention and the adaptive responses related to physical fitness, aerobic and anaerobic performance among karate athletes, the incorporation of RT either individually or at the commencement of CT may result in greater consistency in the adaptations of CMVJ. This approach appears to yield lower IRs in percent change and CVs when compared to the other groups. However, in sprint and 4×9-m shuttle run this observation is vice versa and the groups that employed only sSIT or sSIT + RT indicated lower individual Rs in percent change and CVs that confirm the consistency in adaptive responses in 20-m sprint and 4×9-m shuttle run tests in karate athletes. Furthermore, the training groups that engaged in RT demonstrated lower CVs and Rs in percent change, highlighting the importance of RT in promoting homogeneity in adaptations for strength gains in karate athletes. Both the sSIT + RT and RT + sSIT groups showed similar results in Rs in percent change and CVs for peak and mean power output following the training. However, sSIT alone exhibited lower inter-subject variability in power output performance compared to RT. Additionally, the groups that engaged in sSIT alone or sSIT before RT demonstrated lower CVs and Rs in percent change compared to the RT + sSIT group, indicating better homogeneity in adaptations and highlighting the superiority of sSIT for aerobic performance improvements. Based on the findings presented in this section, it is advisable that the selection of each training program be tailored to the specific type of performance tests. To optimize adaptations in physical fitness, aerobic and anaerobic performance, careful consideration should be given to the appropriate sequence of CT.

This study has a few methodological limitations that warrant discussion. The study was impacted by the low number of included athletes, N = 8 for each group. Nevertheless, after conducting a priori power analysis, it was determined that this sample size was sufficient to achieve adequate statistical power. The results of this study may be beneficial for national-level karate athletes; however, they may not be applicable to elite athletes or female karate practitioners. Further research is required to determine if the findings can be generalized to female athletes or athletes in different sports and age groups. Furthermore, the present study did not quantify the training load. The athletes participating in the training groups engaged in both the training regimen and karate practice, and we did not directly assess the precise load experienced during the training sessions. Future research could incorporate this measurement to elucidate the impact of training load as a variable influencing adaptive responses to the training. Additionally, the absence of laboratory measurements for blood assessment, biochemical (i.e., buffering capacity), and neuromuscular adaptations limit the study's ability to assess the metabolic and muscular adaptations in karate athletes.

Conclusion

The physical fitness, aerobic and anaerobic performance of karate athletes can be significantly improved by including an 8-week sSIT, RT and a combination of them in alternate order. The RT leads to enhanced strength gains compared to sSIT alone, while sSIT induces greater adaptations in $\dot{V}O_{2max}$ compared to RT. Both the alternate order of sSIT and RT show more adaptations in various performance measures such as CMVJ, 20-m sprint, 4 × 9-m shuttle run, strength, peak and mean power output, following the 8-week training. Importantly, there were no observed interference or order effects of sSIT and RT on the athletes' physical fitness, aerobic and anaerobic performance. From a practical perspective, incorporating sSIT and RT in different orders not only serves as a suitable training modality for enhancing the performance of karate athletes but also promotes adaptations with better consistency and without interference effects.

Acknowledgements

The author reports no actual or potential conflicts of interest. While the datasets generated and analyzed in this study are not publicly available, they can be obtained from the corresponding author upon reasonable request. All experimental procedures were conducted in compliance with the relevant legal and ethical standards of the country where the study was carried out.

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Key points

- Incorporating sSIT, RT, sSIT+RT and RT+sSIT are appropriate strategies for designing training programs aiming to enhance physical fitness, aerobic and anaerobic performance, except $\dot{V}O2max$ in the RT group, for karate athletes.
- RT induced superior adaptive responses than sSIT in muscular strength performance.
- sSIT is more effective than RT to induce such adaptations for aerobic performance.
- The combination of sSIT and RT is better than RT or sSIT alone.
- Neither the interference effect nor the order effect was observed in the physical fitness, aerobic and anaerobic performance of karate athletes following the training period.

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