Validity of aerobic capacity indicators derived from the progressive specific taekwondo test for prescribing sport-specific interval training

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Background: The Progressive Specific Taekwondo Test (PSTT) is used to determine indicators of aerobic capacity (heart rate deflection point [HR_{DP}] and kick frequency at the HR_{DP} [KF_{DP}]) useful for prescribing sport-specific training. The aim of this study was to prescribe a sport-specific interval training (IT) session at the KF_{DP}, identified during the PSTT, and to investigate HR response and muscle power performance.

Methods: Thirteen taekwondo athletes of national and international level (mean $\pm$ SD: age: 17.6 $\pm$ 2.7 years) voluntarily participated in the study. In two experimental sessions, athletes performed: the PSTT to identify HR_{DP} and KF_{DP}; a sport-specific IT at the KF_{DP}, using the technical action of bandal-chagi (3 rounds × 2 min/1 min of recovery in-between). During each round of the IT, the HR was recorded to identify the HR_{ROUND}. Before and after each round of the IT, muscle power performance was assessed through three countermovement jump (CMJ) tests.

Results: HR_{ROUND} was significantly correlated with HR_{DP} ($r = 0.774-0.789$; $p < 0.01$). During round 1, HR_{ROUND} was significantly lower ($p = 0.008$) than HR_{DP}. In rounds 2 and 3, there were no difference ($p = 0.067$ and $p = 0.653$, respectively) between HR_{ROUND} and HR_{DP}. No difference was observed between pre- and post-IT CMJ performance ($p = 0.210$). Post-IT CMJ performance was significantly greater ($p = 0.009$) than that in the interval between rounds 1 and 2.

Conclusion: During the IT rounds, expected HR responses emerged and muscle power performance was not compromised. Thus, these results support the use

of PSTT-derived HR_{DP} and KF_{DP} as practical, sport-specific indicators for tailoring IT intensity in taekwondo athletes.

1 Introduction

In the last decade, research has focused on the development and use of sport-specific tests for assessing endurance in taekwondo athletes, in parallel with the widespread use of general tests (Bridge et al., 2014; Hausen et al., 2018; Sant'Ana et al., 2019; Araujo et al., 2021; Taati et al., 2022; Apollaro et al., 2024a). A recent review reported that the currently available sport-specific protocols for endurance are simple to conduct, noninvasive, and easily accessible to stakeholders (Apollaro et al., 2024a). On the other hand, each test has specific methodological and application characteristics, particularly the time structure and aerobic indicators derived, that must be appropriately considered when choosing which test to use (Hausen et al., 2018; Sant'Ana et al., 2019; Araujo et al., 2021; Taati et al., 2022; Apollaro et al., 2024a). To date, the Progressive Specific Taekwondo Test (PSTT) is the most studied test and it has a time structure that was defined following the recommended criteria to identify the heart rate deflection point (HR_{DP}) in maximal progressive tests (Conconi et al., 1996). The concurrent criterion validity of the PSTT was established with the incremental treadmill test (ITT) (Sant'Ana et al., 2019) and the multistage shuttle run test (SRT) (Rocha et al., 2016). In addition, its test-retest reliability was investigated (Sant'Ana et al., 2017; Ouergui et al., 2020; Ouergui et al., 2021). Sant'Ana et al. (2019) found no significant difference for maximal oxygen consumption (VO_{2MAX}), oxygen consumption at HR_{DP} (VO_{2HRDP}), and HR_{DP} between the PSTT and ITT. In particular, the similar HR_{DP} between the two tests supported the assumption that the PSTT can provide indicators of exercise intensity, based on HR, easily applicable to monitor not only power but also aerobic capacity in a sport-specific mode (Sant'Ana et al., 2019).

It is important to highlight that the PSTT was originally developed to indirectly estimate the anaerobic threshold (AT) from the HR_{DP} (Sant'Ana et al., 2009). Sant'Ana et al. (2009) found that HR_{DP} and kick frequency at HR_{DP} (KF_{DP}) in the PSTT were not different and significantly correlated with heart rate at AT (HR_{AT}) and kick frequency at AT (KF_{AT}) during a sport-specific constant load test at the fixed concentration of 4 mmol·L^{-1} of blood lactate [La]. Thus, the PSTT is the only test among those available that allows the determination of both aerobic capacity (i.e., HR_{DP} and KF_{DP}) and power indicators (i.e., maximal heart rate [HR_{MAX}] and maximal kick frequency [KF_{MAX}]) useful for subsequent sport-specific training's prescription (Apollaro et al., 2024a). In contrast, the validity of the fundamental aerobic variables of other sport-specific tests (such as the Continuous Taekwondo-Specific test, Interval Taekwondo-Specific test, Continuous Taekwondo-Specific Cardiopulmonary test, and Interval Taekwondo-Specific Cardiopulmonary test) (Hausen et al., 2018; Araujo et al., 2021) was either not confirmed or no aerobic variables (as in the Taekwondo-Specific Aerobic-Anaerobic-Agility test) were provided

for monitoring and prescribing training (Taati et al., 2022). Sant'Ana et al. (2017) determined aerobic power indicators (i.e., HR_{MAX} and KF_{MAX}), during the execution of the PSTT, aiming to investigate the acute effects of a sport-specific time-to-exhaustion test performed at the previously found KF_{MAX}. Until then, this study was the only one that prescribed sport-specific training from indicators derived from PSTT in taekwondo athletes. Aiming to facilitate and increase the applicability of this testing protocol, the *ITStriker* application (*ETS4ME, São José, SC, Brazil*) was developed. This mobile technology reproduces the typical time regression and linear increase of KF of the PSTT, and automatically derives the internal and external load parameters for their subsequent use in "training mode" (Antonietto et al., 2021; Sant'Ana et al., 2021; Rodrigues et al., 2023; De Oliveira et al., 2024). To date, the rapid real-time data processing and low cost of this app facilitated the execution of the PSTT (Antonietto et al., 2021), the adaptation of the protocol to other combat sports such as karate (Rodrigues et al., 2023) and boxing (De Oliveira et al., 2024), and the first attempt of sport-specific training prescription for taekwondo (Sant'Ana et al., 2021).

Specifically, Sant'Ana et al. (2021) determined indicators of aerobic capacity (i.e., HR_{DP} and KF_{DP}), while performing the PSTT and using the *ITStriker* app. Their objective was to analyze the acute effects of a sport-specific interval training (IT) session that mimics the time structure of the official match (i.e., 3 rounds × 2 min/1 min of recovery in-between), performed at the previously found KF_{DP} and reproduced by the *ITStriker* app, on HR responses, countermovement jump (CMJ) test performance, and parameters associated with neuromuscular and motor performance of the bandal-chagi (i.e., roundhouse kick) (Sant'Ana et al., 2021). Among the results, it was reported that only HR response during round 1 of IT was significantly lower than that observed at the same intensity (i.e., KF_{DP}) during the PSTT. In parallel, CMJ performance (measured before and after each round of the IT) showed no differences between the pre- and post-IT (Sant'Ana et al., 2021). These results supported the use of HR_{DP} and KF_{DP}, obtained during the PSTT, to prescribe IT as expected HR responses emerged and muscle power performance was not compromised (Sant'Ana et al., 2021). However, focusing on the IT protocol, athletes were allowed to perform kicks with technical variations and combining up to three kicks for each sound signal (Sant'Ana et al., 2021). Although this was conducted to reproduce the technical-tactical actions closest to those performed in combat (Sant'Ana et al., 2021), during the PSTT the athlete performs only one bandal-chagi for each sound signal (Sant'Ana et al., 2021). Thus, the different and specific technical-tactical actions of IT might have altered the KF required from the athlete generating HR responses and muscle power performance intensity-specific.

In this sense, to support in the first instance the validity of the aerobic capacity indicators derived in the PSTT (i.e., HR_{DP} and KF_{DP}), to prescribe sport-specific training, it is be appropriate to structure an IT that includes the single technical action of the test (i.e., bandal-chagi) for each sound signal. This step would incentivize the use of aerobic capacity indicators derived from the PSTT to tailor IT intensity. Therefore, the aim of this study was to prescribe a sport-specific IT session (which mimics the time structure of the official match), at the KF_{DP} identified during the PSTT, using the technical action of bandal-chagi, and to investigate HR response and muscle power performance, through CMJ tests, in taekwondo athletes. We hypothesized that: (a) the HR during the three rounds of the sport-specific IT at the KF_{DP} would be lower only in the first round, compared with that observed at the KF_{DP} during PSTT, due to the kinetics of HR as a result of the specific high-intensity required. Consequently, the HR would be similar in the second and third rounds, compared with that observed at the KF_{DP} during PSTT, as HR_{DP} is generally identified at a percentage of HR_{MAX} located in the heavy domain of exercise (Ribeiro et al., 1985; Bunc et al., 1995; Bodner and Rhodes, 2000); (b) three rounds of the sport-specific IT at the KF_{DP} would not cause a decrease in muscle power performance. The CMJ test is commonly used to assess lower limb muscle power in taekwondo athletes, and its positive influence on the ability to repeat high-intensity intermittent efforts is documented (Albuquerque et al., 2022; Apollaro et al., 2024c). In this sense, the hypothesis that the KF_{DP} does not impair muscle power performance would indicate the integrity of the mechanisms underlying the neuromuscular system during the repeated bandal-chagi technical action.

2 Materials and methods

2.1 Study design

Athletes conducted two distinct experimental sessions. On the first day, anthropometric and body composition measurements (i.e., body height, body mass, and body fat) were performed as well as the PSTT to identify HR_{DP} and HR_{MAX}, and their associated KFs (KF_{DP} and KF_{MAX}, respectively). On the second day, after a 48-h interval, athletes performed a sport-specific IT session at the KF_{DP} identified during the PSTT. Before and after each round of the IT, muscle power performance was assessed through CMJ tests. In the 24-h before the two experimental sessions, athletes were asked to avoid any strenuous physical activity, consumption of caffeine, energy drinks, and alcohol.
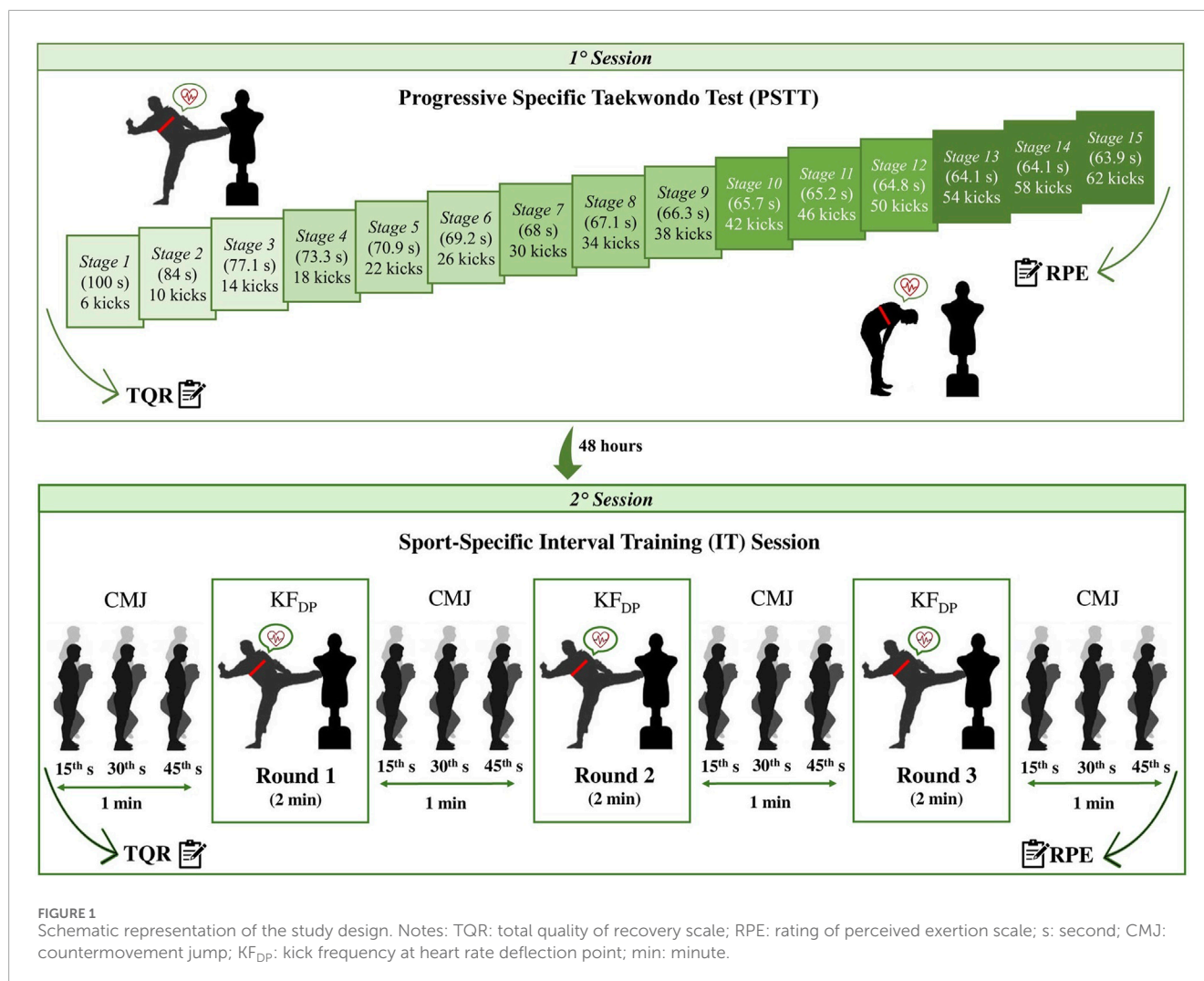
2.2 Participants

A priori power analysis was performed using the *G*Power* software (v. 3.1.9.7; Heinrich Heine University in Düsseldorf, Germany) using the F test family (ANOVA: repeated measures, within factors), with four measurements. The analysis revealed that a total sample size of 11 participants would be sufficient to find medium effects of condition (effect size f = 0.25, α = 0.05) with an

actual power of 0.8 (Ouergui et al., 2023a; Ouergui et al., 2023b). All athletes were recruited from the same club, to prevent potential interference/variation induced by training programs' variation, based on the following inclusions criteria: 1) more than 5 years of experience in taekwondo; 2) be training at least five times a week; 3) not engage in any acute rapid weight loss strategies during the study period; 4) not having suffered muscle and joint injuries in the past 6 months; 5) not having taken drugs, medications or dietary supplements. Thirteen Italian taekwondo black belt athletes (7 males and 6 females; mean ± SD, age: 17.6 ± 2.7 years; 12.3 ± 2.2 years of practice; body height: 171.8 ± 4.8 cm; body mass: 59.1 ± 5.3 kg; body fat: 14.6% ± 8.2%) participated in this study. Athletes followed a standard training program of 8 weekly sessions (~90 min/session) and were regularly engaged in national (i.e., national championships and cups) and international (i.e., G-1/E-1 and/or E-2 competitions, and/or European championships) competitions. In the week prior to the data collection, athletes conducted two familiarization sessions, with all the testing procedures, to minimize the learning effect (Chaabene et al., 2018), and the study was conducted during the competitive season. Athletes provided a written informed consent form after they were informed about the design of the study and the possible benefits and risks associated with it. For athletes under the age of 18, written informed consent was obtained from their parents or guardian. The study was approved by the Local Ethics Committee (University of Genoa, Italy. N. 2024/44) and was conducted according to the principles of the Declaration of Helsinki (World Medical Association, 2013).

2.3 Procedures

Prior to the first session, body height and composition were measured with a stadiometer (*Seca Model 217; SECA GmbH & Co. KG., Hamburg, Germany*) and a bioelectrical impedance scale (*Tanita BC-420 MA; Tanita Corp., Tokyo, Japan*), with 0.1 cm and 0.1 kg resolution, respectively. Both experimental sessions were preceded by a standardized warm-up routine consisting of 2 min of stepping and moving according to the taekwondo-specific techniques and 3 min of low-intensity taekwondo kicks, for a total of 5 min (Mesquita et al., 2020; Albuquerque et al., 2022). After 5 min of passive recovery, athletes performed the PSTT and sport-specific IT (i.e., 3 rounds × 2 min/1 min of recovery in-between) at the KF_{DP}, respectively. Before and after each round of the IT, three attempts of CMJ were allowed (Sant'Ana et al., 2021). Each attempt was made at the 15th, 30th, and 45th seconds of the recovery minute. Thus, a passive recovery interval of 15 s was applied between attempts. HR was continuously measured, beat-by-beat, during the PSTT and rounds of sport-specific IT. Total quality of recovery (TQR) (Kenttä and Hassmén, 1998) was assessed before, while rating of perceived exertion (RPE) (Borg, 1982) was evaluated after PSTT and sport-specific IT, respectively (Figure 1). The experimental sessions were conducted at the athletes' sports center, by a researcher (a taekwondo coach, ≥20 years of taekwondo experience and black belt), at the same time of day (10:00–12:00 a.m.), under similar temperature and humidity conditions (25°C–27°C and 46%–47%, respectively) to avoid any influence of the circadian rhythms.

FIGURE 1
Schematic representation of the study design. Notes: TQR: total quality of recovery scale; RPE: rating of perceived exertion scale; s: second; CMJ: countermovement jump; KF$_{DP}$: kick frequency at heart rate deflection point; min: minute.

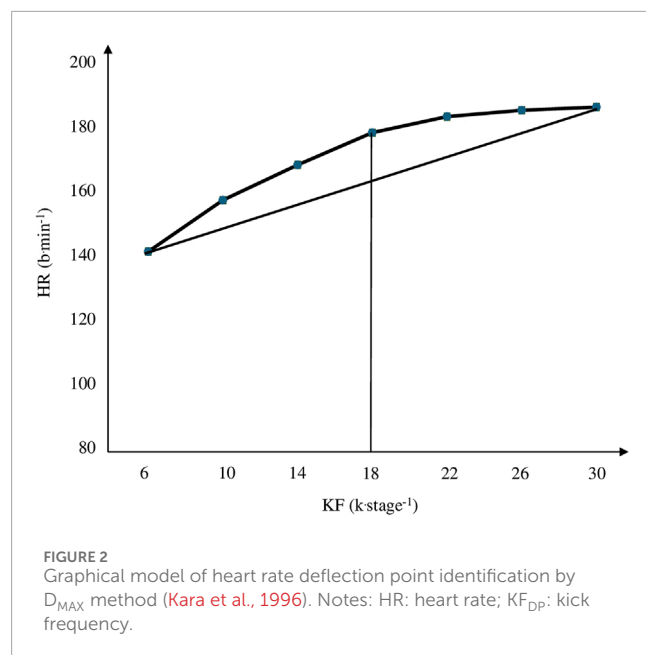## 2.4 Measures

2.4.1 Progressive specific taekwondo test

To perform the PSTT (Sant'Ana et al., 2019; Apollaro et al., 2024a), athlete executed the bandal-chagi (i.e., roundhouse kick) beginning with the right leg, in an area of about 2 × 2 m and using a punching bag equipped with a taekwondo body protector, positioned in same height of the athlete trunk. The first stage began with 6 kicks, alternating legs, and then progressively increasing 4 kicks on each new stage. During the test, athlete remained in step. The pace was dictated by sound signals with fixed intervals between each kick and with the intervals getting shorter every new stage, thus increasing the frequency of kicks. Sound signals were transmitted from a smartphone using the *ITStriker* app (*ETS4ME, São José, SC, Brazil*) containing the track of PSTT (Antonietto et al., 2021; Sant'Ana et al., 2021; Rodrigues et al., 2023; de Oliveira et al., 2024). Athlete was instructed to perform the bandal-chagi throughout the test, maintaining the same technical quality (it was considered adequate when the athlete lifted the knee, rotated the hips and delivered the kick horizontally into the target with the instep) and power of the kick (it was considered adequate when the instep impacted sonorously) as he/she would do in a competition to

score points. Figure 1 details the duration and the frequency of kicks for every stage of the PSTT. The following criteria was used to establish end: 1) the athlete fails to track the KF (determined by beep and controlled by the researcher); 2) the athlete performs the kicks without maintaining the technical and/or power standard effectively (controlled by the researcher); or 3) the athlete stops the test (volitional exhaustion). A tolerance not exceeding 2 consecutive technical failures is allowed.

During the PSTT, the *ITStriker* app and a HR monitor strap (Polar H10; Polar Electro Oy, Kempele, Finland) paired with the app were used to record the following variables: 1) maximal heart rate (HR$_{MAX}$) which is the heart rate recorded at the end of the test; 2) maximal kick frequency (KF$_{MAX}$) which is the highest frequency of kicks reached in the last stage of the test; 3) heart rate deflection point (HR$_{DP}$); 4) kick frequency at the HR$_{DP}$ (KF$_{DP}$); 5) total number of kicks (K$_{TOTAL}$); 6) time to exhaustion.

The HR$_{DP}$, an indirect indicator of the anaerobic threshold (AT) (Bodner and Rhodes, 2000), was identified using the D$_{MAX}$ method (Kara et al., 1996), similarly to previous studies (Sant'Ana et al., 2018; Sant'Ana et al., 2019; de Oliveira et al., 2024). According to de Assis Pereira et al. (2016), the D$_{MAX}$ method does not present significant differences from maximal lactate steady state velocity

FIGURE 2
Graphical model of heart rate deflection point identification by D_{MAX} method (Kara et al., 1996). Notes: HR: heart rate; KF_{DP}: kick frequency.

and there was a high agreement between them (through Bland and Altman analysis). The HR curve was adjusted *versus* the KF obtained at each stage of the PSTT by a polynomial function of third order. Then, the first and last points of the curve were connected by a straight line, and the most distant point of the curve to the line was considered as the HR_{DP}. Only values equal or greater than 140 b min^{-1} were used (Siahkouhian and Meamarbashi, 2013; de Assis Pereira et al., 2016). The KF at the stage corresponding to the HR_{DP} was called KF_{DP} (Figure 2).

2.4.2 Sport-specific interval training session

Athlete performed a sport-specific IT (i.e., 3 rounds × 2 min/1 min of recovery in-between), at the KF_{DP} identified during the PSTT, using a punching bag equipped with a taekwondo body protector, positioned in same height of the athlete trunk. The *ITStriker* app was used in the "training mode" to ensure that the individual KF_{DP} of each athlete was maintained throughout all rounds (Sant'Ana et al., 2021). Thus, the pace was dictated by sound signals, transmitted from a smartphone using the app, with fixed intervals between each kick. During each round of IT, HR was measured, using the *ITStriker* app and a HR monitor strap (Polar H10; Polar Electro Oy, Kempele, Finland) paired with the app, to record round HR (HR_{ROUND}) which is the HR recorded at the end of the round. To perform the IT, athlete executed the bandal-chagi (always alternating the legs and varying the technique with the front and back leg) and steps, hoopings, and movements characteristics of taekwondo between each kick. Athlete was instructed to perform the bandal-chagi throughout the IT, maintaining the same technical quality and power of the kick as he/she would do in a competition to score points.

2.4.3 Countermovement jump test

Athlete performed the CMJ on an electronic contact mat (*Globus Ergo Jump; Globus Inc., Codognè, Italy*), with an accuracy of 0.01 m, to determine the maximum height of the vertical jump. Each athlete

was instructed to stand on mat while keeping their hands on their hips. After that, he/she was asked to rapidly perform a downward squat movement and to jump vertically for maximum height after a verbal command. Before and after each round of the sport-specific IT, three attempts of CMJ were performed, and the highest jump height of each period was used in the data analysis (Sant'Ana et al., 2021). Each attempt was made at the 15th, 30th, and 45th seconds of the recovery minute. Thus, a passive recovery interval of 15 s was applied between attempts. The researcher provided standard verbal encouragement to all athletes during the CMJ tests. Within-session reliability of CMJ measures was computed using the intraclass correlation coefficient (ICC = 0.997, 95% CI = 0.993–0.999, $p <$ 0.001) and the coefficient of variation (CV = 4.5%). Flight time was measured using the contact mat and jump height (cm) was calculated as follows: $9.81 \times$ flight time^2/8 (Bosco et al., 1983). CMJ jump height and the athletes's body mass were used to calculate absolute peak power by the following equation of Sayers et al. (1999): absolute peak power (W) = 60.7 × jump height (cm) + 45.3 × body mass (kg) – 2055.

2.4.4 Perceptual measures

Recovery state was recorded 15 min before each experimental session using the TQR scale (a.u.) (Kenttä and Hassmén, 1998), which ranged from "very very poor recovery" (value 6) to "very very good recovery" (value 20). Immediately at the end (Tayech et al., 2020; Tayech et al., 2022) of PSTT and sport-specific IT, perceived exertion was evaluated using the Borg 6–20 RPE scale (a.u.) (Borg, 1982), which ranged from "very, very light" (value 6) to "*very, very hard*" (value 20).

2.5 Statistical analysis

Data analyses were performed using *Jamovi* software (*v. 2.3.28*; The Jamovi Project, Australia). Within-session reliability of CMJ test measures was computed using an average measures two-way random ICC with absolute agreement and 95% confidence intervals, and the CV. The ICC values were interpreted as follows: <0.5, poor; 0.5–0.75, moderate; 0.75–0.9, good; >0.9, excellent (Koo and Li, 2016). While, CV values were interpreted as follows: <5%: excellent agreement; <10%: very good agreement; <15%: acceptable; >15%: poor (Hopkins et al., 2009). The Shapiro–Wilk test revealed the normal distribution of all the considered variables. Therefore, data are presented as mean ± standard deviation [95% confidence intervals]. Pearson's correlation coefficient (r), with 95% confidence intervals, was used to examine relationships between HR_{DP}, identified during the PSTT, and HR responses during the rounds of sport-specific IT at the KF_{DP}. The magnitude of correlations was assessed using the following benchmarks: <0.1, trivial; 0.1–0.3, low; 0.3–0.5, moderate; 0.5–0.7, large; 0.7–0.9, very large; >0.9, nearly perfect; = 1, perfect (Hopkins et al., 2009). Repeated-measures ANOVA were performed, with Bonferroni's *post hoc* tests, to compare the HR_{DP}, identified during the PSTT, with HR responses, as well as the CMJ performance, during the rounds of sport-specific IT at the KF_{DP}. Assumption of sphericity was assessed using Mauchly test. A Greenhouse-Geisser correction factor was applied to the error and factor degrees of freedom if sphericity was violated. Partial eta-squared (η^2_p) was used as a measure of effect

TABLE 1 Descriptive statistics of Progressive Specific Taekwondo Test performance in taekwondo athletes (values are presented as mean ± standard deviation [95% confidence interval], n = 13).

Variable	Mean ± SD [95% CI]
Progressive specific taekwondo test	
TQR (a.u.)	18 ± 2 [17–19]
HR_{MAX} ($b \cdot min^{-1}$)	191 ± 5 [188–194]
KF_{MAX} ($k \cdot stage^{-1}$)	47 ± 6 [43–50]
KF_{MAX} ($k \cdot min^{-1}$)	43 ± 5 [40–47]
HR_{DP} ($b \cdot min^{-1}$)	169 ± 9 [163–175]
HR_{DP} (%HR_{MAX})	88 ± 4 [86–91]
KF_{DP} ($k \cdot stage^{-1}$)	23 ± 4 [21–25]
KF_{DP} ($k \cdot min^{-1}$)	20 ± 4 [18–22]
KF_{DP} (%KF_{MAX})	46 ± 7 [42–50]
K_{TOTAL} (n°)	303 ± 68 [262–344]
Time to exhaustion (s)	820 ± 94 [763–876]
RPE (a.u.)	18 ± 2 [17–19]

Notes: TQR: total quality of recovery scale; HR_{MAX}: maximal heart rate; KF_{MAX}: maximal kick frequency; HR_{DP}: heart rate deflection point; KF_{DP}: kick frequency at heart rate deflection point; K_{TOTAL}: total number of kicks; RPE: rating of perceived exertion scale.

size for the repeated-measures ANOVA, and values were interpreted as: <0.06, small; 0.06–0.14, moderate; >0.14, large (Cohen, 1988). In addition, Cohen's d was used as an effect size measure for the paired data and were graded as: <0.20, trivial; 0.20–0.59, small; 0.60–1.19, moderate; 1.20–2.00, large; >2.0, very large (Hopkins et al., 2009). Mean changes in CMJ performance after each round of the IT were compared with the smallest worthwhile change (SWC) calculated using baseline CMJ data as: 0.2 × between-subject SD; and minimal detectable change ($MDC_{95\%}$) determined as: standard error of measurement (SEM) × 1.96 × √2 (Weir, 2005; Haley and Fragala-Pinkham, 2006; Hopkins et al., 2009). Lastly, Pearson's correlation coefficient (r), with 95% confidence intervals, was also used to investigate relationships of perceptual measures (TQR and RPE) with HR responses and CMJ performance during the rounds of sport-specific IT. The magnitude of correlations was assessed as previously indicated. The statistical significance was accepted when $p < 0.05$.

3 Results

Table 1 shows PSTT performance in the taekwondo athletes tested.

Before the second experimental session, TQR recorded values of 17 ± 2 [16–18] a.u. During the entire sport-specific IT, athletes performed 116 ± 22 [103–129] kicks. RPE values, collected immediately at the end of the sport-specific IT, were 10 ± 2 [9–12] a.u.

Figure 3 reports the correlations between HR_{DP}, identified during the PSTT, and HR responses during the three rounds of sport-specific IT at the KF_{DP}.

Table 2 presents the HR responses during the three rounds of sport-specific IT at the KF_{DP}, identified during the PSTT. A main effect was found for HR responses during the rounds of sport-specific IT ($F_{9,941} = 1.487$; $p = 0.003$; $\eta^2_p = 0.453$, large). HR was significantly lower in round 1 ($p = 0.008$; $d = 1.14$, moderate) than HR_{DP}. In contrast, no difference was observed between the HR of rounds 2 ($p = 0.067$; $d = 0.83$, moderate) and 3 ($p = 0.653$; $d = 0.48$, small) and HR_{DP}. No difference emerged between the HR of round 1 and 2 ($p = 0.352$; $d = 0.58$, small). In contrast, HR was significantly lower in rounds 1 ($p = 0.011$; $d = 1.11$, moderate) and 2 ($p = 0.009$; $d = 1.13$, moderate) than in round 3.

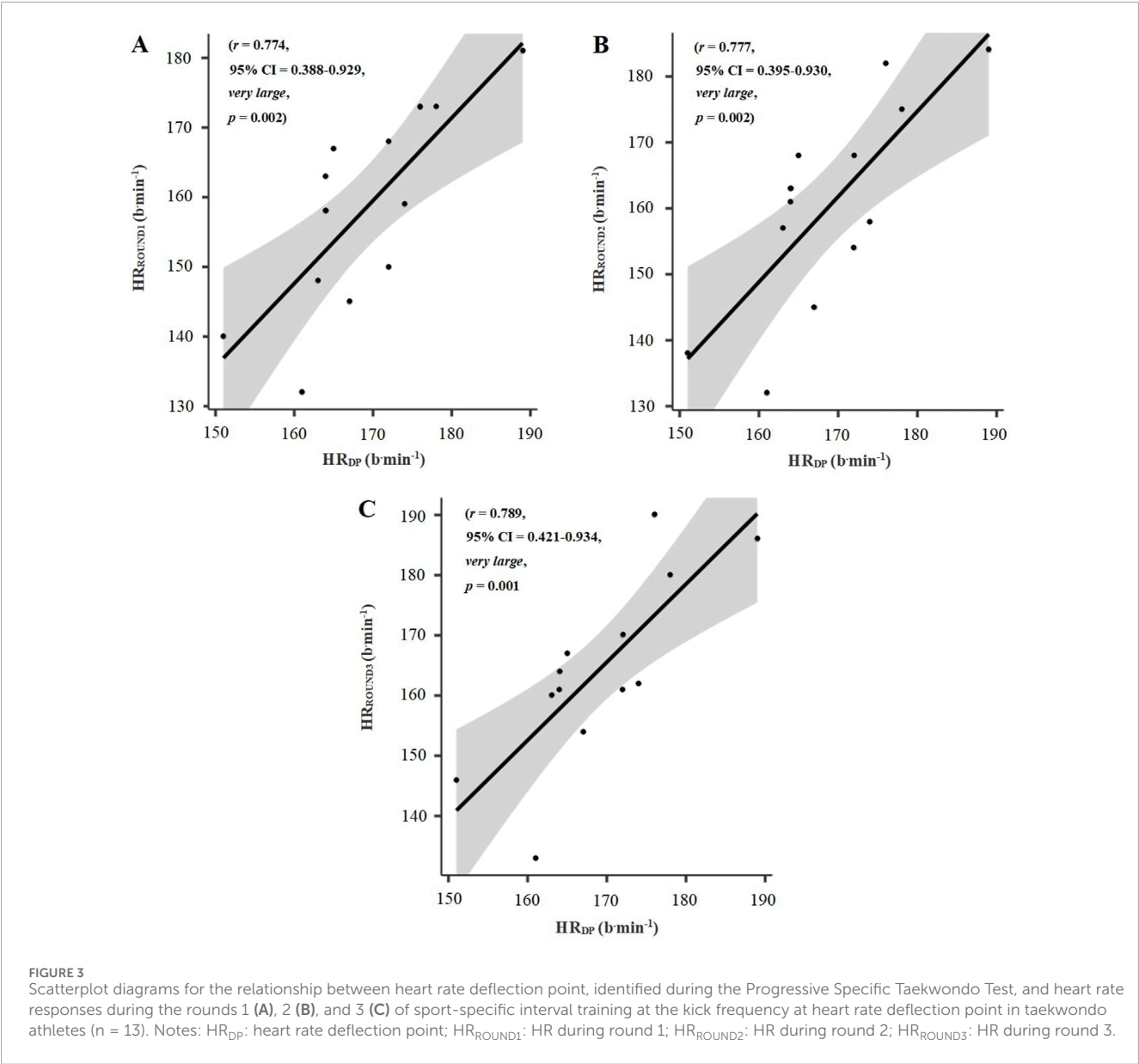Table 3 shows the CMJ performance pre, post, and between the interval of the rounds of sport-specific IT at the KF_{DP}, identified during the PSTT. A main effect was found for CMJ performance during sport-specific IT ($F_{4,144} = 3$; $p = 0.013$; $\eta^2_p = 0.257$, large). No difference was observed between pre- and post-IT CMJ performance ($p = 0.210$; $d = 0.66$, moderate), as well as between pre- and interval CMJ performance of rounds 1 ($p = 1.000$; $d = 0.06$, trivial) and 2 ($p = 1.000$; $d = 0.21$, small). No difference emerged between CMJ performance in round 1 interval and that in round 2 ($p = 1.000$; $d = 0.33$, small), while CMJ performance in round 1 interval was significantly lower ($p = 0.009$; $d = 1.13$, moderate) than that post-IT. In contrast, CMJ performance in the round 2 interval showed no difference with that post-IT ($p = 0.236$; $d = 0.64$, moderate).

$SWC_{0.2}$, SEM, and $MDC_{95\%}$ for baseline CMJ performance were 106 W, 55 W, and 153 W, respectively. The mean changes in CMJ performance, compared with baseline, were the following: Δ CMJ_{REST1}–CMJ_{PRE} = −6 W, −0.3%; Δ CMJ_{REST2}–CMJ_{PRE} = 18 W, 0.5%; Δ CMJ_{POST}–CMJ_{PRE} = 69 W, 2.7%.

Table 4 reports the correlations of perceptual measures (TQR and RPE) with HR responses and CMJ performance during the rounds of sport-specific IT at the KF_{DP}.

4 Discussion

The aim of this study was to prescribe a sport-specific IT session (which mimics the time structure of the official match), at the KF_{DP} identified during the PSTT, using the technical action of bandal-chagi, and to investigate HR response and muscle power performance, through CMJ tests, in taekwondo athletes. The first hypothesis was confirmed as the rounds 2 and 3 of sport-specific IT at KF_{DP} elicited HR responses similar to those observed at KF_{DP} during the PSTT as the required intensity corresponded to ~88% of the HR_{MAX}. In this context, the HR was significantly lower in IT round 1 than the HR_{DP}, due to the slow component of cardiovascular kinetics (i.e., to HR evolution as a function of time and exercise intensity) typical of exercise performed in the heavy domain (Jamnick et al., 2020). On the other hand, HR_{DP} was significantly and positively correlated with HR responses recorded during each round of the IT. The second hypothesis was also confirmed as the three rounds of sport-specific IT at KF_{DP} did not cause a decrease in muscle power performance assessed through

FIGURE 3
Scatterplot diagrams for the relationship between heart rate deflection point, identified during the Progressive Specific Taekwondo Test, and heart rate responses during the rounds 1 **(A)**, 2 **(B)**, and 3 **(C)** of sport-specific interval training at the kick frequency at heart rate deflection point in taekwondo athletes (n = 13). Notes: HR_{DP}: heart rate deflection point; HR_{ROUND1}: HR during round 1; HR_{ROUND2}: HR during round 2; HR_{ROUND3}: HR during round 3.

TABLE 2 Descriptive statistics of heart rate responses during the three rounds of sport-specific interval training at the kick frequency at heart rate deflection point, identified during the Progressive Specific Taekwondo Test (values are presented as mean $\pm$ standard deviation [95% confidence interval], n = 13).

	PSTT	Sport-specific interval training		
	HR_{DP}	HR_{ROUND1}	HR_{ROUND2}	HR_{ROUND3}
HR (b·min⁻¹)	169 ± 9 [163–175] †	158 ± 14 [149–167]	160 ± 16 [151–170]	164 ± 16 [155–174]‡

Notes: PSTT: progressive specific taekwondo test; HR: heart rate; HR_{DP}: heart rate deflection point; HR_{ROUND1}: HR, at the end of round 1; HR_{ROUND2}: HR, at the end of round 2; HR_{ROUND3}: HR, at the end of round 3. †: Significantly different from HR_{ROUND1} ($p < 0.01$); ‡: Significantly different from HR_{ROUND1} and HR_{ROUND2} ($p < 0.01$).

CMJ tests. Specifically, no difference was observed between pre- and post-IT CMJ performance, as well as between pre- and interval CMJ performance of rounds 1 and 2, supporting the idea that the KF_{DP} does not impair the neuromuscular system, in the high force production in small time intervals and in the recruitment of fast twitch muscle fibers, during the repeated bandal-chagi technical action (Sant'Ana et al., 2021).

Similarly to the aim of our study, Sant'Ana et al. (2021) investigated the acute effects of a sport-specific IT session (which mimics the time structure of the official match), performed at

TABLE 3 Descriptive statistics of CMJ performance pre, post, and between the interval of the rounds of sport-specific interval training at the kick frequency at heart rate deflection point, identified during the Progressive Specific Taekwondo Test (values are presented as mean ± standard deviation [95% confidence interval], n = 13).

	Sport-specific interval training			
	CMJ$_{PRE}$	CMJ$_{REST1}$	CMJ$_{REST2}$	CMJ$_{POST}$
CMJ (W)	2602 ± 528 [2284–2921]	2596 ± 547 [2266–2927]	2620 ± 561 [2281–2959]	2672 ± 537 [2347–2996] †

Notes: CMJ: countermovement jump; CMJ$_{PRE}$: CMJ, performance pre-IT; CMJ$_{REST1}$: CMJ, performance during interval between rounds 1 and 2; CMJ$_{REST2}$: CMJ, performance during interval between rounds 2 and 3; CMJ$_{POST}$: CMJ, performance post-IT., Significantly different from CMJ$_{REST1}$ ($p < 0.01$).

TABLE 4 Correlation coefficients of perceptual measures with heart rate responses during the three rounds and CMJ performance pre, post, and between the interval of the rounds of sport-specific interval training at the kick frequency at heart rate deflection point in taekwondo athletes (n = 13).

	CMJ$_{PRE}$ (W)	HR$_{ROUND1}$ (b·min⁻¹)	CMJ$_{REST1}$ (W)	HR$_{ROUND2}$ (b·min⁻¹)	CMJ$_{REST2}$ (W)	HR$_{ROUND3}$ (b·min⁻¹)	CMJ$_{POST}$ (W)	RPE (a.u.)
TQR (a.u.) r [95% CI] *Magnitude* *p*-value	0.011 [-0.543–0.559] *trivial* 0.971	0.241 [-0.358–0.699] low 0.428	−0.057 [-0.590–0.510] *trivial* 0.853	0.207 [-0.389–0.680] low 0.498	−0.016 [-0.562–0.540] *trivial* 0.958	0.166 [-0.423–0.657] low 0.587	−0.050 [-0.585–0.515] *trivial* 0.871	−0.365 [-0.763–0.233] *moderate* 0.220
RPE (a.u.) r [95% CI] *Magnitude* *p*-value	−0.301 [-0.731–0.300] *moderate* 0.318	0.519 [-0.044–0.832] *large* 0.069	−0.313 [-0.737–0.288] *moderate* 0.298	0.573 [0.032–0.854] *large* 0.041	−0.304 [-0.732–0.297] *moderate* 0.313	0.642 [0.141–0.881] *large* 0.018	−0.305 [-0.733–0.296] *moderate* 0.311	–

Notes: TQR: total quality of recovery scale; RPE: rating of perceived exertion scale; CMJ: countermovement jump; CMJ$_{PRE}$: CMJ, performance pre-IT; HR: heart rate; HR$_{ROUND1}$: HR, at the end of round 1; CMJ$_{REST1}$: CMJ, performance during interval between rounds 1 and 2; HR$_{ROUND2}$: HR, at the end of round 2; CMJ$_{REST2}$: CMJ, performance during interval between rounds 2 and 3; HR$_{ROUND3}$: HR, at the end of round 3. CMJ$_{POST}$: CMJ, performance post-IT.

the KF$_{DP}$ found in the PSTT, on HR responses and CMJ test performance. They found that only the HR in IT round 1 was significantly lower at HR$_{DP}$. In contrast, rounds 2 and 3 elicited HR responses similar to those observed at KF$_{DP}$ during the PSTT and significantly greater than that of round 1 (Sant'Ana et al., 2021). In this context, although Sant'Ana et al. (2021) also documented expected HR responses, it is important to highlight that they allowed athletes during the IT to perform kicks with technical variations and combining up to three kicks per sound signal that might have altered the KF required of the athlete by generating intensity-specific responses. In contrast, in our study athletes performed the single technical action of bandal-chagi for each sound signal to reproduce the same KF required to athletes at HR$_{DP}$ during the PSTT, with deep objective to provide a basic methodological control step and consequently incentivize the use of HR$_{DP}$ and KF$_{DP}$ to tailor the intensity of IT. Therefore, the current results support in the first instance the validity of the aerobic capacity indicators derived in the PSTT, to prescribe sport-specific training, and provide a basis for understanding and structuring future ITs that reflect more closely the technical-tactical demands of competitions.

In line with our results, Sant'Ana et al. (2021) found that the three rounds of sport-specific IT at KF$_{DP}$ did not cause a decrease in muscle power performance as no difference was observed between pre- and post-IT CMJ performance, as well as between pre- and interval CMJ performance of rounds 1 and 2. In this context, if kicks with technical variations and up to three kicks for each sound signal, in the IT protocol implemented by Sant'Ana et al. (2021), did not cause a decrease in muscle power performance, it was consequently conceivable that the single technical action of bandal-chagi for each sound signal would provide similar results.

Recent studies have documented the positive influence of muscle power, as assessed by the CMJ test, on the ability to repeat high-intensity intermittent efforts in an anaerobic sport-specific taekwondo test (Albuquerque et al., 2022; Apollaro et al., 2024c). In addition, Sant'Ana et al. (2017) found a significant decrease in bandal-chagi impact after a sport-specific time-to-exhaustion test performed at the KF$_{MAX}$ found in the PSTT. In this sense, the fact the KF$_{DP}$ does not impair muscle power performance and does not generate fatigue is fundamental to support the validity of HR$_{DP}$ and KF$_{DP}$, derived from PSTT, for the prescription of sport-specific IT directed at aerobic capacity conditioning in taekwondo. Additionally, Sant'Ana et al. (2021) also found that after the three rounds of the IT there was a 3.1% improvement in CMJ performance compared with pre, by assuming a post-activation potentiation effect. Similarly, the present study showed that after three rounds of the IT there was a 2.7% improvement in CMJ performance compared with pre. However, the comparison of this increase with SWC$_{0.2}$ and MDC$_{95\%}$ did not show a useful change such as to assume a practical change related to a post-activation potentiation effect.

In addition, we also investigated the relationships between the perceptual measures, recorded pre- and post-IT (i.e., TQR and RPE, respectively), and heart rate responses during the three rounds and CMJ performance pre, post, and between the interval between rounds. No significant relationship emerged between TQR and heart rate responses, as well as between TQR and CMJ performance. The TQR reflects the athlete's general and subjective psycho-physical state and may therefore not be a good predictor of immediate physiological response. In fact, HR can be influenced by several factors other than exercise intensity (e.g., warm-up, environmental temperature, hydration, etc.), as well as the current state of the

neuromuscular system may reflect the type of activity performed and the level of motivation. In parallel, significant relationships emerged between RPE and HR recorded during rounds 2 and 3 of the IT, while no significant relationships emerged between RPE and CMJ performance. In this context, it is important to highlight that the relationship between RPE and HR tends to increase in magnitude round by round. This trend suggests a possible alignment between physiological and perceived exertion load with the intensification of cardiovascular demands throughout the rounds. On the other hand, an inverse relationship logically characterizes the relationship between RPE and CMJ performance, although the lack of significance supports the idea that KF_{DP} does not compromise the neuromuscular system. Finally, no significant relationship emerged between TQR and RPE. This could be justified by the fact that the TQR may be underestimated or overestimated by athletes as it is recorded before training and therefore relates to a relatively long and general period of time. On the contrary, RPE is recorded immediately after a specific type of exercise, thus reflecting the situation at that moment.

The typical intermittency of combat activity generates post-match official [La] values ranging from 6.7 ± 2.5 to 14.0 ± 4.2 mmol L^{-1} (Apollaro et al., 2024b), and during the day of competition the athlete could perform up to 4–6 times. Therefore, the oxidative system is attributed a central role in supporting the recovery process between matches, particularly in the recovery of pH (Apollaro et al., 2024a). In this sense, the prescription of sport-specific training directed at improving aerobic capacity in the taekwondo athletes is one important aspect for performance improvement in this sport and should be based on carefully determined thresholds and training zones (Sant'Ana et al., 2019; Sant'Ana et al., 2021). In this context, the next step of research in this field should focus on studying long-term adaptations to this type of training. Sant'Ana et al. (2011) tested the effects of sport-specific IT (i.e., 4 rounds × 3 min/3 min of active recovery in-between), at a stage higher than KF_{DP} and combined with strength and technical-tactical training, on PSTT aerobic capacity and power indicators after an 8-week training period. They found no changes in aerobic capacity indicators (but a strong trend toward significance for KF_{DP}), while they did find a significant increase in KF_{MAX} and K_{TOTAL}, indicating an improvement in aerobic power. Although this study is the only evidence currently available and involved a very limited number of athletes, it is reasonable to assume that sport-specific aerobic training can improve key aerobic indicators. On the other hand, it is important to highlight that given the substantial increase in the number of national and international level competitions, sport-specific aerobic capacity training can be a valuable tool for coaches in the post-competition period to promote optimal recovery (Apollaro et al., 2024a). Moreover, during the off-season, when general conditioning methods such as running are usually emphasized, this type of training can be a more specific alternative, allowing athletes to maintain technical engagement, improve aerobic efficiency, and elicit specific energy dynamics (Sant'Ana et al., 2011; dos Santos et al., 2018). Among the sport-specific tests currently available for the assessment of endurance in taekwondo, the PSTT is the most studied and used in practice (Apollaro et al., 2024a). It allows the determination of both aerobic capacity (i.e., HR_{DP} and KF_{DP}) and power indicators (i.e., HR_{MAX} and KF_{MAX}), based on HR, useful for the prescription

of sport-specific training (Sant'Ana et al., 2017; Sant'Ana et al., 2021). In the present study, the HR_{DP} was identified at ~88% of the HR_{MAX}, in line with previously reported in taekwondo athletes during the execution of the PSTT (Sant'Ana et al., 2009; Sant'Ana et al., 2011; dos Santos et al., 2018; Sant'Ana et al., 2018) and within the range documented in the literature (Ribeiro et al., 1985; Bunc et al., 1995; Bodner and Rhodes, 2000).

4.1 Limitations and future directions

First, the sample, although not underpowered, includes a limited number of national/international athletes from the junior/senior age categories, which limits the generalizability of the results to athletes from other competitive level (i.e., state/regional) and/or age categories (i.e., cadets). Second, we prescribed a sport-specific IT, which mimics the time structure of the official match, only at the KF_{DP}. In this regard, it might be appropriate to investigate HR responses and muscle power performance also at KF immediately above and below KF_{DP}, to further support the practical validity of aerobic capacity indicators and the results of our study. In parallel, sport-specific ITs with a longer time structure than the official match should also be prescribed, as the duration of the sessions is an aspect to be considered for the improvement of aerobic capacity and the interpretation of HR responses and muscle power performance. Third, it was previously found that the HR_{DP} and KF_{DP} in the PSTT were not different and significantly correlated with the HR_{AT} and KF_{AT} during a sport-specific constant load test at the fixed concentration of 4 mmol·L^{-1} of [La] (Sant'Ana et al., 2009). However, measurements of [La] and VO_2 should be included to provide a direct comparative analysis to improve the experimental external validity and to expand the understanding of internal load with the aim of supporting the validity of HR_{DP} as an indirect indicator of AT. Finally, Sant'Ana et al. (2017) documented test-retest ICCs of 0.98 and 0.97 for the KF_{MAX} and HR_{MAX}, respectively, in the PSTT. However, the implementation of electronic body protector and the elimination of the skipping between kicks could objectify the high- and low-intensity phases to the benefit of test-retest reliability (Apollaro et al., 2024a). Consequently, it would also become possible to study inter-/intra-rater reliability of the PSTT, since the evaluator's task would be limited to just checking the KF.

4.2 Practical applications

The HR_{DP} and KF_{DP}, identified during the PSTT, can be used as valid indicators of aerobic capacity to prescribe a sport-specific IT that mimics the time structure of the official match. In this regard, the current and previous findings (Sant'Ana et al., 2021) suggest that the technical variation and the number of kicks for each sound signal need an appropriate adjustment of the KF, based on the estimated time to perform the different techniques (Falcó et al., 2011), to ensure that the attack/skipping ratio of the KF_{DP} is properly maintained by consequently generating distinct physiological responses. Finally, the *ITStriker* app is a low-cost tool that can be easily used during the execution of the PSTT to automatically derive internal and external load parameters and for their subsequent use in "training mode".

5 Conclusion

The PSTT allows the determination of both aerobic capacity (i.e., HR_{DP} and KF_{DP}) and power indicators (i.e., HR_{MAX} and KF_{MAX}) useful for subsequent prescription of sport-specific training. In the present study, we prescribed an IT session (which mimics the time structure of the official match), at the KF_{DP} identified during the PSTT, in which athletes performed the single technical action of bandal-chagi for each sound signal. During IT rounds, expected HR responses emerged and muscle power performance was not compromised. Overall, the present results support the validity of aerobic capacity indicators, derived from the PSTT and based on heart rate, for the prescription of sport-specific training in taekwondo.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by Local Ethics Committee (University of Genoa). The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation in this study was provided by the participants' legal guardians/next of kin.

Author contributions

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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