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The effects of different work: Rest durations on physiological, neuromuscular, and ratings of perceived exertion responses during taekwondo-specific high-intensity interval training

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ABSTRACT

Purpose: To investigate the effect of different work: rest durations on physiological, neuromuscular, and perceived exertion responses during taekwondo-specific high-intensity interval training (HIIT).

Methods: Thirteen moderate-trained taekwondo athletes (age: 21.7 ± 2.4 years; body mass: 69.1 ± 7.6kg; height: 174 ± 6 cm) completed a familiarization session and three HIIT trials. The trial consisted of three rounds of 2 min roundhouse kicks with 1 min of rest in between. In each round, the work: rest ratio was constant at 1:2, and the work: rest duration varied to be: short (2s:4s), medium (10s:20s), and long (20s:40s). Heart rate (HR) and oxygen uptake ($\dot{V}O_2$) were continuously measured. Blood lactate concentration ([La$^-$]), countermovement jump (CMJ), and rating of perceived exertion (RPE) were recorded before trials and after each round. Energy contribution was estimated.

Results: HR, $\dot{V}O_2$, and CMJ were similar across protocols ($P > .05$) but, [La$^-$] was higher during long than short work: rest duration protocol ($P < .05$). Relative aerobic energy contribution and RPE in round 3 were higher during long than short work: rest duration protocol ($P < .05$). Absolute and relative glycolytic energy contribution in rounds 1 and 2 were higher during long than short work: rest duration protocol ($P < .05$). Relative phosphate energy contribution in rounds 1 and 3 was lower during long than short work: rest duration protocol ($P < .05$).

Conclusion: Different work: rest durations of taekwondo-specific HIIT influenced [La$^-$], energy system contributions, and RPE. The longer work: rest duration protocol (20s:40s) stressed more the glycolytic, aerobic energy systems and perceived exertion, and less the phosphagen energy system.

1. Introduction

Taekwondo has been in the Olympic Games program since the 2000 Sydney Olympics, with the competitions consisting of three 2 min rounds with a 1 min recovery intervals. Athletes execute high-intensity offensive and defensive bouts during combat, and these are interspersed with longer periods of low-intensity actions. Research indicated taekwondo bouts range from 7 to 39, with 70–80 % of them lasting less than 2 s,[1] and the work: rest ratio varies widely, from 1:2 to 1:7.[2] It seems that the aerobic system accounts for 58.4–66.0 % to the total energy supply during a match, phosphagen system accounts for 25.9–30.0 %, and the glycolytic system 4.0–4.5 %.[3–5] These varying demands can lead to a wide range of physiological stressors during competition. Significant physiological responses have been observed, including oxygen uptake (VO_2) ranging from 46.9 to 63.0 ml min^{-1}·kg^{-1}, heart rate (HR) exceeding 90 % of maximum heart rate (HR_{max}), and blood lactate concentration ([La$^-$]) spanning from 6.1 to 14 mmol L^{-1}.[1]

High-intensity interval training (HIIT) is widely recognized as one of the most effective methods for improving cardiorespiratory and metabolic function, thereby enhancing the physical performance of athletes.[6] HIIT involves repeated short-to-long bouts of rather high-intensity exercise interspersed with recovery periods.[6] HIIT is commonly integrated

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into training programs of combat sports, such as judo, karate, and wrestling, to enhance both aerobic and anaerobic energy systems.[7–9] Previous studies have focused on the intensity of taekwondo exercises in short-duration sequences lasting from 10 s to 3 min during various conventional activities in taekwondo.[10,11] Matsushigue et al. proposed the possibility of performing taekwondo-specific HIIT based on the time structure and the physiological responses observed during taekwondo competitions.[12] Subsequently, Haddad et al. reported that the taekwondo-specific HIIT induced similar HR responses, perceived exertion and training loads as did short-duration interval running in adolescent taekwondo athletes.[13] Batra et al. and Ouergui et al. further indicated that taekwondo-specific HIIT not only improves VO_{2max} and anaerobic capacity but also the agility of athletes.[14,15] Nevertheless, there are many differences in HIIT protocols among these studies, including the duration of each single bout (i.e., 6s, 10s, 30s), the work: rest ratios (i.e., 1:1, 1:2, 1:3), the inter-set rest intervals (i.e.,1 min, 4 min), and the overall training load.

At least nine variables can be manipulated to prescribe different HIIT sessions,[16] and the intensity and duration of work and rest intervals are the key influencing factors.[17] In practice, taekwondo athletes typically use a work: rest ratio of 1:2 with work: rest durations of 10s:20s and 20s:40s for taekwondo-specific HIIT. However, these work: rest durations significantly exceed the time of each bout of taekwondo combat. Previous research indicated that when maintaining a constant work: rest ratio, an increase in work duration will also increase the glycolytic energy contribution and the Rating of perceived exertion (RPE) in running and rowing.[18,19] Given the bouts in taekwondo competitions are typically very short (less than 2 s[1]), more research is needed on the physiological responses during this kind of bout.

As we all know, during the preparatory and competitive phases of the season, coaches or practitioners formulate long-term training protocols and exercise prescriptions to enhance athletes' competitive abilities and performance. Different particular HIIT protocols will impose varying internal loads or stresses on athletes, including physiological responses, neuromuscular fatigue, and perceived exertion.[18] Understanding the differences among them is of utmost significance and value in aspects such as training periodization, load monitoring, preventing overuse, or overtraining to avoid injuries or promote recovery.

Therefore, the purpose of the present study was to compare the physiological responses, neuromuscular fatigue, and perceived exertion across different work: rest durations during taekwondo-specific HIIT. It was hypothesized that the longer work: rest duration would elicit higher physiological responses, neuromuscular fatigue, and perceived exertion.

2. Methods

2.1. Participants

A sample size of 12 was determined a priori using G*Power (version 3.1.9.2) based on a repeated-measures analysis of variance using a within factors design (alpha = .05, power = .80, effect size = .25, correlation among repeated measures = .6). Thirteen moderate-trained (between tier 2 and tier 3) college-level taekwondo athletes,[20] including nine males (age 22.2 ± 2.5 years; body mass 70.8 ± 7.1 kg; height 176 ± 6 cm) and four females (age 20.7 ± 2.4 years; body mass 65.2 ± 8.4 kg; height 1.70 ± 4 cm) volunteered to participate in this study. They were all training 10–15 h per week and had been practicing taekwondo for 7 ± 2 years, reporting no injuries or illnesses in the 6 months preceding the study. Participants were instructed not to consume alcoholic beverages for one week, suspend resistance training for 72 h, and avoid exercising for 24 h prior to the trials. Before the trials, athletes were informed of the procedures, including the possible risks involved, and signed an informed consent form. The study protocol received approval from the Ethics Committee of Shanghai University of Sport (102772021RT132).

2.2. Design

During the first visit to the laboratory, the demographics and other information of the participants were collected, and the participants were familiarized with the trial process. Following that, they completed the 2 s, 10 s, and 20 s maximum capacity of the roundhouse kick test. During this session, athletes had to perform roundhouse kicks as fast as possible on a free-standing punching bag and the number of kicks executed by each athlete was recorded to ascertain the training intensity, reported as the number of kicks per second. Simple randomization was used in this study using a randomization table designed by Microsoft Excel. On subsequent visits to the laboratory, participants randomly performed three different HIIT protocols. The design of the three protocols was consistent with the competition, which is divided into three rounds of 2 min roundhouse kicks and 1 min rest between rounds. During the HIIT protocols, the work: rest ratio was constant at 1:2 but the work: rest duration varied. Three configurations of work: rest duration was used; the short (2s:4s), the medium (10s:20s), and the long one (20s:40s). Testing sessions were separated by at least 24 h of rest. All tests were conducted in the laboratory during the winter and the environmental conditions were similar in all trials (temperature:14–18 °C, relative humidity: 43–55 %, and barometric air pressure:1013–1030 mbar).

2.3. Experimental sessions

Before the start of each trial, athletes performed a 10-min standardized warm-up including running, dynamic stretching, countermovement jump, and roundhouse kicks. Subsequently, the athletes had a 10 min break before the beginning of the main trial. During this period, athletes were connected to the heart rate (Polar Accurex Plus, Polar Electro, Finland) and the portable gas analyser (Metamax 3B, Cortex, Germany). A pre-test $[La^-]$ was collected and the baseline countermovement jump (CMJ) performance was recorded. The athletes then started 3 rounds of 2 min of roundhouse kicks under specific instructions, with the intensity of the exercise being set at 2 beats/s based on the pre-test results, using continuous left and right roundhouse kicks to a free-standing punching bag equipped with electronic protector (JS-JT01, Jijin Smart, China). During this period, an auxiliary helped to stabilize the sandbag, and the effectiveness of roundhouse kicks was monitored by the electronic point recording system. During the rest intervals following each round, $[La^-]$, RPE, and CMJ metrics were collected. After the end of the last round, athletes were instructed to remain seated quietly for 6 min to allow the measurement of post-exercise oxygen consumption (see Fig. 1).

2.4. Cardiopulmonary measures

HR and $\dot{V}O_2$ were continuously monitored throughout the testing protocol. The mean heart rate (HR_{mean}) and oxygen uptake ($\dot{V}O_2mean$) during exercise were calculated based on the averages recorded over the 2 -min of each round. The peak heart rate (HR_{peak}) was defined as the highest value during each round., while peak oxygen uptake ($\dot{V}O_2peak$) was defined as the highest 15 s average value of $\dot{V}O_2$ measured during each round.[21]

2.5. Blood lactate

$[La^-]$ were collected under resting conditions, immediately after round 1 and round 2, and immediately, 3, 5, and 7 min after exercise. The lactate samples, amounting to 10 μl each, were extracted from the participant's earlobe and analyzed using the blood lactate analyzer (Biosen S_Line, EKF Diagnostics, Germany).

2.6. Energy system contribution calculation

Estimates of aerobic, anaerobic lactic ($W_{[la-]}$), and anaerobic alactic system use was carried out through the measurement of oxygen consumption during activity, the peak blood lactate concentration, and the fast phase of excess oxygen consumption after exercise ($EPOC_{fast}$), respectively.[5] Aerobic energy (W_{aer}) was calculated from VO_2 above rest, caloric-equivalent-adjusted for the corresponding respiratory-exchange ratio and body mass using the formula W_{aer} (J) = VO_2 (ml) × caloric equivalent (J·ml^{-1}). The resting VO_2 was defined as 3.5 ml kg^{-1}·min^{-1} for females and 4.0 ml kg^{-1}·min^{-1} for males.[22] $W_{[la]}$ was determined from changes in pre-and post-round blood lactate (Δ [la$^-$]), O_2-lactate equivalent, caloric equivalent, and body mass using formula $W_{[la]}$ (J) = Δ [la$^-$] (mmol·L^{-1}) × O_2-lactate equivalent (ml·kg^{-1}·mmol·L^{-1}) × caloric equivalent (J·mL^{-1}) × body mass (kg) with the O_2-lactate equivalent of 3 ml kg^{-1}·mmol·L^{-1} and a caloric equivalent of 21.131 J mL^{-1}.[23]

Repayment of high-energy phosphates (W_{pcr}) was assumed to correspond to the fast component of post round oxygen uptake (VO_{2pcr}) and calculated from the latter and its caloric equivalent of 21.1311 J mL^{-1}: W_{pcr} (J) = VO_{2pcr} (ml) × caloric equivalent (J/ml).[23] W_{pcr} was estimated considering the oxygen consumption during the interval between rounds and the $EPOC_{fast}$ after the round 3.[23] The time course of the VO_2 in the recovery after exercise was in templated using a bi-exponential function as described by: $VO_2(t) = a\ e^{-t/\tau a} + b\ e^{-t/\tau a} + c$.[24] where $VO_2(t)$ is the oxygen uptake at time t, a and b are the amplitudes of the fast and slow components, respectively, τa and τb the corresponding time constants and c is the VO_2 at rest.

2.7. Countermovement jump

Countermovement jump has been one of the most used trials for monitoring neuromuscular status in individual and team sports.[25] CMJ performance assessment was conducted pre-trial and after each round utilizing a wireless portable jump test mat, with good reliability [ICC = .89, 95 %CI (.76–.95)] (Smart Jump, Canberra, Australia).[26] Participants commenced in an upright standing posture with hands on hips. Upon auditory cue, the subject executed a rapid squat followed by an explosive upward leap, exerting maximal effort. It was imperative that during the flight phase, the subjects' legs remained perpendicular to the mat surface. Upon landing, each individual absorbed the impact in a controlled manner before returning to a fully erect stance. Two CMJs were performed, separated by 10 s, and the average value was used in the results.

2.8. Rating of perceived exertion

The rating of perceived exertion (RPE), as per the Borg scale ranging from 6 to 20,[27] was employed to quantify the subjective load experienced during each interval training bout.[28] To ensure that the RPE scores solely reflected the effort of the interval training, they were obtained from the athletes immediately subsequent to each round. Prior to the commencement of the study, all participants were thoroughly acquainted with the use of the RPE scale to guarantee accurate self-assessment.

2.9. Statistical analysis

Data was analyzed using IBM SPSS Statistics 26 (SPSS Institute, Chicago, IL, USA). The Shapiro-Wilk test was applied to assess the normality of data distribution. All data was normally distributed. The variables were compared using a two-way (trial × round) analysis of variance (ANOVA) with repeated measurements. The wholeness of the data for all study variables was verified in accordance with the Mauchly test, and the Greenhouse-Geisser adjustment was used when the sphericity assumption was violated. The Bonferroni test was used as post hoc

Table 1
Changes in the physiological responses and energy system contribution during trials.

	2s:4s			10s:20s			20s:40s		
	Round 1	Round 2	Round 3	Round 1	Round 2	Round 3	Round 1	Round 2	Round 3
HR_{mean} (beat·min^{-1})	159.8 ± 10.3	171.6 ± 6.9^a	176.1 ± 9.7 ^{ab}	158.8 ± 10.2	170.5 ± 6.8^a	175.8 ± 5.4 ^{ab}	160.2 ± 6.8	172.1 ± 5.8^a	175.3 ± 6.8 ^{ab}
HR_{peak} (beat·min^{-1})	173.7 ± 8.5	181.0 ± 7.3^a	185.7 ± 7.1 ^{ab}	173.3 ± 8.8	180.0 ± 7.3^a	184.5 ± 6.9 ^{ab}	176.8 ± 6.2	182.6 ± 5.4^a	185.5 ± 6.3 ^{ab}
VO_{2mean} (ml·kg^{-1}·min^{-1})	32.9 ± 4.3	37.8 ± 4.3^a	39.0 ± 4.5^a	33.5 ± 3.3	36.8 ± 2.9^a	38.0 ± 3.7^a	33.5 ± 3.4	37.5 ± 3.7^a	37.3 ± 3.2^a
VO_{2peak} (ml·kg^{-1}·min^{-1})	42.2 ± 5.2	44.0 ± 4.4	45.6 ± 5.7^a	41.2 ± 3.9	42.7 ± 3.9	44.4 ± 3.7^a	40.6 ± 3.1	43.1 ± 4.0^a	43.1 ± 4.0
[La$^-$], mmol·L^{-1}	4.22 ± 1.60	6.32 ± 2.12^a	7.92 ± 2.51 ^{ab}	4.87 ± 1.34	7.80 ± 2.27^a	9.32 ± 2.70 ^{ab}	6.30 ± 2.34 *	9.90 ± 3.50^{a}*	12.13 ± 3.89 ^{ab}*
W_{pcr} (kJ)	38.15 ± 14.72	35.63 ± 14.32	37.42 ± 14.55	33.63 ± 8.17	34.98 ± 9.20	31.96 ± 12.22	28.74 ± 11.49	32.09 ± 11.70	23.63 ± 9.34 *
$W_{[La]}$ (kJ)	12.15 ± 5.87	9.39 ± 3.81	7.23 ± 2.98^a	15.35 ± 6.69	13.07 ± 5.42	6.73 ± 4.27 ^{ab}	21.63 ± 8.57 *	16.14 ± 6.23^{a}*	9.91 ± 3.28 ^{ab}
W_{aer} (kJ)	76.53 ± 11.42	87.96 ± 13.94^a	91.74 ± 13.66^a	82.48 ± 10.18	94.90 ± 10.58^a	97.34 ± 12.64^a	90.39 ± 11.93 *	99.87 ± 15.47^a	99.30 ± 11.12^a
W_{total} (kJ)	126.83 ± 20.52	132.98 ± 23.25	136.39 ± 24.12^a	131.46 ± 11.35	142.95 ± 15.25^a	136.01 ± 22.51	140.76 ± 22.68	148.10 ± 25.15	132.84 ± 16.51 ^{b}

Note: HR_{mean} = mean heart rate; HR_{peak} = peak heart rate; VO_{2mean} = mean oxygen uptake; VO_{2peak} = peak oxygen uptake; W_{aer} = aerobic energy; W_{pcr} = anaerobic alactic energy; $W_{[La]}$ = anaerobic lactic energy; W_{total} = total energy; 2s:4s = short work: rest duration protocol; 10s:20s = medium work: rest duration protocol; 20s:40s = long work: rest duration protocol. ^{a} $P < .05$ = significantly different from round 1; ^{b} $P < .05$ = significantly different from round 2; *$P < .05$ = significantly different from the short work: rest duration protocol.

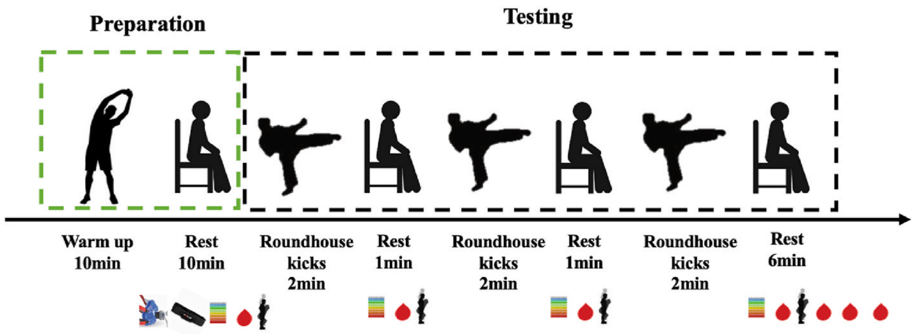


Fig. 1. Experimental protocol.

test. The statistical significance level used was $P < .05$. Partial eta squared (η_p^2) is a measure of effect size for repeated measures ANOVA. The effect sizes were categorized as follows: small ($.01 \le \eta_p^2 \le .06$), moderate ($.06 \le \eta_p^2 < .14$), or large ($\eta_p^2 \ge .14$).[29] Data is presented as mean and standard deviation unless otherwise stated.

3. Results

The differences on physiological responses and energy system contribution are presented in Table 1. For HR_{mean} ($F_{(1.369,\ 49.282)} = 142.620$, $P < .001$, $\eta_p^2 = .798$) and HR_{peak} ($F_{(1.246,\ 44.870)} = 16.794$, $P < .001$, $\eta_p^2 = .318$), there was a round effect, with higher values during round 3 compared with round 1 and 2. For VO_{2mean} ($F_{(1.688,60.762)} = 91.850$, $P < .001$, $\eta_p^2 = .718$) and absolute aerobic energy contribution ($F_{(1.385,\ 49.858)} = 48.833$, $P < .001$, $\eta_p^2 = .576$), there was a round effect, with higher values during round 2 and 3 compared with round 1. For $[La^-]$, there was a round and trial interaction effect ($F_{(6,108)} = 6.232$, $P < .001$, $\eta_p^2 = .257$), with higher values during round 3 compared with round 1 and 2. Moreover, the long work: rest duration elicited higher values compared with short work: rest duration. For absolute glycolytic energy contribution, there was a round and trial interaction effect ($F_{(4,72)} = 2.852$, $P = .030$, $\eta_p^2 = .137$), with lower values during round 2 and 3 compared with round 1. Moreover, the long work: rest duration elicited higher values compared with short work: rest duration during round 1 and 2.

The differences on the percentages of the three energy system contributions were presented in Fig. 2, respectively. For relative aerobic energy contribution, there was a round effect ($F_{(2,72)} = 29.272$, $P < .001$, $\eta_p^2 = .448$), with higher values during round 3 compared with round 1. Moreover, long work: rest duration elicited higher values compared with short work: rest duration during round 3. For relative glycolytic energy contribution, there were round ($F_{(1.697,3.393)} = 57.208$, $P < .001$, $\eta_p^2 = .614$) and trial ($F_{(2,36)} = 5.765$, $P = .007$, $\eta_p^2 = .243$) effects, with medium and long work:rest durations eliciting lower values during round 3 compared with round 1 and 2. Moreover, long work:rest duration elicited higher values compared with short work:rest duration during round 1 and 2. For relative phosphate energy contribution, there were round ($F_{(1.599,57.581)} = 3.538$, $P = .045$, $\eta_p^2 = .089$) and trial ($F_{(2,36)} = 7.214$, $P = .002$, $\eta_p^2 = .286$) effects, with short work: rest duration eliciting lower values during round 2 compared with round 1. Moreover, long work: rest duration elicited lower values compared with short work: rest duration during round 1 and 3.

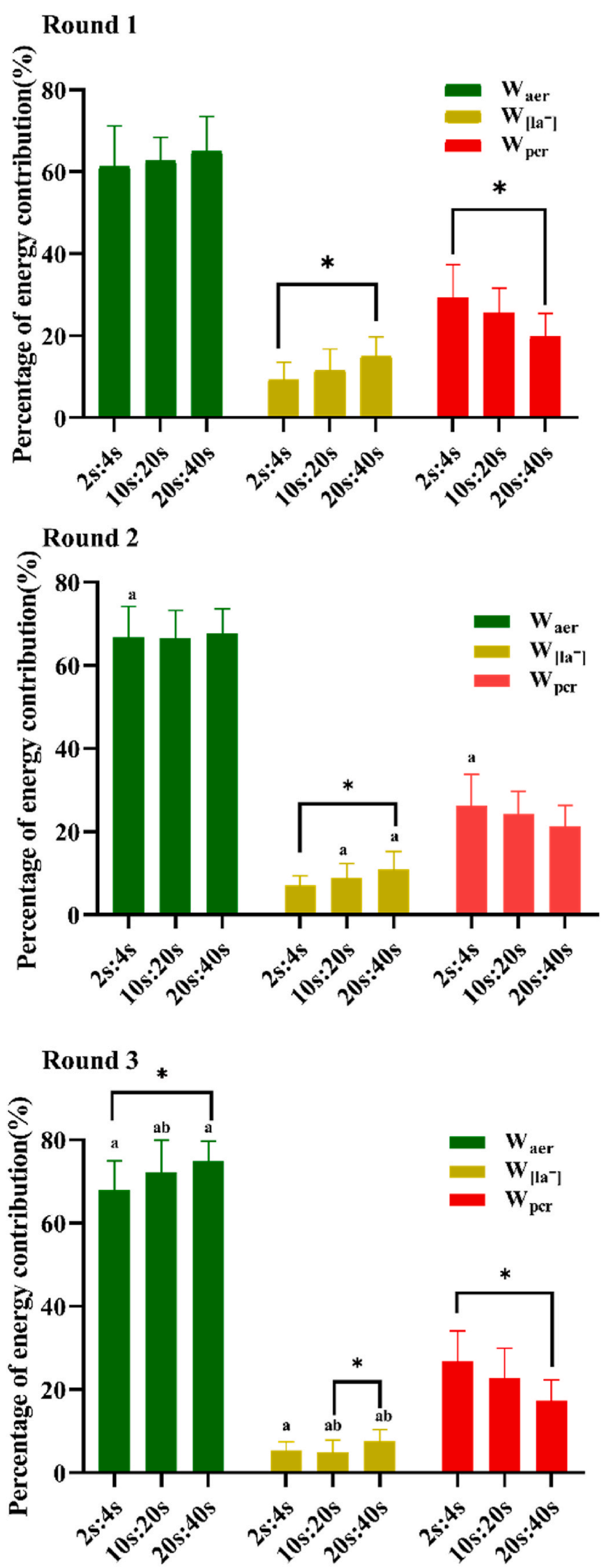
The differences on the CMJ and RPE were presented in Table 2. There was no difference in baseline CMJ and RPE across three protocols ($P > .05$). For CMJ, there was a round effect ($F_{(3,\ 108)} = 4.572$, $P = .010$, $\eta_p^2 = .113$), with lower values during round 3 compared with baseline and round 1 in long work: rest duration. For RPE, there was a round and trial interaction effect ($F_{(3.325,\ 59.842)} = 3.031$, $P = .032$, $\eta_p^2 = .144$), with higher values during each subsequent round. Moreover, long work: rest duration elicited higher values compared with short work: rest duration during round 3. The accumulative RPE of the three work: rest durations from round 1 to 3 were 3.0 ± 1.4, 4.3 ± 1.4, and 4.4 ± 1.5, respectively. There were differences among the trials ($F_{(2,\ 24)} = 7.383$, $P = .003$, $\eta_p^2 = .381$), and the short work: rest duration was significantly lower than the medium and long work: rest duration.

4. Discussion

The main findings of the present study confirmed partially our hypotheses, that different work: rest duration of taekwondo-specific HIIT induced different physiological responses, perceived exertion, and similar neuromuscular fatigue. Specifically, the longer work: rest duration protocol stressed the aerobic, glycolytic energy system, and perceived exertion, and less the phosphagen energy system. To our knowledge, this is the first study so far in this field. The findings can be used for taekwondo coaches to prescribe sport-specific HIIT protocols.

This study examined the proportion of three energy system contributions across short, medium, and long work: rest duration protocols. The data showed that the percentage of energy contributions in the three protocols was different, with relative aerobic contribution increasing in round 3 irrespective of the work: rest duration. Moreover, the longer work: rest duration results in higher reliance on the aerobic energy system in round 3. The findings match those observed in earlier studies with repeated sprints on the bike,[30] indicating that during the last sprint, power output was supported by the energy that was mainly derived from phosphocreatine degradation and increased aerobic metabolism. However, regardless of the work: rest duration of taekwondo-specific HIIT, the aerobic energy system was the major source of energy throughout the exercise (61–75 % of total energy contribution), followed by the phosphagen (17–29 % of total energy contribution), and the glycolytic (5–12 % of total energy contribution). The selection of the most suitable HIIT protocol to maximize aerobic system improvements requires further investigation. Further analysis revealed that for the short work: rest duration protocol, the proportions of energy system contribution closely mirror those observed during simulated competitions.[3,5] In contrast, the extended work: rest duration protocols deviate from these simulated competition characteristics, resulting in increased engagement of the aerobic and glycolytic energy systems, along with a substantial reduction in phosphagen system utilization. The findings match those observed in previous studies, indicating that extended work: rest duration protocols yield higher $[La^-]$.[31,32]

In the present study, there was little effect of taekwondo-specific HIIT on CMJ (i.e., a decrease was only identified in rounds 2 and 3 from baseline for the long work: rest duration protocol, Table 2), which was attributed to lower neuromuscular fatigue. This lower neuromuscular fatigue ensures good power output and movement quality throughout multiple rounds of training. Previous studies had shown



(caption on next column)

Fig. 2. Changes in percentage of energy contribution across three trials.
Note: W_{aer} = aerobic energy; W_{pcr} = anaerobic alactic energy; $W_{[La]}$ = anaerobic lactic energy; 2s:4s = short work: rest duration protocol; 10s:20s = medium work: rest duration protocol; 20s:40s = long work: rest duration protocol. $^{a}P < .05$ = significantly different from round 1; $^{b}P < .05$ = significantly different from round 2; $^{*}P < .05$ = significantly different from the short work: rest duration protocol. $^{\#}P < .05$ = significantly different from the medium work: rest duration protocol.

significant neuromuscular fatigue after repeated 30 s cycling sprints or 300-m runs.[33] Furthermore, while not implying cause and effect, impairment in muscle function during high-intensity exercise is generally accompanied by high blood lactate levels, i.e. > 10–12 mmol L^{-1}.[34] Compared with long work: rest duration, short and medium work: rest duration did not induce neuromuscular fatigue, which may be due to the shorter single work duration and less glycolysis energy contribution. Nevertheless, whether such a long work: rest duration protocol will induce kinematic changes and risk of injuries, further study is needed.

Numerous preceding investigations have corroborated the use of the RPE as an indicator of training intensity during HIIT.[35,36] Seiler et al. reported that RPE increased by 2–4 Borg scale units over all of the interval sessions.[31] Similarly, the present study elicited an increase of 3–4 Borg scale units during the three protocols. Our data also supported the findings of Astrand et al., indicating that HIIT protocols with longer work:rest durations might have increased the RPE, due to higher [la^{-}].[37] Additionally, further analysis indicated that the changes in RPE during short work: rest duration protocol mirrored those reported by Bridge et al. in the international taekwondo competitions.[32] Specifically, the RPE ranged from 11 in round 1 to 13 in round 2, and then to 14 in round 3, with perceived exertion levels ranging from “light” to “hard”.

Cluster sets (CSs) is a popular resistance training strategy categorized by short rest periods implemented between single or groups of repetitions.[38] CS training increases the frequency or duration of rest through CS structures, a factor that favors the resynthesis of creatine phosphate. Consequently, this type of training reduces neuromuscular fatigue, promotes fatigue recovery, and decreases the perceived fatigue.[38–41] Although HIIT and strength training are two different training formats, the underlying principles of changing from long to short work: rest duration format are similar. According to the findings of this study, the short work: rest duration protocol can decrease the metabolic stress, and perceived fatigue, and may potentially reduce the decline in movement quality or power output when conducting multiple rounds of high-intensity training by increasing the frequency of rest. Therefore, coaches can choose the short work: rest duration protocol to complete the same training volume with minimal internal load/pressure and perceived fatigue, or they can choose the long work: rest duration protocol with a high blood lactate content and a fatiguing effect to meet the training requirements. In addition, during the preparatory phase of periodized training, it is necessary to ensure that athletes complete sufficient training volume while preventing the risk of overtraining. Given that the short work: rest duration protocol is more specific to the real game situation and induces lower metabolic stress and perceived fatigue, it can be an alternative method of periodized training.

Several limitations must be considered when interpreting the current findings. First, the sample size was relatively small (N = 13), including both male and female participants. This limited sample size may affect the generalizability of the results, and physiological differences between genders could have influenced the outcomes. Additionally, resting oxygen consumption was estimated rather than directly measured, which introduces potential error and reduces the precision of the data.

5. Conclusions

In the 2 min × 3 rounds of taekwondo-specific HIIT, athletes showed comparable VO_2, HR, and neuromuscular fatigue across different work: rest durations protocols, while the long work: rest duration protocol

Table 2
Changes in the CMJ and RPE during trials.

	CMJ (cm)			RPE		
	2s:4s	10s:20s	20s:40s	2s:4s	10s:20s	20s:40s
Baseline	37.34 ± 5.54	37.56 ± 5.47	37.89 ± 6.69	7.8 ± 1.5	7.3 ± 1.4	7.5 ± 1.5
Round 1	37.20 ± 6.31	37.14 ± 5.12	36.17 ± 6.49	11.2 ± 1.2[a]	10.9 ± 1.6[a]	11.8 ± 1.9[a]
Round 2	36.91 ± 7.68	37.11 ± 5.12	35.30 ± 6.00[a]	13.2 ± 1.5 [ab]	13.5 ± 1.8 [ab]	14.1 ± 1.9 [ab]
Round 3	36.91 ± 6.78	36.83 ± 5.20	34.10 ± 6.44 [ab]	14.2 ± 1.7 [abc]	15.2 ± 1.8 [abc]	16.2 ± 2.0 [abc]*

Note: CMJ = counter movement jump; RPE = rating of perceived exertion 2s:4s = short work: rest duration protocol; 10s:20s = medium work: rest duration protocol; 20s:40s, long work:rest duration protocol. [a] $P < .05$ = significantly different from baseline; [b] $P < .05$ = significantly different from round 1; [c] $P < .05$ = significantly different from round 2. *$P < .05$ = significantly different from short work: rest duration protocol.

induced higher [La$^-$], and higher RPE. The major source of energy for the three protocols was the aerobic system, followed by the phosphagen system, with the glycolytic system contributing the least. The long work: rest duration protocol may be suitable for fatigue training, while the short work: rest duration protocol serves as an effective aerobic-based HIIT for developing the game-specific aerobic energy system without inducing excessive fatigue.

Author statement

Hang Zheng: Conceptualization, Methodology, Formal analysis, Writing- Original draft.
Guochao Zhang: Resources, Data curation.
Yuming Zhong: Resources, Visualization,
George P. Nassis: Review and Editing.
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Conflict of interest

The authors declare no conflict of interest.

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