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Effects of different work-to-rest ratios of high-intensity interval training on physical performance and physiological responses in male college judo athletes☆

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1. Introduction

Judo is an intermittent and metabolically demanding combat sport in which the main goal is to obtain an ippon (full point, achieved via throwing, immobilization, strangling, or elbow locking through various techniques) or score multiple technical points.[1,2] A judo match has a regular duration of typically lasts for 4 min, and it can be ended with an ippon at any time or extended into extra time when if a tie occurs at the conclusion of regular time.[3] A study indicated that the judo match primarily relies on aerobic energy systems, whereas the scoring actions require both strength and power, which are supported by the anaerobic energy systems.[4] Judo athletes perform many actions, including approaching, gripping disputes, attacking, defensive actions, and groundwork attempts, during each match, and medal contenders have to complete 5–7 matches in a single competition.[5] Thus, judo athletes need to develop muscular power, strength, and endurance to be successful in competitions.

High-intensity interval training (HIIT), which is characterized by short bouts of above-maximal lactate steady-state intensity exercises separated by periods of insufficient recovery,[6] is a time-efficient method to develop both aerobic and anaerobic endurance and repeated power performance.[7,8] HIIT has been used in combat sports (e.g., judo, taekwondo, wrestling, and boxing) as a complement to standard sports-specific training for a long time, but it has drawn increased attention from researchers only in the past 20 years.[9]

Proper HIIT protocols are beneficial for judo training due to its high-intensity and intermittent nature.[10,11] However, research on HIIT in judo is limited, primarily focusing on aerobic and anaerobic adaptations. In one of these studies, Lee et al.[12] found that combining standard judo training with HIIT (treadmill sprints, 30 s:240 s, 6–10 reps, fourth per week, over 12 weeks) increased VO_{2max} more significantly for judo athletes compared to the control group (CG). Similarly, Kim et al.[13] observed significant improvements in anaerobic mean and peak power among well trained male judo athletes using a similar but shorter HIIT protocol (8 weeks), with no significant impact on VO_{2max} levels. Franchini et al.[14] examined the effects of three short-term (4 weeks), low-volume (twice/week) HIIT protocols (upper-body, lower-body, and uchi-komi) combined with standard judo training. The uchi-komi HIIT group showed improved peak power in both upper- and lower-body Wingate tests. Based on karate research on karate, a 7-week HIIT program conducted twice a week resulted in significant improvements in aerobic and anaerobic performance among elite karate athletes.[15] To optimize performance outcomes and prevent overtraining, judo athletes should employ effective periodization strategies, considering their frequent participation in competitions throughout the year. Previous research suggests that training sessions lasting 4–7 weeks, twice a week, can effectively improve the aerobic and anaerobic performance of judo and karate athletes. However, the duration and frequency of these training periods may be adjusted based on individual athletes' seasonal and training needs, with short-term intensified training periods of 4–6 weeks being commonly utilized in judo due to its unique demands.

These studies used general performance tests instead of judo-specific tests, likely due to the lack of specific assessments for various aspects of judo performance. Studies have suggested that performance disparities

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among judo athletes were observed in tests such as medicine ball put (MBP),[16] countermovement jump (CMJ),[17] VO_{2max},[16] and mean/peak power.[18] Correlations were found between medicine ball throws and high-intensity time during judo matches.[19] The Cunningham and Faulkner Anaerobic Test showed a relationship between high:low intensity ratio and couple throws in judo matches, while VO_{2max} and Vertical Jump were associated with effective actions during matches.[19] Moreover, the number of throws in the special judo fitness test (SJFT) correlated with the 30-m sprint and VO_{2max} estimated by the 20-m multistage shuttle run test.[20] The SJFT index (heart rate immediately after the test + heart rate 1 min after the test)/number of throws) related to agility in the 4 × 9-m test.[21] Furthermore, a correlation was identified between the number of te-waza techniques used in simulated competitions and post-arm Wingate test blood lactate levels ($r = 0.85$).[22] Additionally, blood lactate levels after a judo combat correlated with post-arm Wingate test blood lactate levels ($r = 0.69$).[22] Therefore, this study employed suitable general tests to comprehensively assess judo athletes' physical performance and physiological responses.

The primary components of HIIT protocols are the intensity and duration of exercise and recovery intervals.[23] These parameters determine the work-rest ratios, which have been varied in previous studies, ranging from 3:1 for aerobic interval exercise[24] to 1:12 for HIIT.[25] In a taekwondo study by Seo et al.,[26] a 4-week HIIT with a 1:4 work-rest ratio (30 s:120 s) resulted in significant improvements in aerobic and anaerobic performance in adolescent athletes compared to the ~~1:2 group (30 s:60 s)~~ CG, while showing similar effects on anaerobic power and capacity as the 1:8 group (30 s:240 s). Another acute study in 2013[27] demonstrated that a 10 s:10 s work-rest ratio led to higher VO_2 levels during active intervals compared to a 30 s:30 s work-rest ratio. However, a different study[28] used a fixed work duration of 40 s and completed 6 sets of HIIT with varying rest intervals: 40 s (1:1), 120 s (1:3), and 200 s (1:5). The results showed that blood lactate concentration increased in the 1:1 and 1:3 groups during the 5th and 6th sets, while the 1:5 group reached peak blood lactate earlier with lower values, likely due to longer rest intervals. In contrast, Ceylan et al.[29] conducted judo-specific HIIT with a fixed work duration of 20 s and varying rest durations of 10, 20, 40, and 60 s. Lactate measurements taken at different time points after exercise were similar. Currently, no published article compares the chronic training effects of HIIT protocols with different work-rest ratios on the aerobic and anaerobic performance of judo athletes.

Judo matches typically last 3–4 min[30] with efforts of 20–30 s and interruptions of around 10 s,[10,11] resulting in a work-rest ratio of approximately 2:1–3:1. Based on this structure and previous studies, we designed a study to investigate the effects of two HIIT protocols on judo athletes: 3:1 (30 s:10 s) and 2:1 (20 s:10 s). We also compared these results with a ~~standard~~ judo training group. We hypothesized that (1) the adopted two HIIT protocols would be effective in improving aerobic power and (2) the post-training anaerobic power and capacity in the 2:1 group would be better than that in the 3:1 group.

2. Method

2.1. Experimental approach to the problem

A randomized controlled study was designed to investigate the effects of HIIT with work–rest ratios of 3:1 and 2:1 on male college judo athletes' physical performance and physiological responses. All subjects completed a pre-test battery within 1 week before starting the intervention. After the pre-tests, the subjects were randomly assigned to either the 2:1 group, the 3:1 group, and the ~~control group~~ CG for 6 weeks of intervention. Post testing was performed 1 week after the cessation of the intervention. The experimental design is presented in Fig. 1. All athletes were informed of the risks and benefits of this study before signing a written informed consent form. This study was approved by the Ethics Committee of Guangzhou Sport University (approval number 2021LcLL-18), and all experimental procedures followed the tenets of the Declaration of Helsinki.

2.2. Subjects

Initially, 60 male college judo athletes aged 19–22 years were recruited from Guangzhou Sport University. The inclusion criteria in this study were as follows: (1) medalists in provincial or national youth judo competitions, (2) having regular judo training sessions, (3) without any cardiovascular disease or musculoskeletal injuries in the past 6 months, and (4) voluntary participation. Twelve of them were excluded from the intervention procedure: five had injuries, five declined to participate, and two were participating in another experiment. Forty-eight eligible subjects were randomly allocated to one of three groups: (1) the 3:1 group ($n = 16$; age = 19.7 ± 0.7 yr; height = 173.6 ± 4.4 cm; body mass = 72.3 ± 11.9 kg; and training experience = 4.7 ± 1.2 yr); (2) the 2:1 group ($n = 16$; age = 19.8 ± 0.7 yr; height = 174.5 ± 6.6 cm; body mass = 73.4 ± 11.3 kg; and training experience = 4.8 ± 2.2 yr); and (3) the ~~control group~~ CG ($n = 16$; age = 20.1 ± 0.8 yr; height = 175.9 ± 7.2 cm; body mass = 72.0 ± 11.2 kg; and training experience = 4.5 ± 2.0 yr). During the intervention period, the athletes underwent four judo training sessions per week, along with one strength training session.

2.2.1. Training protocol

To control for the potential influence of overall training volume and conditioning, all participants followed a similar daily training program during the study period. Due to the competition schedule, a 6-week period was chosen for this training program. Consequently, in addition to daily judo training, HIIT protocols were performed for 6 weeks with two sessions per week. The 2:1 group performed two sets of nine repetitions of 20:10-s high-intensity training. The 3:1 group performed two sets of six repetitions of 30:10-s high-intensity training. The ~~control group~~ CG continued its regular training program as before. The specific movements used in the HIIT protocols include O-soto-gari, O-goshi,

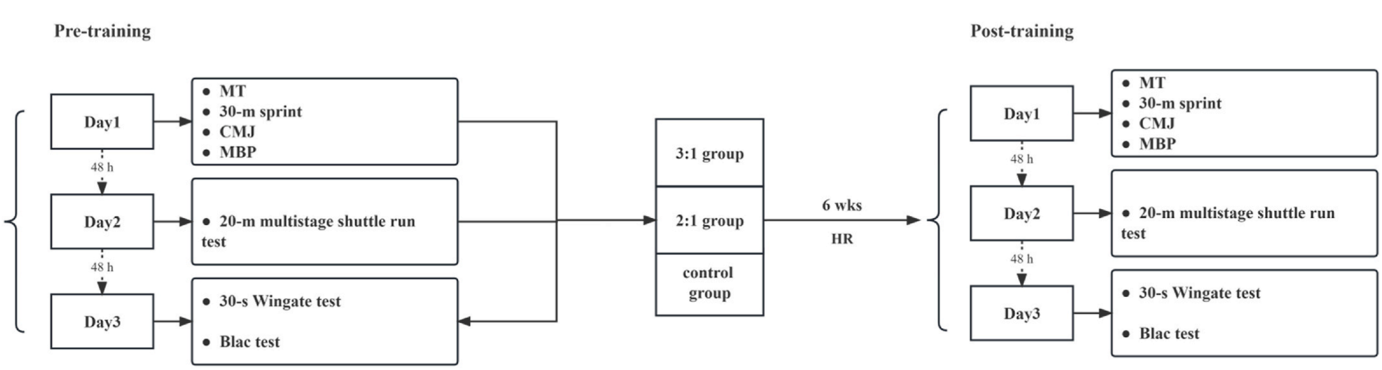

Fig. 1. Experimental design diagram. MT, Modified T-test; CMJ, countermovement jump; MBP, medicine ball put; Blac test, blood lactate test; HIIT, high-intensity interval training; 3:1 group, HIIT group with a work-rest ratio of 3:1; 2:1 group, HIIT group with a work-rest ratio of 2:1; HR, heart rate.

Seoi-nage, burpees, specific jump drills, and crunning (running on four limbs). These movements are present in Fig. 2. O-soto-gari, O-goshi, and Seoi-nage were performed using a cloth dummy that weighed 50% or 60% of the subjects' body mass (Table 1).

The exercise intensity was monitored using a heart rate monitor (Team2, POLAR, Finland) during training. Supervisors closely monitored changes in the heart rate (HR) of participants using a HR monitor. If a participant's HR during exercise dropped below 85% of his individual maximum heart rate during exercise, the supervisors encouraged him to intensify his efforts and increase the exercise intensity, with a 10-s positive rest interval. Regrettably, the HR monitor used in this study malfunctioned, hindering data export for each session. This is a limitation of the study.

Participants were asked before each session if they wished to continue. If a participant was unable to continue due to injuries, illnesses, or any other reason, they were instructed to stop. Participants were required to sign after completing the training. Any participant who missed more than two training sessions was excluded from the analysis. In the 3:1 group, four participants missed 1 or 2 training sessions, resulting in an average attendance rate of 96.9%. In the 2:1 group, eight participants missed 1 or 2 sessions, leading to an average attendance rate of 94.3%. In the CG, three participants missed 1 or 2 sessions, resulting in an average attendance rate of 97.9%.

The subjects were instructed to continue their normal diet and refrain from alcohol and caffeine.

2.3. Procedures

Given that this study primarily aimed to investigate the training effects of HIIT with different work-rest ratios, and considering that the results obtained from the general tests can provide valuable insights for other sports in the combat sport or different types of sports. Therefore, to ensure the test could be completed within the limited time available, we made the decision to prioritize the use of more suitable general tests.

The performance assessments, including change of direction (COD), speed, power, aerobic power, and anaerobic power and capacity tests, were performed both 1 week before and after the training intervention. Measurements were performed on 3 separate days, with a 48-h interval, following the same order for both pre-tests and post-tests. All subjects were familiarized with the test protocols and experimental devices in advance. The subjects were also instructed to avoid strenuous exercises and to sleep at least 7 h within 24 h before each test day. Testing was started with a warm-up consisting of 5 min of jogging and 10 min of dynamic stretches as directed by the researcher.

The repeated tests required for the intra-class correlation coefficient (ICC) analyses were not conducted for the 20-m multistage shuttle run test and the 30-s Wingate test due to resource constraints. These constraints include limited equipment and funds, which result in substantial demands on time and personnel resources. The ICC analysis for the Modified T-test, 30-m sprint test, Countermovement jump test, and Medicine ball put test was conducted with a sample size of 16 participants, and the interval duration between repeated tests was set at 3–5 min.

2.3.1. Modified T-test

A modified T-test (MT)[31] was used to assess COD ability. In this test, four markers were placed at points A, B, C, and D, forming a T, and the subjects moved according to route A–B–C–D–B–A. The distance between A and B was 5 m, and the distance between B and C and between B and D is both 2.5 m, which differs from the traditional T-test. Each subject underwent twice trials, and the optimal score was recorded. Time was recorded using a stopwatch, and the optimal measurement was considered. The ~~intra-class correlation coefficient (ICC)~~ for the test-retest reliability was 0.902.

2.3.2. 30-m sprint test

The 30-m sprint test was used to assess the speed performance of the subjects. The tests were performed on a synthetic track. Time was recorded using wireless photocell gates (Timing Systems, Brower, USA). The subjects started from a standing position with their front foot placed 20 cm behind the timing gate. The optimal performance of two tests was adopted for the analysis. The ICC for the test-retest reliability was 0.935.

2.3.3. Countermovement jump test

CMJ is one of the most commonly used methods for leg power assessment. The subjects stood on a vertical jump mat, with hands on their waist, jumping vertically upward as far as possible after a quick squat. A vertical jump mat (SmartJump, Fusion Sport, Australia) was used to measure the height of CMJ. The optimal score of two tests was recorded as the result. The ICC for the test-retest reliability was 0.957.

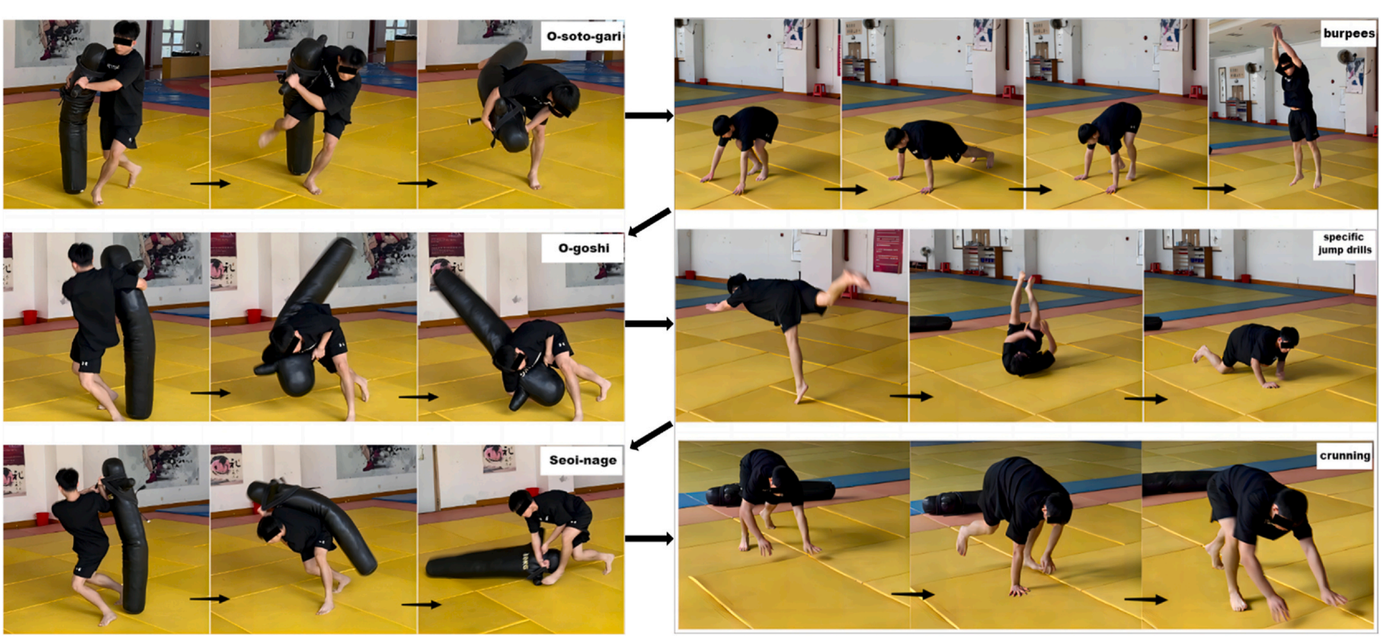

Fig. 2. Specific movements. Performed these movements in the order from left to right.

Table 1
Details of HIIT protocols for 6 weeks.

Weeks						
	Sets/reps	Specific movements	Weight of dummy	Sets/reps	Specific movements	Weight of dummy
0	Pretest					
1–3	[2 × 9 × (20:10 s) × (≥85% HR_{max})]/2.5 min	O-soto-gari, burpees, O-goshi, specific jump drill, Seoi-nage,	50% Body weight	[2 × 6 × (30:10 s) × (≥85% HR_{max})]/2.5 min	O-soto-gari, burpees, O-goshi, specific jump drill, Seoi-nage,	50% Body weight
4–6	Total work time: 6 min	crunning	60% Body weight	Total work time: 6 min	crunning	60% Body weight
7	Posttest					

HIIT, high-intensity interval training; HR_{max}: maximum heart rate. [2 × 9 × (20~~s~~:10 s) × 85% HR_{max}]/2.5 min means two sets of nine repetitions of 20:10-s HIIT with the heart rate higher than 85% individual HR_{max}, and the interval between sets was 2.5 min. 20:10 s means the work duration is 20 s and the rest duration is 10 s.

2.3.4. Medicine ball put test

The MBP test is a reliable and valid method to evaluate upper-body power in college students.[32] The test was performed using an adjustable bench with the upper and lower halves of the bench adjusted at an angle of 135° and a 9-kg medicine ball. The subjects sat on the bench, pushed the ball forward with both hands, and kept their body on the bench throughout the test, and the testers recorded the distance from the ball's landing point to the initial position. Each subject performed the test twice with the furthest distance used for the analysis. The concurrent validity between the MBP test and the bench press power test was 0.861 for men.[32] The ICC for the test-retest reliability was 0.926.

2.3.5. 20-m multistage shuttle run test

The 20-m multistage shuttle test was performed to evaluate the athletes' aerobic capacity. The subjects continuously performed 20-m shuttle runs to keep pace with the audio signals. Testers gave verbal encouragement until the subjects were not able to maintain the required speed three consecutive times. The final speed in the last completed stage was recorded to calculate the maximum oxygen uptake (VO_{2max}) using the formula $VO_{2max} = 31.025 + 3.238X - 3.248A + 0.1536AX$, where A is the age and X is the final speed.[33]

2.3.6. 30-s Wingate test

A Wingate test was performed to assess the subjects' anaerobic power and capacity using a cycle ergometer (Ergomedic 894 E, Monark Exercise AB, Sweden). The height of the seat was adjusted according to each subject. The subjects performed a warm-up of 5-min pedaling, followed by a 3-min rest. Then, the subjects performed a 30-s all-out test with a resistance of 7.5% body mass. Subjects were encouraged to push as hard as they could during the test. Peak power (PP), relative peak power (PP/kg), average power (AP), relative average power (AP/kg), and power drop (PD) were considered in the analysis.

Capillary blood samples were collected from the subjects' fingertips 3, 5, 10, and 15 min after the Wingate test. Blood lactate concentration was analyzed using a portable lactate analyzer (Lactate Scout 4, Leipzig, Germany). The lactate elimination rate ([La]ER) was calculated using the following formula:

[La]ER = (peak lactate concentration − minimum lactate concentration)/peak lactate concentration.

2.4. Statistical analyses

Data analyses were performed with academic statistics software (SPSS 25.0, IBM, New York, USA). Data were reported as mean ± standard deviation. The normality of the variables was verified using the Shapiro–Wilk test. ICC was used to examine the test–retest reliability of variables. Two-way repeated measures analysis of variance (ANOVA) was applied to determine significant main effects and/or an interaction. In the event of a significant interaction or main effects were observed, Bonferroni's post-hoc tests were used to determine differences. The Greenhouse–Geisser correction was performed if the sphericity assumption was violated. To assess the magnitude of differences, effect sizes were calculated using partial eta squared (η_p^2) for repeated measures ANOVA and Cohen's d for post-hoc tests. The threshold values of η_p^2 were ≤0.01 (trivial), >0.01–0.06 (small), >0.06–0.14 (moderate), and >0.14 (large).[34] The threshold values of Cohen's d were ≤0.20 (trivial), >0.20–0.50 (small), >0.50–0.80 (moderate), and >0.80 (large). The level of statistical significance was set at $p < 0.05$.

3. Results

The aerobic power, agility, speed, power, anaerobic power and capacity of the 3:1 group, 2:1 group, and ~~control group (~~CG~~)~~ are presented in Table 2.

3.1. Change of direction and speed

COD was assessed using the MT. For the T-test, statistical results indicated a significant main effect for time ($F = 74.215$, $p < 0.001$, $\eta_p^2 = 0.623$) and a significant interaction for time * group ($F = 4.842$, $p = 0.012$, $\eta_p^2 = 0.177$). There were significant decreases in MT after the training period in the 3:1 group (−9.2%, $p < 0.001$, 95%CI: 0.73 to −0.40, $d = -2.11$ (large)), the 2:1 group (−6.8%, $p < 0.001$, 95%CI: 0.60 to −0.27, $d = -1.14$ (large)), and the CG (−3.4%, $p = 0.012$, 95% CI: 0.38 to −0.05, $d = -0.71$ (medium)). The MT of the 3:1 group (5.65 ± 0.29 s) was significantly better than that of the CG (6.04 ± 0.31 s) post-training ($p = 0.004$, 95%CI: −0.67 to −0.11).

Speed was assessed using the 30-m sprint. For the 30-m sprint, no significant main effects for time ($F = 0.704$, $p = 0.406$, $\eta_p^2 = 0.015$) or group ($F = 1.924$, $p = 0.158$, $\eta_p^2 = 0.079$), and no significant interaction for time * group ($F = 1.326$, $p = 0.276$, $\eta_p^2 = 0.056$), were found.

3.2. Power

Power was assessed using the MBP and CMJ tests. For the CMJ test, there were no significant main effects for time ($F = 0.135$, $p = 0.715$, $\eta_p^2 = 0.003$), group ($F = 2.553$, $p = 0.089$, $\eta_p^2 = 0.102$), time * group ($F = 0.699$, $p = 0.502$, $\eta_p^2 = 0.030$).

For the MBP test, no significant interaction for time * group was found. However, the statistical results indicated a significant main effect for time ($F = 52.609$, $p < 0.001$, $\eta_p^2 = 0.539$). The results showed that there were significant increases in MBP after the training period in the 3:1 group (+8.6%, $p < 0.001$, 95%CI: 0.14 to 0.39, $d = 0.90$ (large)), the 2:1 group (+8.5%, $p < 0.001$, 95%CI: 0.13 to 0.38, $d = 0.88$ (large)), and the CG (+8.4%, $p < 0.001$, 95%CI: 0.14 to 0.39, $d = 0.75$ (medium)).

3.3. Aerobic power

Aerobic capacity was assessed using the VO_{2max} ~~and [La]ER~~ derived from the 20-m multistage shuttle run test and [La]ER.

For VO_{2max}, there were significant main effects for time ($F = 31.969$, $p < 0.001$, $\eta_p^2 = 0.415$) and group ($F = 4.821$, $p = 0.013$, $\eta_p^2 = 0.176$) and a significant interaction for time * group ($F = 6.595$, $p = 0.003$, $\eta_p^2 = 0.227$). There were significant increases in VO_{2max} after the training

Table 2
Comparison of physical performance between pre-tests and post-tests (mean ± standard deviation) of the 3:1 group, 2:1 group, and control group.

performance	tests	3:1 (n = 16)			2:1 (n = 16)			CG (n = 16)			Time	Group	Time * group
		Pretest	Posttest	ES	Pretest	Posttest	ES	Pretest	Posttest	ES			
Aerobic power	VO_{2max}(ml·kg^{-1}·min^{-1})	44.63 ± 5.32	47.13 ± 5.64§*	0.46	42.03 ± 4.84	46.14 ± 4.51§*	0.88	39.99 ± 6.76	40.42 ± 5.52	0.07	**p < 0.001**	**p = 0.013**	**p = 0.003**
	[La]ER	0.31 ± 0.15	0.31 ± 0.13	0.05	0.29 ± 0.14	0.32 ± 0.10	0.15	0.31 ± 0.16	0.27 ± 0.12	−0.25	p = 0.902	p = 0.885	p = 0.638
Change of direction	MT(s)	6.22 ± 0.24	5.65 ± 0.29§*	−2.11	6.30 ± 0.40	5.87 ± 0.35§	−1.14	6.25 ± 0.29	6.04 ± 0.31§	−0.71	**p < 0.001**	p = 0.093	**p = 0.012**
Speed	30-m sprint(s)	4.54 ± 0.18	4.52 ± 0.19	−0.11	4.49 ± 0.25	4.50 ± 0.17	0.05	4.38 ± 0.15	4.44 ± 0.22	0.32	p = 0.406	p = 0.158	p = 0.276
Power	MBP(m)	3.02 ± 0.34	3.28 ± 0.23§	0.90	3.05 ± 0.30	3.31 ± 0.26§	0.88	3.09 ± 0.36	3.35 ± 0.33§	0.75	**p < 0.001**	p = 0.760	p = 0.987
	CMJ(cm)	43.34 ± 5.37	43.82 ± 3.38	0.11	42.95 ± 6.56	42.58 ± 5.37	−0.06	47.01 ± 5.44	46.48 ± 5.91	−0.09	p = 0.715	p = 0.089	p = 0.502
anaerobic power and capacity	PP(W)	646.19 ± 130.16	689.99 ± 93.10§	0.39	660.67 ± 131.62	674.75 ± 146.86	0.10	687.68 ± 100.65	666.19 ± 116.68	−0.20	p = 0.222	p = 0.968	**p = 0.032**
	AP(W)	472.81 ± 93.21	503.32 ± 58.35	0.39	483.17 ± 96.69	488.33 ± 92.88	0.05	482.69 ± 75.64	488.66 ± 67.22	0.08	p = 0.116	p = 0.995	p = 0.405
	PP/kg(W/kg)	8.96 ± 1.26	9.63 ± 1.15§	0.56	8.98 ± 0.84	9.14 ± 0.89	0.18	9.92 ± 0.87	9.62 ± 1.40	−0.26	p = 0.203	p = 0.123	**p = 0.022**
	AP/kg(W/kg)	6.57 ± 0.99	7.06 ± 0.94	0.50	6.56 ± 0.60	6.65 ± 0.63	0.13	6.97 ± 0.76	7.06 ± 0.65	0.13	p = 0.053	p = 0.238	p = 0.254
	PD (%)	58.78 ± 9.46	59.77 ± 7.13	0.12	59.42 ± 8.10	62.56 ± 10.87	0.33	62.92 ± 9.45	60.39 ± 7.44	−0.30	P = 0.751	P = 0.589	P = 0.380

[La]ER, lactate elimination rate; MT, modified T-test; MBP, medicine ball put; CMJ, countermovement jump; PP, Peak power; AP, average power; PP/kg, relative peak power; AP/kg, relative average power; PD, power drop; CG, control group. * Significant difference compared with CG, $p < 0.05$. § Significant difference compared with the pre-test, $p < 0.05$. Time * group: interaction of time and group.

period in the 3:1 group (+5.6%, $p = 0.001$, 95%CI = 1.05 to 3.95, d = 0.46 (small)) and the 2:1 group (+9.8%, $p < 0.001$, 95%CI: 2.66 to 5.56, $d = 0.88$ (large)). In addition, the VO_{2max} in both the 3:1 (47.13 ± 5.64 ml kg^{-1}·min^{-1}, $p = 0.002$, 95%CI = 2.11 to 11.31) and 2:1 groups (46.14 ± 4.51 ml kg^{-1}·min^{-1}, $p = 0.010$, 95%CI: 1.12 to 10.32) were significantly better than that in the CG (40.42 ± 5.52 ml kg^{-1}·min^{-1}) post-training.

For [La]ER, no significant main effects for time ($F = 0.015$, $p = 0.902$, $\eta_p^2 = 0.000$) or group ($F = 0.123$, $p = 0.885$, $\eta_p^2 = 0.005$), and no significant interaction for time * group ($F = 0.454$, $p = 0.638$, $\eta_p^2 = 0.020$), were found.

3.4. Anaerobic power and capacity

Anaerobic power and capacity were assessed using PP, AP, PP/kg, and AP/kg.

For PP, the statistical results showed a significant interaction for the time * group ($F = 3.715$, $p = 0.032$, $\eta_p^2 = 0.142$). In the 3:1 group, there was a significant increase in PP after the training period (+6.8%, $p = 0.013$, 95%CI: 9.65 to 77.96, $d = 0.39$ (medium)).

For PP/kg, the interaction effect for time * group was significant ($F = 4.170$, $p = 0.022$, $\eta_p^2 = 0.156$). The statistical results showed that there was a significant increase in PP/kg after the training period (+7.5%, $p = 0.007$, 95%CI: 0.20 to 1.16, $d = 0.56$ (medium)) in the 3:1 group.

3.5. Physiological responses

Blood lactate values at the 5th minute after the 30-s Wingate test, the main effects for time ($F = 15.224$, $p < 0.001$, $\eta_p^2 = 0.253$) and group ($F = 5.482$, $p = 0.007$, $\eta_p^2 = 0.196$) were significant. Furthermore, there was a significant decrease in blood lactate values at the fifth minute after the training period in the 3:1 group (−11.6%, $p = 0.029$, 95%CI: −2.85 to −0.16, $d = -0.58$). In the blood lactate values at the fifth minute for the post-training, the 3:1 group was significantly lower than that in the 2:1 group ($p = 0.012$, 95%CI: −4.82 to −0.48).

Blood lactate values at the 10th minute after the 30-s Wingate test, there was a significant main effect for group ($F = 5.263$, $p = 0.009$, $\eta_p^2 = 0.190$). In the post-test blood lactate values at the 10th min, the 3:1 group was significantly lower than that in the 2:1 group ($p = 0.005$, 95% CI: −5.96 to −0.90).

Blood lactate values at the 3rd ($F = 2.107$, $p = 0.133$, $\eta_p^2 = 0.086$; $F = 2.123$, $p = 0.152$, $\eta_p^2 = 0.045$; $F = 0.262$, $p = 0.771$, $\eta_p^2 = 0.011$) and 15th (F = 6.078, p = 0.005, η2p = 0.213; F = 1.813, p = 0.185, η2p = 0.039; F = 0.964, p = 0.389, η2p = 0.041) minute after the 30-s Wingate test, there were no significant main effects for group and time, as well as no significant interaction for time * group.

The physiological response results are presented in Fig. 3.

4. Discussion

The study findings suggest that both the 2:1 and 3:1 groups experienced significant improvements in VO_{2max} after training, compared to the ~~control group (~~CG~~)~~. Furthermore, the 2:1 group (ES = 0.88 (large)) showed greater ~~improvements~~ effect size in VO_{2max} compared to the 3:1 group (ES = 0.46 (small)). However, there were no statistically significant differences between the two groups. Importantly, both intervention groups demonstrated significant enhancements compared to pre-test. Compared to the ~~control group (~~CG~~)~~, the 3:1 group showed significant improvements in MT. However, neither the 3:1 group nor the 2:1 group demonstrated significant improvements in speed and power, specifically in the 30-m sprint, MBP, or CMJ. Regarding anaerobic power and capacity, both the 3:1 group and the 2:1 group did not exhibit significant improvements compared to the CG. However, there were small-to-moderate effect sizes observed for PP and PP/kg in the 3:1 group, suggesting some positive impact.

The proportion of aerobic energy in a judo match is higher than 50%,[4] in which the maintenance of technical movements and the recovery between each attack draws from the aerobic energy supply to provide energy[5]; so, excellent aerobic power is an essential ability in judo. The results of this study suggested that the 2:1 and 3:1 groups had greater improvement in aerobic power improvement than the CG ~~group~~. Thus, aerobic adaptation was induced regardless of the work-rest ratios. The results of our study align with previous research conducted by Lee et al. and Kim et al. regarding aerobic adaptations in judo athletes. Lee et al.[12] demonstrated significant enhancements in VO_{2max} by combining standard judo training with a 12-week HIIT protocol involving treadmill

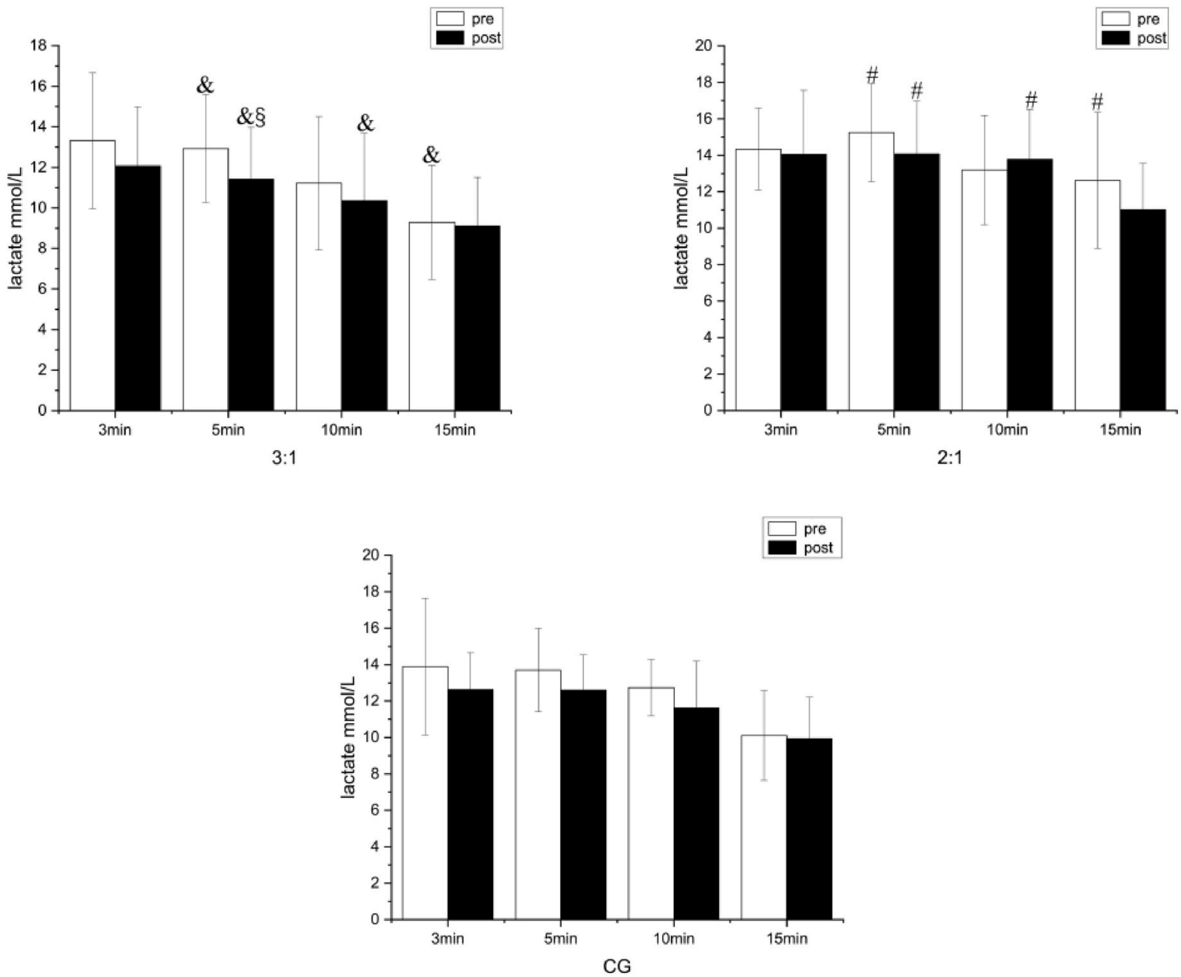

Fig. 3. Changes in blood lactate values of the 3:1 group, 2:1 group, and control group between pretest and posttest. * Significant difference compared with CG, $p < 0.05$. & Significant difference compared with the 2:1 group, $p < 0.05$. # Significant difference compared with the 3:1 group, $p < 0.05$. § Significant difference compared to the pre-test, $p < 0.05$.

sprints (30 s on, 240 s off, 6–10 repetitions, four times per week). Similarly, Kim et al.[13] reported significant improvements in anaerobic power among well-trained male judo athletes using a similar, albeit shorter, 8-week HIIT protocol, with no significant changes observed in VO_{2max}. In contrast to our study, the longer rest intervals between sprints in the studies conducted by Lee et al.[12] and Kim et al.[13] may not have sufficiently stimulated physiological processes to improve aerobic power. In our study, the total time of the 2:1 group was longer than that of the 3:1 group, and although the total work time was the same for both, the 2:1 group used 18 sets of training, whereas the 3:1 group used only 12 sets, which may have contributed to the better aerobic power improvement effect of the 2:1 group. This is because during HIIT, as the number of repetitions increases, the high concentration of hydrogen ions (H^+) in the muscle inhibits the activity of glycogen phosphorylase.[35] This inhibition, in turn, limits the supply of energy from glycolysis and promotes a higher proportion of energy supply from aerobic sources,[36] thereby enhancing aerobic power. In addition to the explanation as regards the energy metabolic system, the differences between HIIT with different work-to-rest ratios in improving musculoskeletal and cardiovascular systems in terms of improving aerobic power remain to be explored.

The results of the present study suggested that the MT was significantly improved after training in both the 3:1 and 2:1 groups, and the 3:1 group had better results. These results are similar to the findings of Fernandez-Fernandez et al.,[37] who used 15:15 s of running-based HIIT. It can be observed that HIIT with short intervals improves COD performance, but that study used running. Unlike the running intervention, the interventions in this study used specific movements such as crunning, burpees, and specific jump drills, which may have contributed to the improvement in COD performance. Burpees involve an upward jump, which we required the subjects to perform quickly; thus, this process produces a stretch-shortening cycle,[38] which can improve COD ability after several exercise sessions.[39] Although there is no evidence yet that both crunning and the specific jump drill include acceleration and deceleration phases, which may improve the COD ability, more studies are needed to verify this. A meta-analysis[7] suggested that HIIT was effective in improving athletes' sprint performance, but not their vertical jump performance. Unfortunately, these studies did not include judo athletes, and there are no studies examining the effects of HIIT on neuromuscular parameters in judo athletes, which need to be verified in more studies. However, our results were similar to the aforementioned meta-analysis results in vertical jump performance but diverged in sprint performance, possibly because most of the interventions in the meta-analysis were high-intensity running or sprinting[7]; thus, the efficiency and fluidity of movement could be improved in constant sprinting. Furthermore, the improvement of the 30-m sprint and vertical jump requires optimal-load training and heavy-load training.[40] The body mass of the cloth dummy in our study may be insufficient or unsuitable for the athletes to improve their strength and power; so, the 30-m sprint and vertical jump were not improved.

The results of this study suggested that PP and PP/kg were effectively improved in the 3:1 group after a 6-week training program, but not in the 2:1 group. For HIIT on judo athlete studies, some of the results have verified that HIIT with 30- or 20-s training intervals can improve absolute and relative PP. For example, Kim et al.[13] used the 30-s protocol, and after 8 weeks of training, the judo athletes' PP and AP were improved. Franchini et al. indicated that 20-s work interspersed with 10-s rest in judo technique training had improved PP scores and had better scores in upper-body Wingate tests.[14] This may be related to the fact that judo technique training requires more upper-extremity involvement. However, no studies have used both 30-s and 20-s training intervals in the same experiment for comparison, and there is no uniformity in the way different studies were tested. This study compared HIIT with work–rest ratios of 2:1 and 3:1. The increase in absolute and relative PP in the 3:1 group in this study was possible because the 30-s training time and the 30-s anaerobic test used the same exercise time, in addition to the fact that the experimental monitors required the subjects to train at an "all-out" intensity; therefore, the 3:1 group was more similar to the 30-s anaerobic test regarding mobilization of physiological systems. This may explain the improved absolute and relative PP with the 3:1 training protocol. Regarding physiology, during all-out exercise, the glycogenolysis and pyruvate production rates of the body reach their peak within initial 15 s of all-out exercise. Consequently, the lactate production rate reaches its maximum at 15 s.[41] The duration of the 30-s exercise, during which glycogenolysis and pyruvate production rates continue at elevated levels, extends beyond 15 s. This prolonged duration results in a greater accumulation of lactate and enhances the body's ability to buffer and adapt to lactate. Consequently, there is an increase in the capacity of the glycolytic energy supply. In our study, we observed a significant improvement in PP during the Wingate test in the 3:1 group. However, we did not observe a significant improvement in CMJ and 30-m sprint, despite the fact that CMJ and 30-m sprint were correlated with PP.[42,43] This variation can be attributed to differences in the underlying physiological mechanisms. The PP of the Wingate test is determined by the torque and rotational velocity of the flywheel.[44] Participants perform the Wingate test by moving their feet in a circular motion on the pedals while maintaining constant contact with them. The time taken to reach PP in the Wingate test is typically more than 1 s. On the other hand, the PP of the CMJ depends on the ground reaction force and instantaneous velocity, with participants taking approximately 0.7 s from the start to takeoff.[43] Similarly, sprint performance depends on vertical and propulsive forces,[45] with ground contact time lasting around 0.2 s.[42] The differences in force direction and time to reach peak power highlight the contrasting results of CMJ 30-m sprint, and the Wingate test. Furthermore, O-soto-gari, O-goshi, and Seoi-nage involve specific movements, with participants maintaining contact with the ground throughout. Similarly, during the Wingate test, participants continuously pedal against resistance. These temporal characteristics likely account for the significant improvement in peak power observed in the Wingate test.

The measurement of peak blood lactate after the 30-s Wingate test reflects the contribution of the subjects' glycolytic energy system during work, and this measurement has high reliability.[46] The results of this study indicate that blood lactate values at the fifth minute after the Wingate test in the 3:1 group decreased significantly after training. In addition, ~~there was a significant difference between~~ the 3:1 group ~~and~~ showed significantly lower blood lactate values than the 2:1 group ~~in~~ at the 5th and 10th minute ~~in~~ during the post-test. In the 2:1 group, it was observed that blood lactate values peaked between the 5th minute and the 10th minute. In a related study, Larsen et al.[47] employed a training protocol consisting of 4–6 sets of 30-s cycle ergometer sprints, followed by 4 min of recovery, and found that the ATP production from the glycolytic energy system decreased after a total of six training sessions over 2 weeks, which may explain our study's results of lower lactate values in the 3:1 group. Similarly, Burgomaster et al.[48] used the same training protocol, period, and frequency and suggested a reduction in lactate accumulation in subjects after training. However, in contrast to the two studies, Jacobs et al.[49] suggested that with 6 weeks of 2–6 bouts of 15-s and 30-s cycle ergometer sprints training 2.5 times per week, there was a significant increase in peak lactate after the Wingate test in the sprint group and no change in the ~~control group~~ CG. Therefore, the changes that occur in peak blood lactate after the Wingate test caused by HIIT using a 30-s work duration are still controversial. In line with prior research, Kim et al.[13] discovered significant reductions in blood lactate levels at 10 min and 15 min after the graded exercise test (GAT) following 8 weeks of HIIT intervention in their judo-related study, when compared to the ~~control group (~~CG~~)~~. However, in the present study, the 3:1 group showed a significant decrease at 5 min after the Wingate test, after which there was no significant decrease. This indicates that 30 s of HIIT and 30 s of HIIT based on the judo technique could produce a lactate recovery adaptation. However, unlike our study, where blood lactate was measured after the Wingate test, Kim et al.[13] measured blood lactate after the GAT. Furthermore, the highest lactate value in their study was approximately 7 mmol/L, while that of our study was 14 mmol/L, indicating that the participants had a higher demand for glycolytic energy when performing the Wingate test. In this regard, the changes observed in blood lactate values in our study may be attributed to aerobic adaptations induced by training in the 3:1 and 2:1 groups. These adaptations likely increased the proportion of aerobic energy supply and improved lactate buffering capacity,[47] ultimately leading to a decrease in blood lactate accumulation. Furthermore, studies have shown that HIIT could enhance the capacity for lactate transport,[50,51] leading to improved removal of lactate from the blood. This may also explain the observed changes in blood lactate values. In our study, the effect sizes of [La]ER were positive for both the 3:1 group (ES = 0.05) and the 2:1 group (ES = 0.15). Notably, the effect size of [La]ER was greater in the 2:1 group compared to the 3:1 group. This difference may be attributed to the overall reduction of blood lactate in the 3:1 group, resulting in a more modest change in [La]ER. In addition, the 2:1 group exhibited peak lactate occurrence at the 5th minute in the pre-test and at the 5th minute to the 10th minute in the post-test, indicating that the 2:1 group delayed the time of peak blood lactate occurrence because of higher aerobic adaptation.

In terms of compliance, our results indicate that in the 3:1 group, four participants; in the 2:1 group, eight participants; and in the CG, three participants missed 1 or 2 training sessions. The average attendance rates were 96.9%, 94.3%, and 97.9%, respectively. It is evident that all three groups exhibited a high attendance rate, which is consistent with a meta-analysis showing that supervised HIIT generally achieves high attendance rates (averaging 89.4%) based on an analysis of 166 studies.[52] However, it is important to note that participants with minor injuries or illnesses may not have been able to perform movements to the same standardized level, potentially impacting the overall training outcome. Unfortunately, we did not specifically record instances of injuries or illnesses, but rather asked participants before each session if they were able to continue training. Nevertheless, in cases where training was not entirely impossible, participants chose to continue, possibly indicating the presence of minor injuries or illnesses that we were unable to identify. Research has shown that judo athletes experience grade I injuries (requiring 1–3 days of treatment) in 47% of competitions,[53] while combat athletes have an injury incidence of 58% during training.[54] As a result, judo athletes may have a higher tolerance for injuries, enabling them to continue training despite minor injuries. It is worth mentioning that athletes with high compliance have a lower risk of injuries.[55] Therefore, judo athletes in our study who exhibited high compliance may be less likely to experience injuries. However, we still emphasize the importance of monitoring athletes for injuries, as they can significantly affect the effectiveness of training and potentially lead to further harm.

This study has some limitations, one of which is that the anaerobic test method used a lower body Wingate test, while judo sport places greater emphasis on the upper body. Therefore, an upper body Wingate test would have been more suitable. However, Due to constraints in the laboratory resources, we had to utilize the lower body Wingate test.

Secondly, the selection of only general fitness tests, which could be considered a limitation of this study, is recommended that future studies consider incorporating appropriate judo-specific tests when time allows. This would provide a more comprehensive evaluation of performance specifically related to judo. Thirdly, due to equipment issues that prevented the acquisition of valid HR data, the analysis of our study was likely limited.

5. Practical applications

In this study, we found that judo-specific HIIT twice a week for 6 weeks was effective in improving MT and VO_{2max}. In addition, HIIT with a 3:1 work-to-rest ratio significantly improved absolute and relative peak power. During a judo match, athletes rely on a combination of anaerobic and aerobic power and capacities. Periodized training can incorporate HIIT with various work-to-rest ratios to target specific adaptations. One approach is to begin with HIIT using 2:1 work-to-rest ratio emphasizing the development of VO_{2max} and establishing a solid aerobic foundation for advanced training levels. Subsequently, the work-to-rest ratio can be adjusted to 3:1 to enhance both absolute and relative peak power, as well as further improve VO_{2max}. This progression allows for a systematic and structured approach to optimize training outcomes. The specific arrangement of exercises should be customized by the coach based on the training program. The arrangement of exercises in this study, including O-soto-gari, O-goshi, Seoi-nage, burpees, specific jump drills, and crunning, has been verified to produce increased physical performance and physiological response adaptations in judo athletes. Judo coaches can incorporate these exercises into their training activities to maximize the training effect based on the findings of this study.

Author statement

(i) all authors agree with the content of the article and approve of its submission to the journal;
(ii) the material contained in the manuscript has not been previously published and is not being concurrently submitted elsewhere;
(iii) the experiments reported in the article were undertaken in compliance with the current laws of the country in which the experiments were performed.

Authors will be held responsible for false statements.

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Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT in order to improve language and readability. After using this tool, the authors reviewed and edited the content as needed and takes full responsibility for the content of the publication.

Declaration of competing interest

Nothing to declare.

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