Journal of Exercise Science & Fitness 21 (2023) 286–294

Contents lists available at ScienceDirect

Journal of Exercise Science & Fitness

journal homepage: www.elsevier.com/locate/jesf

Practical internal and external cooling methods do not influence rapid recovery from simulated taekwondo performance

Pariya Pariyavuth [a, b], Jason Kai Wei Lee [c, e, f], Pearl Min Sze Tan [c], Kanokwan Vichaiwong [d], Christopher Mawhinney [a], Metta Pinthong [a, *]

[a] College of Sports Science and Technology, Mahidol University, Nakhon Pathom, Thailand
[b] Faculty of Physical Education, Srinakharinwirot University, Nakhon Nayok, Thailand
[c] Human Potential Translational Research Programme, Yong Loo Lin School of Medicine, National University of Singapore, Singapore
[d] Faculty of Physical Therapy, Srinakharinwirot University, Nakhon Nayok, Thailand
[e] Department of Physiology, Yong Loo Lin School of Medicine, National University of Singapore, Singapore
[f] Heat Resilience and Performance Centre, National University of Singapore, Singapore

A R T I C L E I N F O

Article history:
Received 17 February 2023
Received in revised form
8 May 2023
Accepted 24 May 2023
Available online 25 May 2023

Keywords:
Cold Water Immersion
Core Temperature
Heat Stress
Ice Slurry Ingestion
Recovery
Taekwondo

A B S T R A C T

Background/Objectives: The influence of post-exercise cooling on recovery has gained much attention in the empirical literature, however, data is limited in regards to optimizing recovery from taekwondo performance when combat is repeated in quick succession within the same day. The aim of this study was therefore to compare the effects of external and internal cooling after simulated taekwondo combat upon intestinal temperature (T_{int}), psychomotor skills (reaction time, response time, movement time), and neuromuscular function (peak torque, average power, time to reach peak torque).

Methods: Using a randomized counterbalanced crossover design, 10 well-trained male taekwondo athletes completed four recovery methods on separate occasions: passive recovery (CON), a 5-minute thermoneutral water immersion (35°C) (TWI), a 5-min cold water immersion (15°C) (CWI), and ice slurry ingestion (-1°C) (ICE; consumed every 5 min for 30 min). Heart rate (HR), blood lactate (Blac) concentrations, and T_{int} were determined at rest, immediately after combat, and at selected intervals during a 90-min recovery period. Neuromuscular functional (measured with isokinetic dynamometer) and psychomotor indices were assessed at baseline and after the recovery period.

Results: ICE led to a significantly lower T_{int} at 30 min ($P<0.01$) and 45 min ($P<0.01$) after simulated combat; 15-30 min after cessation of ingesting ice slurry, compared with the CON and TWI conditions, respectively. However, there were no differences in T_{int} across time points between the other conditions ($P>0.05$). Psychomotor skills and neuromuscular function indices returned to baseline values after the 90 min recovery period ($P>0.05$) with no differences observed between conditions ($P>0.05$).

Conclusion: The present findings suggest that internal (ICE) and external (CWI) recovery methods appear to have little impact on physiological and functional indices over the time course required to influence repeated taekwondo combat performance.

1. Introduction

Taekwondo is a modern Olympic combat sport that is comprised of three rounds (2 min per round) per match interspersed with 1 min of rest between each round, and completion of up to four matches in a single day to reach a final.[1] During competition, taekwondo athletes wear a uniform (Dobok) and protective equipment comprising of a trunk protector, groin guard, forearm guard, shin guard, hand protector, sensing socks, gloves, and mouthpiece.[2] Similar to the uniform and protective equipment in American football, this protective equipment may limit heat loss and increase the thermal strain of athletes during performance.[3] Therefore, optimizing recovery is an important consideration for taekwondo athletes, particularly when limited time is provided between consecutive matches.

* Corresponding author. College of Sports Science & Technology, Mahidol University, Salaya Campus, Nakhon Pathom, 73170, Thailand.
E-mail addresses: metta.pin@mahidol.edu, metta.pin@mahidol.ac.th (M. Pinthong).

https://doi.org/10.1016/j.jesf.2023.05.003
1728-869X/

A high core temperature can increase physiological strain and decrease performance[3]; higher core temperatures demonstrated to decrease central nervous system function and muscle function.[4] In an attempt to maintain optimal performance, athletes may apply strategies to lower their core temperature and reduce muscular fatigue during the rest period between competitive matches.[5] Indeed, this can be considered particularly important in taekwondo, with multiple matches within a single day separated by as little as ~1 h during the recent Tokyo Olympic games.[6] The cumulative heat stress may be hypothesized to lead to fatigue during intra-day taekwondo competition bouts and may be further be exacerbated by weight-making strategies (sauna, fluid restriction) that are employed to gain a potential competitive advantage.

Cooling techniques that are widely used to decrease core temperature after exercise have included external cooling techniques, such as cold-water immersion (CWI)[7] and cooling vests,[8] and internal cooling techniques, such as ice slurry (ICE)[9,10] and cold-water ingestion.[9] External cooling techniques provide a cooling effect on muscle tissue, resulting in a greater reduction in rectal, muscle, and skin temperature after exercise.[7] In contrast, internal cooling decreases core temperature without affecting skin temperature.[11] This may be beneficial as cooling the skin and muscle tissue may result in reduced nerve conduction properties[12] which subsequently impact neuromuscular performance when the next taekwondo match is completed in quick succession. Internal cooling may also initially increase the rate of reduction in core temperature compared with short-duration CWI (i.e., <15 min) which activates shivering thermogenesis in an attempt to maintain core temperature.[13] Moreover, the conductive heat transfer kinetics associated with CWI lowers deep muscle tissue over time[14]; likely causing an after-drop in core temperature.[15] Nevertheless, heat stress and efficacy of between-match cooling strategies remains to be established in taekwondo athletes,[11] with the magnitude and time-course of core temperature reductions following CWI and ICE applications, and impact on physiological and neuromuscular responses, not well documented.

We aimed to compare the effects of CWI and ICE cooling methods, seated rest (CON) and thermoneutral water immersion (TWI) after simulated taekwondo combat upon physiological, psychomotor, and neuromuscular function. We hypothesized that internal cooling with ICE would initially lower intestinal temperature (T_{int}) at a faster rate compared with CWI, CON and TWI, however, ICE and CWI would be practically equivalent at 1 h post-intervention. We also hypothesized that external cooling with CWI would lead to decreased psychomotor and neuromuscular function compared with ICE, CON and TWI.

2. Methods

2.1. Ethical approval

The study was approved by the Mahidol University Institutional Review Board (MU-CIRB 2016/062.0804), with all procedures performed in accordance with the latest revision of the declaration of Helsinki. Participants were briefed on the experimental procedures and potential risks of the study before providing their written informed consent to participate.

2.2. Participants

Ten experienced male taekwondo athletes (age, 20 ± 1 yr; height, 1.69 ± 0.2 m; body mass, 74.7 ± 13.0 kg; taekwondo experience, 8 ± 1 yr) volunteered to participate in this study. Participants were excluded from the study if they were currently taking any pharmacological medications, had an allergy to the cold, history of cardiovascular or neurological disease, or an existing musculoskeletal injury. The participants were requested to abstain from alcohol and caffeine-containing beverages for at least 24 h before the commencement of experimental testing and to avoid strenuous exercise within 48 h of commencing the experimental protocol. Due to the exploratory nature of our study, a formal sample size estimation is not presented. The sample size of 10 participants is primarily based on available resources and is representative of similar within-subject designs within this domain.[16]

2.3. Experimental design

A randomized counterbalanced repeated measures design was employed requiring participants to report to the laboratory on five separate occasions: one familiarization session and four experimental sessions separated by at least seven days.[17] The participants were briefed on the experimental procedures and recovery interventions during the familiarization session. All experimental sessions were performed at the same time of day to limit the potential effects of circadian rhythm on physiological (and psychomotor and neuromuscular) measurements[18] and performed at the same environmental temperature (~27 °C) and relative humidity (60–65%).

Upon arrival at the laboratory, participants were asked to change into their Dobok and had a chest heart rate telemetry belt fitted before resting semi-reclined for ≥20 min to ensure resting physiological status (heart rate, and blood pressure) were stabilized.[14] Baseline heart rate, T_{int}, and blood lactate were recorded and the participants were then asked to complete a psychomotor skill test and neuromuscular assessments. The participants then performed simulated taekwondo combat against their coach and were subsequently moved from the laboratory to the recovery room. The transition time, including rest before commencing the recovery intervention, was approximately 10 min, anecdotally mimicking common practice for taekwondo athletes. Recovery interventions were then performed with participants randomized to receive passive recovery (CON), 5-min thermoneutral water immersion at 35 °C (TWI), 5-min CWI at 15 °C, or ICE (−1 °C) in a counterbalanced order. Upon completion of the recovery intervention, the participants were asked to rest in a seated period for 90-min (recovery period) to mimic the typical recovery duration during taekwondo competitions.[19] Intestinal temperature (T_{int}) and heart rate (HR) measurements were continuously monitored. Blood lactate (B_{lac}) concentrations were measured at baseline, immediately post-exercise, and at 15 min, 30 min, 60 min, and 90 min post-intervention. Psychomotor skills and neuromuscular function were assessed at baseline and the end of the 90 min recovery period. A schematic of the experimental design is displayed in Fig. 1.

2.4. Simulated taekwondo combat

The simulated taekwondo combat was performed in accordance with World Taekwondo Federation (WTF) official rules.[2] The protocol consisted of three rounds of 2 min work bouts with a 1 min rest period between rounds (passive recovery sat on a chair). To simulate competition, participants wore their Dobok, and protective headgear, trunk protector, groin guard, forearm guards, shin guards, hand protector, socks, gloves, and mouthpiece, and performed combat against their coach. The combat movements consisted of both defense and offense techniques to elicit ~85–95% heart rate maximum (%HR_{max}).[20] In line with past research,[21] a 1:7 ratio of high-intensity (combat) to low-intensity (non-combat) action was employed for the simulated protocol. High-intensity actions corresponded to kicking and punching techniques whereas low-intensity actions included slide, bounce, and step movements.

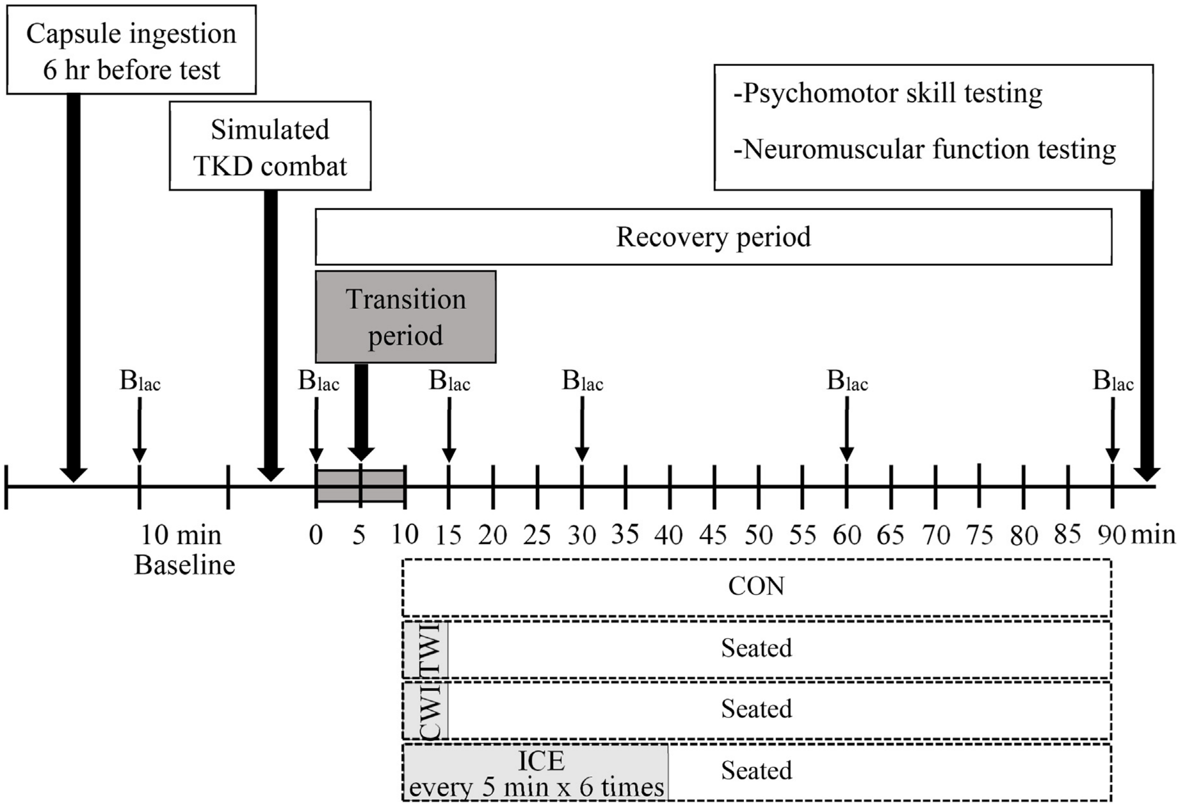

Fig. 1. Schematic of the experimental protocol. B_{lac}, blood lactate; CON, control; TWI, thermoneutral water immersion (35 °C), CWI cold water immersion (15 °C); ICE, ice slurry ingestion (−1 °C); TKD, taekwondo.

2.5. *Recovery interventions*

In the CON condition, participants passively recovered in a seated position throughout the recovery period. In the CWI condition, participants were immersed semi-reclined in water up to the anterior superior iliac spine at a water temperature of 15 °C for 5 min. This duration has been reported to be effective in lowering body temperature, and CWI at 15 °C is reportedly well-tolerated.[22] In TWI, the water temperature was set at 35 °C for 5 min and was chosen to allow comparison with CWI via accounting for the effects of hydrostatic pressure (i.e., only compare temperature effects).[23]

After completing 5 min of immersion, participants were towel-dried, moved to the laboratory, and then seated for the remainder of the recovery period. During CON, TWI, and CWI, participants drank 7.5 g/kg BM of warm sports drink (37 °C, Sponsor®, sucrose 7.0%, dextrose 4.0%, NaCl 0.13%, KCl 0.03%). A temperature of 37 °C was chosen for the sports drink to ensure thermal balance.[24] For the ICE session, participants passively recovered in a seated position and ingested 7.5 g/kg BM of ice slurry prepared from the sports drink (aforementioned) using a commercially available ice blender (Philips, HR2115, 600 W). To ensure a consistent hydration status between interventions, the rate of ingestion was similar across all recovery interventions: boluses of 1.25 g/kg BM were taken once every 5 min between the 10th and 35th minutes of the recovery period (i.e., 6 times).[25]

2.6. *Physiological measurements*

2.6.1. *Intestinal temperature*

Participants were asked to ingest a telemetric thermometer capsule (CorTemp®, HQ Inc., FL, U.S.A.) 6 h before each experimental session. The ingestible temperature pill was checked for location in the gastrointestinal tract upon the participants' arrival at the laboratory. The sensor pill data was recorded via a data logger which was worn around the waist of each participant throughout experimental testing.

2.6.2. *Blood lactate*

B_{lac} concentration was measured using a fingertip blood sample and analyzed using a portable analyzer (Lactate Scout+, EKF Diagnostic, Barleben, Germany). The tip of the index finger was swabbed with an alcohol swab (Alcohol Pad, 3 M, MN, U.S.A.) and pricked with a lancet (Accu-Chek Safe-T Pro Plus, Roche Diagnostics, U.S.A.). The fingertip was then squeezed to expose a drop of blood and wiped clean with a tissue. The fingertip was squeezed again and a ~0.7 μl blood sample was collected on the test strip for analysis.

2.6.3. *Heart rate*

HR was recorded using a heart rate wrist monitor and telemetry chest strap (Polar, RS800 Polar Electro Oy, Kempele, Finland). HR values were averaged over 1 min at the end of baseline, immediately post-exercise, and every 15 min until the completion of the recovery period.

2.7. *Psychomotor skills*

Participants performed five-round kicks against a target using both the dominant and non-dominant legs in a randomized order, separated by a 30-s rest between kicks. A movement sensor pad and the sensor target were connected to a computer, and a light stimulus was used to indicate when the participant should kick the target. The participants' heels were placed on the movement sensor pad to determine the movement of the foot, and the sensor target was used to record the moment of impact. The target of the round kick was set around the abdominal area, and the participant's trochanteric height (the full length from the trochanter to the floor) was measured to determine the distance to the target. Response time was determined as the total time between the light stimulus and contact with the sensor target. Reaction time was defined as the time between the light stimulus and the movement of the foot from the sensor pad. Movement time was calculated from the reaction time subtracted from the response time and represented the time between the movement of the foot from the sensor pad to contact with the sensor target. For each test, the quickest and slowest kicks were excluded, and the test score was defined as the mean of the three remaining kicks.[21]

2.8. Neuromuscular function

An isokinetic dynamometer (Biodex System 3; Biodex Medical, Inc., Shirley, NY, USA) was used to assess neuromuscular function. As previously described,[26] participants were strapped into the dynamometer in a seated position with the lateral femoral condyle of the dominant knee used as the anatomical reference for the axis of rotation. The pad of the lever arm was placed proximal to the medial malleolus and a gravity correction was applied to account for the mass of the lever arm. Following 10 submaximal contractions (warm-up), the knee extensors and flexors were concentrically measured at an angular velocity of $60^{\circ}s^{-1}$ using 5 maximal voluntary contractions.[26] Indices of peak torque, average power, and time to attain peak torque were all recorded. The same procedure was repeated on the non-dominant leg. During the test, participants were verbally encouraged and allowed to view their torque graphs as a form of visual feedback.

2.9. Data processing and statistical analyses

A random intercept linear mixed model (estimated using REML and BOBYQA optimizer) was used to examine differences between conditions across time points. Standard residual diagnostics were performed via visual inspection of the residual plots. For physiological (T_{int}, B_{lac}, and HR), psychomotor (reaction time, response time, movement time), and functional performance (peak torque, average power, time to peak torque) variables, fixed effects included condition [CON, TWI, CWI, ICE], time [baseline, post-bout, post 15 min, post 30 min, post 45 min, post 60 min, post 75 min, post 90 min] and leg [dominant, non-dominant] in the model (formula: outcome ~ condition * time *leg) where appropriate. The model random effects included participant as the random effect (formula: ~1 | subject). When significant main effects were found, post hoc pairwise comparisons were performed using a Holm correction and the estimated marginal means were interpreted. Statistical significance was accepted at the $P \leq 0.05$ level. All data are presented as mean ± 95% confidence intervals [95% CI] unless otherwise stated. Effects sizes are also reported for main effects and expressed at partial eta squared (η_p^2), with 0.01, 0.06, and 0.14 representative of a small, medium, and large effects, respectively.[27]

Estimated marginal means and lower and upper 95% confidence intervals were obtained from the linear mixed model to support inferences related to practical equivalence at 60 min post-intervention. Equivalence thresholds were based upon an observable 0.1 °C difference between conditions (ingestible temperature pill accuracy is ±0.1 °C).[28] If either the upper or lower 95% CI bounds included the pre-determined equivalence thresholds, conditions were declared practically equivalent. Statistical analyses and figure production were undertaken using the R statistical framework (version 4.0, R Foundation for Statistical Computing).

3. Results

3.1. Physiological response

3.1.1. Intestinal temperature

A significant main effect of condition ($F_{(3,279)} = 17.85$; $P < 0.001$; $\eta_p^2 = 0.16$) and time ($F_{(7,279)} = 144.51$; $P < 0.001$; $\eta_p^2 = 0.78$) were observed for T_{int}. There was also a significant interaction between condition x time ($F_{(21,279)} = 2.08$; $P < 0.01$; $\eta_p^2 = 0.14$). T_{int} was similar between all conditions at baseline ($P > 0.05$; Fig. 2A) and at the end of the simulated taekwondo combat ($P > 0.05$; Fig. 2A). At 30–45 min during recovery, T_{int} was significantly lower in the ICE condition compared with CON ($P < 0.05$) and TWI ($P < 0.01$; Fig. 2. A) conditions, respectively. T_{int} values subsequently remained similar between conditions until the end of the 90-min period ($P > 0.05$; Fig. 2. A). At the 60 min post-intervention time point, differences in intestinal temperature were practically equivalent between all conditions (Fig. 2. B).

3.1.2. Heart rate

The main effect of condition on HR was significant ($F_{(3,279)} = 3.08$; $P = 0.028$; $\eta_p^2 = 0.03$). HR values in the CWI condition were generally lower throughout the recovery period compared with the CON ($P = 0.031$; Fig. 3. A). There was also a significant main effect for time on HR ($F_{(7,279)} = 1213.94$; $P < 0.001$; $\eta_p^2 = 0.97$). HR generally increased after completion of the simulated taekwondo combat ($P < 0.001$) before rapidly decreasing during the first 15 min of the recovery ($P < 0.001$) and stabilizing until the end of the 90 min period; yet remained above baseline values ($P < 0.001$; Fig. 3. A). There was no significant interaction between condition x time ($F_{(21,279)} = 0.52$; $P = 0.963$; $\eta_p^2 = 0.04$) for HR observed.

3.1.3. Blood lactate

A significant main effect for time ($F_{(5,207)} = 208.18$; $P < 0.001$; $\eta_p^2 = 0.97$) was observed for lactate concentration. Lactate concentration levels were generally elevated ($P < 0.001$) immediately at the end of the simulated taekwondo combat before gradually decreasing but remaining above baseline values at the end of 90 min recovery period ($P < 0.001$; Fig. 3. B). There were no significant main effects noted for condition ($F_{(3,207)} = 2.15$; $P = 0.096$; $\eta_p^2 = 0.03$) or condition × time interaction ($F_{(15,207)} = 0.52$; $P = 0.927$; $\eta_p^2 = 0.04$).

3.2. Psychomotor skills

The main effect of time on response time was significant ($F_{(1,135)} = 37.74$; $P < 0.001$; $\eta_p^2 = 0.22$). When performing a round kick, response times were generally quicker at the end of the 90 min recovery period ($P < 0.001$; Table 1). There were no significant main effects for condition ($F_{(3,135)} = 0.47$; $P = 0.702$; $\eta_p^2 = 0.01$) or interaction between condition x leg x time ($F_{(3,135)} = 0.30$; $P = 0.829$; $\eta_p^2 = 0.01$; Table 1).

Similarly, the main effect of time on reaction time was significant ($F_{(1,135)} = 47.26$; $P < 0.001$; $\eta_p^2 = 0.26$). Reaction times were generally quicker at the end of the recovery period ($P < 0.001$; Table 1). There were no significant main effects for condition ($F_{(3,135)} = 0.24$; $P = 0.867$; $\eta_p^2 = 0.01$) or interaction between condition x leg x time ($F_{(3,135)} = 0.22$; $P = 0.884$; $\eta_p^2 = 0.01$) for reaction time (Table 1).

For movement time, there were no significant main effects for condition ($F_{(3,135)} = 1.82$; $P = 0.146$; $\eta_p^2 = 0.04$), time ($F_{(1,135)} = 0.10$; $P = 0.753$; $\eta_p^2 = 0.00$), or interaction between condition x leg x time ($F_{(3,135)} = 0.67$; $P = 0.569$; $\eta_p^2 = 0.01$; Table 1).

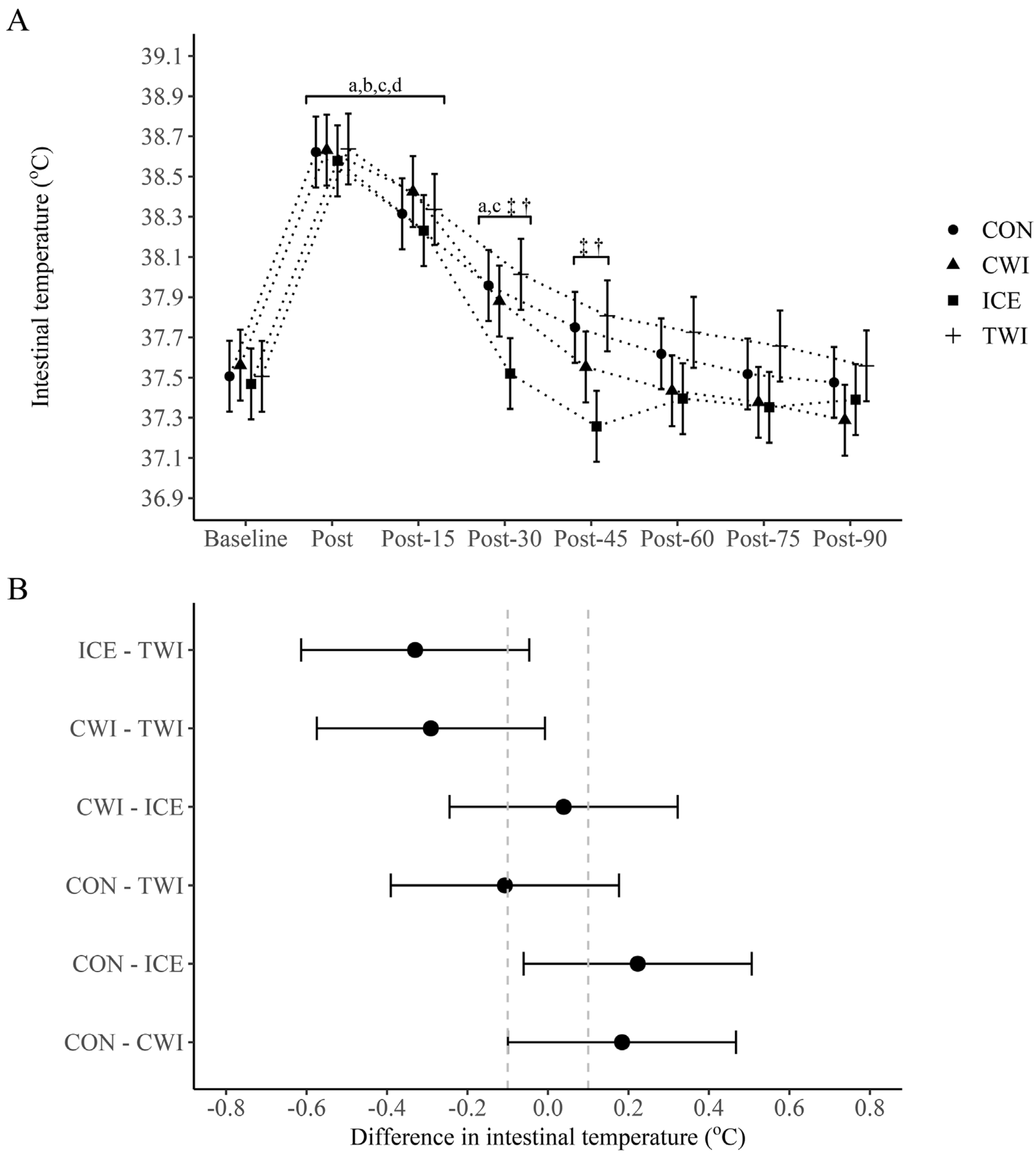

Fig. 2. Intestinal temperature during the 90 min recovery period **(A)** and practical equivalence between conditions at 60 min (**B**). CON = control; TWI = thermoneutral water immersion (35 °C); CWI = cold water immersion (15 °C); ICE = ice slurry ingestion (−1 °C). ‡ Significant difference between CON and ICE conditions; † significant difference between TWI and ICE conditions; a, b, c, d indicates CON, CWI, TWI, and ICE, respectively, are significantly different from baseline values at specific time points. Practical equivalence is based on upper and lower 95% CI's extending beyond a pre-determined ±1 °C threshold (vertical dotted line).

3.3. Neuromuscular function

There was a significant main effect of time for peak torque of the knee extensors ($F_{(1,135)} = 7.88$; $P < 0.01$; $\eta_p^2 = 0.06$) and knee flexors ($F_{(1,135)} = 51.19$; $P < 0.001$; $\eta_p^2 = 0.27$). Peak torque generally increased during both movements when measured at the end of the 90 min recovery period (Table 2). However, there were no significant main effects for condition ($P > 0.05$) or interaction between condition x leg x time ($P > 0.05$; Table 2) for either movement.

For the time to attain peak torque, there was a significant main effect of time observed for knee flexion ($F_{(1,135)} = 16.28$; $P < 0.001$; $\eta_p^2 = 0.11$; Table 2). However, there were no significant main effects for condition ($P > 0.05$) or interaction between condition x leg x time ($P > 0.05$; Table 2).

For average power, a significant main effect for time was observed for both knee extension $P = 0.013$; $\eta_p^2 = 0.04$) and flexion ($P < 0.001$; $\eta_p^2 = 0.16$). There were no significant main effects for condition ($P > 0.05$) or interaction between condition x leg x time ($P > 0.05$; Table 2) observed for either movement.

4. Discussion

We investigated the effects of external (CWI) and internal cooling (ICE) applications on physiological and neuromuscular indices after simulated taekwondo combat. Our main findings demonstrated that ICE reduced T_{int} at a greater rate compared with CON and TWI at 30–45 min during the recovery period. However,

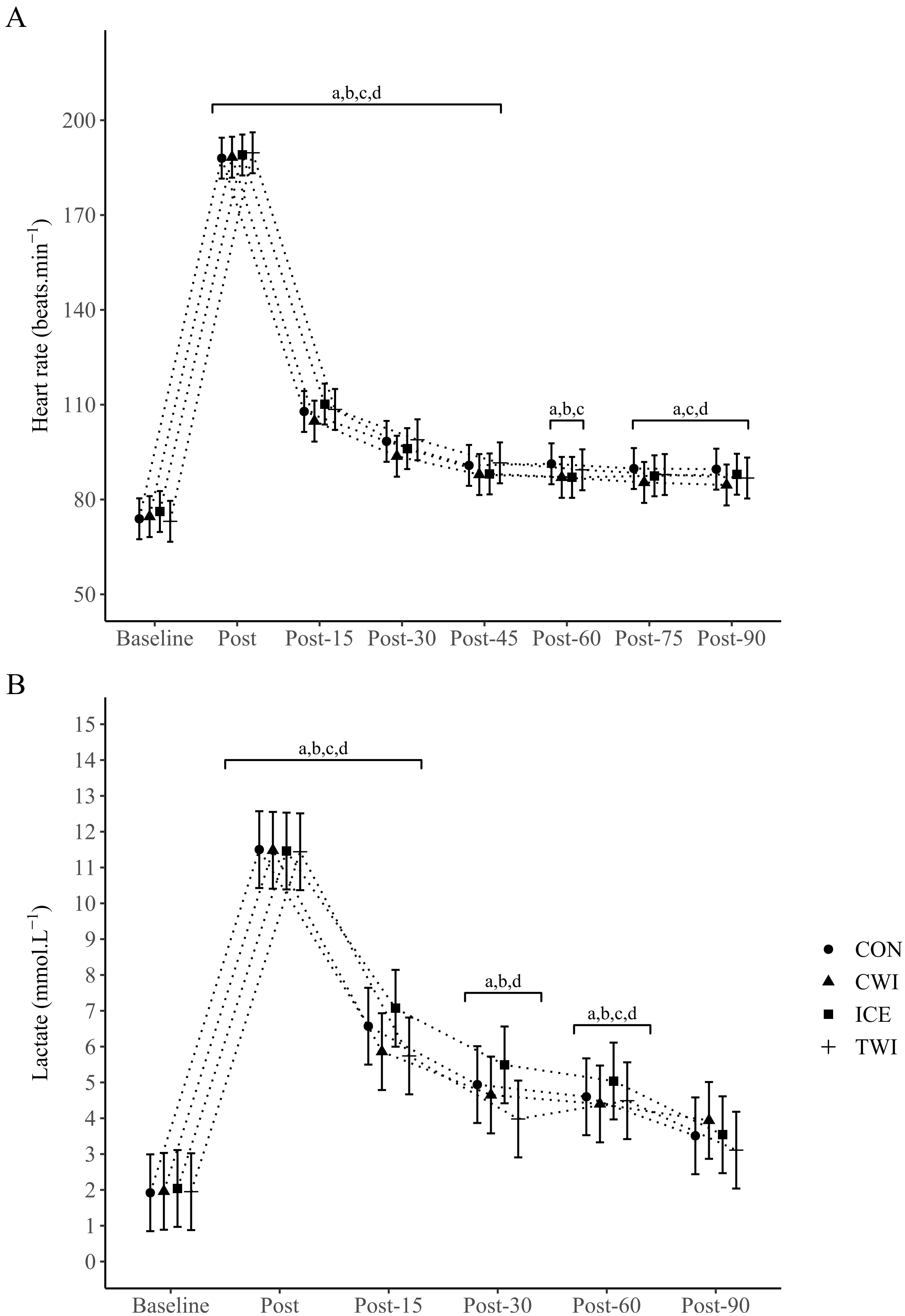

Fig. 3. Heart rate **(A)** and Blood lactate concentration **(B)** during the 90 min recovery period. CON = control; TWI = thermoneutral water immersion (35 °C); CWI = cold water immersion (15 °C); ICE = ice slurry ingestion (−1 °C); a, b, c, d indicates CON, CWI, TWI, and ICE, respectively, are significantly different from baseline values at specific time points.

Table 1
Psychomotor skills of the dominant and non-dominant legs at baseline and after the recovery period (mean ± [95% CI]).

	Baseline	CON	TWI	CWI	ICE
Response time (s)					
Dom	0.77 [0.73,0.82]	0.73 [0.69,0.78]	0.71 [0.66,0.76]	0.71 [0.67,0.76]	0.72 [0.67,0.76]
Ndom	0.76 [0.71,0.81]	0.74 [0.70,0.79]	0.74 [0.70,0.79]	0.73 [0.69,0.78]	0.72 [0.67,0.76]
Reaction time (s)					
Dom	0.54 [0.50,0.57]	0.50 [0.46,0.53]	0.49 [0.46,0.53]	0.49 [0.46,0.53]	0.49 [0.46,0.53]
Ndom	0.54 [0.50,0.57]	0.50 [0.47,0.54]	0.52 [0.48,0.55]	0.50 [0.47,0.54]	0.49 [0.46,0.53]
Movement time (s)					
Dom	0.24 [0.20,0.27]	0.24 [0.20,0.27]	0.22 [0.18,0.25]	0.22 [0.19,0.25]	0.22 [0.19,0.25]
Ndom	0.24 [0.21,0.27]	0.29 [0.26,0.32]	0.24 [0.20,027]	0.23 [0.20,0.26]	0.23 [0.19,0.26]

CON = control; TWI = thermoneutral water immersion (35 °C); CWI = cold water immersion (15 °C); ICE = ice slurry ingestion (−1 °C); Dom = dominant leg; Ndom = non-dominant leg

Table 2
Neuromuscular function of the dominant and non-dominant legs during isokinetic knee extension and flexion at baseline and after the recovery period (mean ± [95% CI]).

		Baseline	CON	TWI	CWI	ICE
Peak torque (N·m)						
Extension	Dom	132 [121,124]	136 [124,147]	136 [125,148]	139 [127,150]	139 [128,151]
	Ndom	129 [117,140]	132 [120,143]	129 [118,141]	131 [120,143]	132 [120,144]
Flexion	Dom	62 [54,70]	72 [64,80]	75 [67,83]	77 [69,85]	81 [73,89]
	Ndom	62 [54,70]	70 [62,78]	70 [62,78]	75 [66,83]	75 [67,83]
Time to peak torque (msec)						
Extension	Dom	264 [237,291]	254 [227,281]	259 [232,286]	260 [233,287]	262 [235,289]
	Ndom	261 [234,288]	269 [242,297]	262 [235,289]	255 [228,282]	265 [238,292]
Flexion	Dom	305 [227,383]	376 [298,454]	348 [270,426]	423 [345,501]	345 [267,423]
	Ndom	378 [300,456]	430 [352,508]	410 [332,488]	389 [311,467]	410 [332,488]
Average power (W)						
Extension	Dom	211 [190,233]	222 [200,244]	221 [199,242]	220 [198,242]	231 [210,253]
	Ndom	208 [186,230]	213 [191,235]	210 [189,232]	210 [188,231]	217 [195,239]
Flexion	Dom	102 [80,123]	122 [101,143]	125 [104,146]	127 [105,148]	136 [115,157]
	Ndom	100 [79,122]	115 [94,137]	111 [90,132]	118 [96,139]	121 [99,142]

CON = control; TWI = thermoneutral water immersion (35 °C); CWI = cold water immersion (15 °C); ICE = ice slurry ingestion (−1 °C); Dom = dominant leg; Ndom = non-dominant leg.

we did not observe any marked difference in T_{int} between conditions beyond this time point; all conditions were practically equivalent at 1 h post-intervention. We also did not observe any beneficial (or negative) effect of cooling methods on neuromuscular function or psychomotor skills when measured at the end of the recovery period.

The T_{int} at the end of simulated taekwondo combat was increased by ~1 °C from baseline values (Fig. 2A) indicating a moderate degree of thermal strain imposed on the body from the exercise protocol. The HR response from the exercise stimulus (Fig. 3. A) was comparable to both actual taekwondo competition events[16,20,29,30] and previously employed simulated protocols.[16] B_{lac} concentrations at the end of the simulated taekwondo combat (11–12 mmol/L; Fig. 3. B), were also similar to actual taekwondo competition events,[20,29] suggestive of high activation of anaerobic glycolysis. In combination, the physiological responses to the simulated taekwondo combat provided support for the ecological validity of the adopted protocol in this study.

In the current study, a marked difference in T_{int} was observed in ICE compared with the TWI and CON conditions at 35–45 min of the recovery period; the acute period after which the final ice slurry bolus was consumed. This observation is similar to a previous study that reported ice ingestion to acutely decrease rectal temperature after exercise.[11] The likely mechanism of T_{int} reduction related to ice slurry absorbing a large amount of heat during its phase change from solid to liquid.[31] In contrast, we did not observe CWI to impact on T_{int} throughout the recovery period, with similar core temperature values noted compared with the TWI and CON conditions (Fig. 2. A). Despite the employed CWI protocol in our study previously reported to lower body temperature,[22] our data suggests that lower body immersion in 15 °C water for 5 min was not efficacious to achieve this outcome. Although difficult to ascertain, the disparity in findings may be related to differences in participant characteristics (e.g., body fat, body surface area) providing a body insulative effect in opposing core temperature reduction.[32] Alternatively, activation of the shivering response, which can help to acutely maintain core temperature,[13] may have prevented the reduction in T_{int} in the CWI condition. Irrespective of CWI not influencing core temperature, we did not observe any clear difference in T_{int} between the cooling conditions throughout the recovery period (Fig. 2. A). Importantly, the primary objective of cooling the body between competitive taekwondo matches is to reduce thermal strain (and optimize performance) on the body before the next competitive match. Our data suggest that T_{int} was practically equivalent across all conditions at the 1 h post-exercise time point (Fig. 2. B). Ultimately, this implies that the ICE and CWI protocols adopted in this study would be of little benefit in reducing thermal strain before subsequent taekwondo combat.

The HR response in the CWI condition was generally lower (condition effect) compared with CON throughout the study period (Fig. 3. A). The consistently lower heart rate values with external cooling could be related to CWI promoting faster reactivation of cardiac parasympathetic activity compared with passive recovery after intense exercise.[33] Another physiological measure, blood lactate concentration, was similar across all conditions during the study period (Fig. 3. B). It has been proposed that water immersion has a hydrostatic pressure effect that promotes fluid shift within the body from the extremities toward the central cavity. This fluid shift may increase substrate translocation (i.e., lactate) from peripheral to central areas, increase venous return, and increase cardiac output.[34] However, in agreement with a previous study[17] which demonstrated CWI after exercise did not affect blood lactate concentration compared with non-immersed seated recovery, we presently did not observe any effect of water immersion, TWI, or CWI, on blood lactate concentrations.

While an excessive increase in core temperature during sports competitions is well-documented to decrease sports performance,[35,36] we did not observe a decrement in indices of neuromuscular function or psychomotor skills across recovery interventions. Indeed, reaction and response times to performing a round kick were generally quicker at the end of the 90 min recovery period compared with baseline values (Table 1). It may be speculated that muscle activation from the simulated combat led to a greater neural drive to the muscle at the end of the recovery period (i.e., post-activation performance enhancement).[37] Nevertheless, this is difficult to confirm without accompanying electromyography (EMG) data. Alternatively, it may simply be a consequence of the simulated taekwondo combat not meeting a core temperature threshold for reducing muscle activation (i.e., >39 °C)[35]; limiting the ability to observe a performance benefit with cooling methods. In regards to this point, as taekwondo athletes often undertake weight making strategies to gain a potential advantage in a particular weight category,[38] the risk of hypohydration is elevated prior to competition. While not considered in the present study, higher post-combat core temperatures may be achieved under these conditions. Thus, it is recommended that future studies incorporate ecologically valid study designs, which take into account weight making strategies (i.e., sauna, fluid restriction). It was hypothesized that external cooling would slow nerve conduction velocity to the muscle and impact on muscle force production.[12] However, as indices of neuromuscular function and psychomotor skills were not different between conditions, likely, the magnitude of reduction in muscle temperature from CWI cooling was not sufficient to cause a decrement in any key parameter. The absence of muscle temperature assessment in the present study represents a study limitation and should also be considered for inclusion in future work.

Several other limitations are associated with the present study. To maintain a practical approach required for taekwondo competition, a relatively short duration of CWI exposure was selected, however, this may have limited the ability to modulate key physiological indices. It has been suggested that a CWI temperature and duration of 1:1.1 (i.e., 10 °C for 11 min) should be applied to optimize CWI recovery protocols.[39] Accordingly, future studies may consider using lower water temperatures or longer immersion durations of CWI when attempting to make comparisons against other cooling methods. We only assessed neuromuscular and psychomotor skills at baseline and the end of the recovery period. Therefore, potential differences between recovery interventions at the 1 h recovery time point cannot be excluded. Future studies may also attempt to focus on sport-specific performance by utilizing longer duration/high repetitive psychomotor tests, and/or undertake cognitive function assessments to compare ice slurry ingestion against other cooling methods. Finally, an all-male participant cohort was chosen, thus the non-recruitment of females, who typically possess different morphological characteristics, may not allow direct extrapolation of our findings to females.

5. Conclusions

The current findings may be of interest to coaches and support practitioners who make decisions on employing recovery strategies with taekwondo athletes in competition. The present findings suggest that either internal cooling with ice slurry ingestion, or external cooling with CWI, cannot acutely influence physiological, neuromuscular, or psychomotor performance measures. Nevertheless, the ICE protocol did reduce T_{int} in the immediate 15 min period after cessation of ingesting ice slurry; 30–45 min after simulated combat. Accordingly, a similar ICE protocol utilized in this study may be considered by athletes in other sports disciplines to rapidly decrease core temperature (thermal load) if repeating performance within an acute (15 min) period after ICE ingestion.

Author statement

P. Pariyavuth: Conceptualization, methodology, data collection, analysis and interpretation of data, writing—original draft preparation, and editing; J.K.W. Lee: Methodology, and review and editing; P.M.S. Tan: Review and editing; K. Vichaiwong: Methodology and data acquisition; C. Mawhinney: Analysis and interpretation of data, and revising the manuscript; M. Pinthong: Conceptualization and design of study, writing—original draft preparation, review and revising, visualization, and supervision.

Funding

This work was supported by the Faculty of Graduate Studies, Mahidol University under the Doctoral research assistantship program to PP.

Declaration of competing interest

The authors report there are no competing interests to declare.

Acknowledgments

The authors would like to thank the athletes and coaches for their participation in this study.

References

1. Chiodo S, Tessitore A, Cortis C, et al. Effects of official Taekwondo competitions on all-out performances of elite athletes. *J Strength Condit Res*. 2011;25(2):334–339. https://doi.org/10.1519/JSC.0b013e3182027288.
2. World taekwondo. http://www.worldtaekwondo.org/rules-wt/rules.html. Accessed November 21, 2022.
3. Armstrong LE, Johnson EC, Casa DJ, et al. The American football uniform: uncompensable heat stress and hyperthermic exhaustion. *J Athl Train*. 2010;45(2):117–127. https://doi.org/10.4085/1062-6050-45.2.117.
4. Peiffer JJ, Abbiss CR, Nosaka K, Peake JM, Laursen PB. Effect of cold water immersion after exercise in the heat on muscle function, body temperatures, and vessel diameter. *J Sci Med Sport*. 2009;12(1):91–96. https://doi.org/10.1016/j.jsams.2007.10.011.
5. Bongers CCWG, Hopman MTE, Eijsvogels TMH. Cooling interventions for athletes: an overview of effectiveness, physiological mechanisms, and practical considerations. *Temperature (Austin)*. 2017;4(1):60–78. https://doi.org/10.1080/23328940.2016.1277003.
6. Taekwondo schedule and results archive - CBC Tokyo 2020 Olympics. CBC. https://www.cbc.ca/sports/olympics/summer/taekwondo/schedule. Accessed November 21, 2022.
7. Mawhinney C, Jones H, Joo CH, Low DA, Green DJ, Gregson W. Influence of cold-water immersion on limb and cutaneous blood flow after exercise. *Med Sci Sports Exerc*. 2013;45(12):2277–2285. https://doi.org/10.1249/MSS.0b013e31829d8e2e.
8. Chaen Y, Onitsuka S, Hasegawa H. Wearing a cooling vest during half-time improves intermittent exercise in the heat. *Front Physiol*. 2019;10:711. https://doi.org/10.3389/fphys.2019.00711.
9. Naito T, Ogaki T. Comparison of the effects of cold water and ice ingestion on endurance cycling capacity in the heat. *J Sport Health Sci*. 2017;6(1):111–117. https://doi.org/10.1016/j.jshs.2015.12.002.
10. Yeo ZW, Fan PWP, Nio AQX, Byrne C, Lee JKW. Ice slurry on outdoor running performance in heat. *Int J Sports Med*. 2012;33(11):859–866. https://doi.org/10.1055/s-0032-1304643.
11. Stanley J, Leveritt M, Peake JM. Thermoregulatory responses to ice-slush beverage ingestion and exercise in the heat. *Eur J Appl Physiol*. 2010;110(6):1163–1173. https://doi.org/10.1007/s00421-010-1607-3.
12. Cheng AJ, Willis SJ, Zinner C, et al. Post-exercise recovery of contractile function and endurance in humans and mice is accelerated by heating and slowed by cooling skeletal muscle. *J Physiol*. 2017;595(24):7413–7426. https://doi.org/

10.1113/JP274870.
13. Blondin DP, Labbé SM, Phoenix S, et al. Contributions of white and brown adipose tissues and skeletal muscles to acute cold-induced metabolic responses in healthy men. *J Physiol*. 2015;593(3):701–714. https://doi.org/10.1113/jphysiol.2014.283598.
14. Mawhinney C, Jones H, Low DA, Green DJ, Howatson G, Gregson W. Influence of cold-water immersion on limb blood flow after resistance exercise. *Eur J Sport Sci*. 2017;17(5):519–529. https://doi.org/10.1080/17461391.2017.1279222.
15. Webb P. Afterdrop of body temperature during rewarming: an alternative explanation. *J Appl Physiol*. 1985;60(2):385–390. https://doi.org/10.1152/jappl.1986.60.2.385, 1986.
16. Bridge CA, Sparks AS, McNaughton LR, et al. Repeated exposure to taekwondo combat modulates the physiological and hormonal responses to subsequent bouts and recovery periods. *J Strength Condit Res*. 2018;32(9):2529–2541. https://doi.org/10.1519/JSC.0000000000002591.
17. Anderson D, Nunn J, Tyler CJ. Effect of cold (14° C) vs. Ice (5° C) water immersion on recovery from intermittent running exercise. *J Strength Condit Res*. 2018;32(3):764–771. https://doi.org/10.1519/JSC.0000000000002314.
18. Waterhouse J, Drust B, Weinert D, et al. The circadian rhythm of core temperature: origin and some implications for exercise performance. *Chronobiol Int*. 2005;22(2):207–225. https://doi.org/10.1081/cbi-200053477.
19. Butios S, Tasika N. Changes in heart rate and blood lactate concentration as intensity parameters during simulated Taekwondo competition. *J Sports Med Phys Fit*. 2007;47(2):179–185.
20. Bridge CA, Jones MA, Drust B. Physiological responses and perceived exertion during international Taekwondo competition. *Int J Sports Physiol Perform*. 2009;4(4):485–493. https://doi.org/10.1123/ijspp.4.4.485.
21. Santos VGF, Santos VRF, Felippe LJC, et al. Caffeine reduces reaction time and improves performance in simulated-contest of taekwondo. *Nutrients*. 2014;6(2):637–649. https://doi.org/10.3390/nu6020637.
22. Peiffer JJ, Abbiss CR, Watson G, Nosaka K, Laursen PB. Effect of cold-water immersion duration on body temperature and muscle function. *J Sports Sci*. 2009;27(10):987–993. https://doi.org/10.1080/02640410903207424.
23. Al Haddad H, Laursen PB, Chollet D, Lemaitre F, Ahmaidi S, Buchheit M. Effect of cold or thermoneutral water immersion on post-exercise heart rate recovery and heart rate variability indices. *Auton Neurosci*. 2010;156(1-2):111–116. https://doi.org/10.1016/j.autneu.2010.03.017.
24. Lee JKW, Shirreffs SM, Maughan RJ. Cold drink ingestion improves exercise endurance capacity in the heat. *Med Sci Sports Exerc*. 2008;40(9):1637–1644. https://doi.org/10.1249/MSS.0b013e318178465d.
25. Siegel R, Maté J, Watson G, Nosaka K, Laursen PB. Pre-cooling with ice slurry ingestion leads to similar run times to exhaustion in the heat as cold water immersion. *J Sports Sci*. 2012;30(2):155–165. https://doi.org/10.1080/02640414.2011.625968.
26. Bradic A, Bradic J, Pasalic E, Markovic G. Isokinetic leg strength profile of elite male basketball players. *J Strength Condit Res*. 2009;23(4):1332–1337. https://doi.org/10.1519/JSC.0b013e3181a0227e.
27. Cohen J. *Statistical Power Analysis for the Behavioral Sciences*. second ed. Routledge; 1988. https://doi.org/10.4324/9780203771587.
28. Bongers CCWG, Hopman MTE, Eijsvogels TMH. Using an ingestible telemetric temperature pill to assess gastrointestinal temperature during exercise. *J Vis Exp*. 2015;104. https://doi.org/10.3791/53258.
29. Matsushigue KA, Hartmann K, Franchini E. Taekwondo: physiological responses and match analysis. *J Strength Condit Res*. 2009;23(4):1112–1117. https://doi.org/10.1519/JSC.0b013e3181a3c597.
30. Bridge CA, McNaughton LR, Close GL, Drust B. Taekwondo exercise protocols do not recreate the physiological responses of championship combat. *Int J Sports Med*. 2013;34(7):573–581. https://doi.org/10.1055/s-0032-1327578.
31. Naito T, Ogaki T. Pre-cooling with intermittent ice ingestion lowers the core temperature in a hot environment as compared with the ingestion of a single bolus. *J Therm Biol*. 2016;59:13–17. https://doi.org/10.1016/j.jtherbio.2016.04.006.
32. Stephens JM, Halson SL, Miller J, Slater GJ, Chapman DW, Askew CD. Effect of body composition on physiological responses to cold-water immersion and the recovery of exercise performance. *Int J Sports Physiol Perform*. 2018;13(3):382–389. https://doi.org/10.1123/ijspp.2017-0083.
33. Stanley J, Buchheit M, Peake JM. The effect of post-exercise hydrotherapy on subsequent exercise performance and heart rate variability. *Eur J Appl Physiol*. 2012;112(3):951–961. https://doi.org/10.1007/s00421-011-2052-7.
34. Wilcock IM, Cronin JB, Hing WA. Physiological response to water immersion: a method for sport recovery? *Sports Med*. 2006;36(9):747–765. https://doi.org/10.2165/00007256-200636090-00003.
35. González-Alonso J, Teller C, Andersen SL, Jensen FB, Hyldig T, Nielsen B. Influence of body temperature on the development of fatigue during prolonged exercise in the heat. *J Appl Physiol*. 1985;86(3):1032–1039. https://doi.org/10.1152/jappl.1999.86.3.1032, 1999.
36. Nybo L, Nielsen B. Hyperthermia and central fatigue during prolonged exercise in humans. *J Appl Physiol*. 1985;91(3):1055–1060. https://doi.org/10.1152/jappl.2001.91.3.1055, 2001.
37. Blazevich AJ, Babault N. Post-activation potentiation versus post-activation performance enhancement in humans: historical perspective, underlying mechanisms, and current issues. *Front Physiol*. 2019;10:1359. https://doi.org/10.3389/fphys.2019.01359.
38. Janiszewska K, Przybyłowicz KE. Pre-competition weight loss models in taekwondo: identification, characteristics and risk of dehydration. *Nutrients*. 2020;12(9):2793. https://doi.org/10.3390/nu12092793.
39. Vromans BA, Thorpe RT, Viroux PJ, Tiemessen IJ. Cold water immersion settings for reducing muscle tissue temperature: a linear dose-response relationship. *J Sports Med Phys Fit*. 2019;59(11):1861–1869. https://doi.org/10.23736/S0022-4707.19.09398-8.