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## Influence of post-exercise hot-water therapy on adaptations to training over 4 weeks in elite short-track speed skaters

Thibaut Méline<sup>a, b, c, d, 1</sup>, Robert Solsona<sup>a, 1</sup>, Jean-Philippe Antonietti<sup>e</sup>, Fabio Borrani<sup>f</sup>, Robin Candau<sup>b</sup>, Anthony M.J. Sanchez<sup>a, \*</sup><sup>a</sup> University of Perpignan Via Domitia, Faculty of Sports Sciences, Laboratoire Interdisciplinaire Performance Sante Environnement de Montagne (LIPSEM), UR 4640, 7 Avenue Pierre de Coubertin, 66120, Font-Romeu, France<sup>b</sup> University of Montpellier, INRAE UMR 866, Dynamique Musculaire et Métabolisme (DMEM), 2 Place Viala, 34060, Montpellier, France<sup>c</sup> Fédération Française des Sports de Glace, France<sup>d</sup> Centre de Ressources, d'Expertise et de Performance Sportives, Centre National d'Entraînement en Altitude, Font-Romeu, France<sup>e</sup> Institute of Psychology, University of Lausanne, Lausanne, Switzerland<sup>f</sup> Institute of Sport Sciences, University of Lausanne, Lausanne, Switzerland

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## ABSTRACT

This study aimed to investigate the effects of regular hot water bathing (HWB), undertaken 10 min after the last training session of the day, on chronic adaptations to training in elite athletes. Six short-track (ST) speed skaters completed four weeks of post-training HWB and four weeks of post-training passive recovery (PR) according to a randomized cross-over study. During HWB, participants sat in a jacuzzi (40 °C; 20 min). According to linear mixed models, maximal isometric strength of knee extensor muscles was significantly increased for training with HWB ( $p < 0.0001$ ;  $d = 0.41$ ) and a tendency ( $p = 0.0529$ ) was observed concerning  $\dot{V}O_2max$ . No significant effect of training with PR or HWB was observed for several variables ( $p > 0.05$ ), including aerobic peak power output, the decline rate of jump height during 1 min-continuous maximal countermovement jumps (i.e. anaerobic capacity index), and the force-velocity relationship. Regarding specific tasks on ice, a small effect of training was found on both half-lap time and total time during a 1.5-lap all-out exercise ( $p = 0.0487$ ;  $d = 0.23$  and  $p = 0.0332$ ;  $d = 0.21$ , respectively) but no additional effect of HWB was observed. In summary, the regular HWB protocol used in this study can induce additional effects on maximal isometric strength without compromising aerobic and anaerobic adaptations or field performance in these athletes.

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## Introduction

Chronic exercise induces quantitative and metabolic muscular adaptations such as increases in fiber size or improved cell oxidative capacity.<sup>1–3</sup> In addition, sustained and intense exercise may increase the levels of circulating muscle damage markers, such as serum creatine kinase (CK), lactate dehydrogenase (LDH) and myoglobin (Mb) as well as hormones, such as cortisol, which is involved in the activation of catabolic processes and in the inhibition of anabolic effects of testosterone.<sup>4</sup> Considering that muscle

damages induced by exercise increase the recovery period and negatively affect performance, several recovery practices have been examined in the last decades (i.e. nutritional or pharmacological interventions and physiological issues such as active recovery, massage, cryotherapy or heat therapy).<sup>5,6</sup> However, the effects of a regular use of recovery methods on long-term adaptations to training are poorly studied, especially in field condition in elite athletes. Indeed, emphasis is often placed on acute effects of recovery on acute symptoms of exercise-mediated muscle damage but chronic adaptations may be affected by recovery choices.<sup>7</sup> Inappropriate recovery techniques can blunt chronic adaptations or lead to maladaptation,<sup>8–10</sup> hence the need to match recovery mechanisms with the nature of training stimuli and to take into account individuals.<sup>7</sup> These issues are critical to favor performance improvements and to avoid adverse outcomes.

\* Corresponding author.

E-mail addresses: [anthony.sanchez@univ-perp.fr](mailto:anthony.sanchez@univ-perp.fr), [anthony.mj.sanchez@gmail.com](mailto:anthony.mj.sanchez@gmail.com) (A.M.J. Sanchez).<sup>1</sup> These authors contributed equally to this work.

Among physiological recovery methods, the use of cold and heat have been increasingly considered in the last decades. Cold water immersion (CWI) has been the most investigated in the past few years but it may blunt adaptive responses to resistance exercise,<sup>9,11</sup> resulting in lower gains in muscle isometric strength and mass during long-term resistance training.<sup>9</sup> In contrast to cold treatments, heat therapies (or 'kaumatherapy'<sup>10</sup>), are increasingly examined. These methods refer to sauna bathing, heat water bathing immersion (HWB), microwave diathermy, heat/steam sheets, or heated environmental chamber,<sup>12</sup> and are commonly used as relaxation modalities for athletes. In humans, far-infrared sauna bathing seems favorable for recovery of the neuromuscular system after maximal endurance exercises<sup>13</sup> but post-exercise heat produced mixed results concerning other physiological parameters in humans.<sup>12</sup>

Concerning the potential beneficial effect of heating in adaptations to strength training, there is growing evidence that heating may elicit some cellular adaptations such as upregulation of genes involved in muscle growth and differentiation.<sup>12</sup> For instance, heat shock proteins (HSPs) expression increases after heat exposure<sup>14</sup> and these proteins are known to play a role in skeletal muscle regeneration and increases in cross-sectional area.<sup>15,16</sup> In addition, heat stress significantly enhances (with or without exercise) the phosphorylation level of several kinases involved in MTORC1 axis,<sup>17–20</sup> a critical pathway involved in mRNA translation.<sup>2,21</sup> This result suggests enhanced protein synthesis under heat stress.

Regarding the impact of heat on adaptations to endurance exercise, it was shown that post-exercise whole body heat application may promote some mitochondrial adaptations in mice.<sup>22</sup> In humans, heat stress produces an increase in plasma volume leading to hemodilution and hypovolemia that may be linked to improvements in time trial performance.<sup>23</sup> Repeated exposures to sauna bathing could also augment some acute physiological responses (e.g. weight loss) after exercise<sup>24</sup> and 12 bathing sessions over three weeks did enhance endurance performance of sub-elite athletes by 2%.<sup>25</sup> However, it was also recently found that regular HWB may impair some adaptations in elite teen archers.<sup>26</sup> Indeed, in a recent study, shooting performance and postural stability were decreased after HWB application (30 min at 40 °C twice a week for two weeks).<sup>26</sup> The authors hypothesized that the use of endogenous sources by skin cells for thermal adaptation should compromise some adaptations to training, especially in young people. Thus, this result suggests that HWB should be avoided for activities with high control of postural stability. Nevertheless, data on the effects of HWB on training adaptations in other disciplines, especially high-intensity sports, are currently lacking.

Therefore, the aim of this randomized counter-balanced crossover study was to examine the effects of regular HWB, undertaken immediately after the last training session of the day, on aerobic/anaerobic capacities and field performance in elite short-track (ST) speed skaters. ST speed skating is a sport that combines isometric, concentric and eccentric constraints, explosive power, strategies and high coordination at high-intensity.<sup>27–30</sup> Considering the potential beneficial effects of HWB on muscles adaptations from aerobic and strength exercises, it was expected improvements in aerobic and/or anaerobic performance but the effects of HWB on field test performance were also investigated since HWB could alter postural stability. Thus, a battery of tests was performed to evaluate the impact of training and recovery on variables important for athlete tracking and performance in this discipline.<sup>28,31–33</sup> These tests included isometric strength tests, an incremental peak power output exercise (iPPO), jump exercises, a force-velocity test, ice tasks, and anthropometric measurements.

## Materials and methods

### Participants

The present study was conducted in elite ST speed skaters who are very rare. The study includes six (three males and three females) athletes (mean  $\pm$  SD; age  $21.0 \pm 2.4$  years; height  $169 \pm 8$  cm) who are members of a national team. Two athletes have previously participated in the Winter Youth Olympics and Winter Olympics in 2016 and 2018, respectively. Athletes live and train at  $\approx 1800$  m. Participants were fully informed about data collection of this study and written consent was obtained from them. The study procedures complied with the Declaration of Helsinki on human experimentation. All participants were strongly encouraged during each test.

### Study design

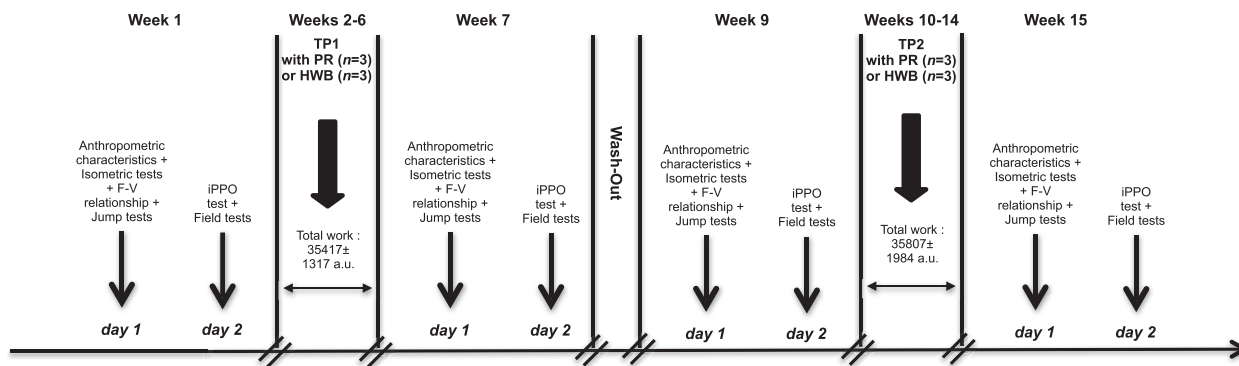
Athletes were randomized (simple random sampling) into two groups in equal number by an independent researcher blinded to the individuals for a counter-balanced crossover study of two training periods (TP1 and TP2, respectively) of five weeks. TP1 and TP2 included four weeks of normal or HWB training and were separated by a 10-day washout (Fig. 1). At four occasions (before and after TP1 and TP2), athletes performed a battery of tests on two consecutive days. All tests were performed at the same time of the day in order to minimize the effects of circadian cycles, and according to the same passage order and similar environmental conditions. The participants were instructed to maintain their dietary habits without alcohol consumption throughout the study period and to abstain from caffeine for 24 h before each test to avoid interactions. Athletes did not take dietary supplements or ergogenic aids during all the studied period. The day preceding each experiment, a standardized diet (55% carbohydrate, 15% protein, and 30% fat) was proposed to the athletes. Participants were advised not to consume medication or dietary supplement to avoid interference with recovery. To avoid possible influence of acute effect of HWB, post-tests were assessed three days after the last HWB session. No static stretching was allowed before each testing protocol.

### Hot baths and passive recovery

Hot baths occurred sitting in a spa (Water'clip, Civens, France) 10 min after the last training session of the day from the second week of each TP. Water temperature in spa (square 185 cm, height 65 cm) was  $40.3 \pm 0.6$  °C and air relative humidity in the room was about 92%. Athletes followed 16  $\pm$  3 HWB sessions. Passive recovery (PR) occurred sitting in a room next to the spa at  $20.3 \pm 0.9$  °C with a relative humidity about 70%. Athletes were asked to stay in the spa or in the room during 20 min. Fluid intake was ad libitum. To avoid acute effects of HWB on the course of training sessions performed on the same day, athletes were asked to follow a standardized active recovery (i.e. walking, running or cycling at low intensity) after morning sessions.

### Anthropometry and estimation of thigh muscle cross-sectional area

Body composition was assessed using bioelectrical impedance analysis (InBody 770, Cheonan, Chungcheongnam, South Korea). Thigh dimensions were taken on both the dominant (based on kicking preference) and nondominant thighs. The participants were instructed to stand erect with the feet approximatively shoulder



**Fig. 1.** Sequence of the experimental protocol. Athletes were randomized into two groups for a counter-balanced crossover study of two training periods (TP1 and TP2, respectively) of five weeks, including four weeks of PR or HWB training. At four occasions, athletes were asked to perform a battery of tests on two consecutive days. TP, training period; PR, passive recovery; HWB, hot water bathing; F–V relationship, force-velocity relationship; SJ, squat jump; CMJ, countermovement jump; iPPO, incremental peak power output.

width apart. The midthigh circumference and skinfold thickness measurements were taken midway between the proximal border of the patella and the inguinal crease. Quadriceps, hamstrings and total thigh muscle cross-sectional area (CSA, cm<sup>2</sup>) was predicted using the following equations<sup>34</sup>:

**Quadriceps CSA**

$$= (2.52 \times \text{midthigh circumference}) - (1.25 \times \text{anterior thigh skinfold}) - 45.13$$

**Hamstrings CSA**

$$= (1.08 \times \text{midthigh circumference}) - (0.64 \times \text{anterior thigh skinfold}) - 22.69$$

**Total thigh muscle CSA**

$$= (4.68 \times \text{midthigh circumference}) - (2.09 \times \text{anterior thigh skinfold}) - 80.99$$

where midthigh circumference and anterior thigh skinfold are expressed in cm and mm, respectively. All the anthropometric dimensions were taken three times (an average was done) by the same experimenter who had showed test-retest reliability ( $r > 95\%$ ).

**Isometric strength**

These tests were conducted between 07:00 am and 11:00 am. Athletes performed a warm-up consisting in 5 min of jogging on a treadmill, a set of 10 squats and 10 isometric incremental contractions on a chair-fixed dynamometer (LegControl, Matsport Training, Saint Ismier, France). Athletes were also asked to perform 10 sets of isometric contractions on a Swiss ball during the recovery before measurements of knee flexor muscles isometric strength. Maximal isometric strength of knee extensor and flexor muscles was evaluated using three single maximal trials on the chair-fixed dynamometer that was used during warm-up. All the values were retained for statistical analysis. The rest period between trials was 1 min and 7 min between the different tests. The knee angle was 90° and device settings were the same between the sessions for each athlete.

**Force–velocity test**

After 6 h of PR, athletes performed a warm-up consisting of 5 min of submaximal cycling (150W and 100W for men and women, respectively), followed by two short-accelerations (3 s) at ≈ 1000W

and ≈ 650W for men and women, respectively. After 5 min of PR, athletes performed a force-velocity test consisting in five to seven repetitive maximal short sprints of 5 s against increasing braking forces according to the power-velocity profile characteristics of athletes. The sprints were separated by 3 min of rest. The home trainer CycleOps H2 (Matsport Training, Saint Ismier, France) was used, equipped with their personal bike. Power output measurement was based on the Powertape technology. The accuracy of measurements announced by the manufacturer was ± 2%. The device was equipped with a 9.1 kg flywheel. The device was calibrated for each athlete according to the manufacturer's recommendations. The torque, velocity and power signals were transmitted by Bluetooth to a PC. The power-velocity relationship was described using a second-degree polynomial function. The maximal power output was obtained from this relationship. The torque-velocity relationship was described using a linear relationship. The x and y axes intercept made it possible to determine the maximal torque and the maximal velocity, respectively.

**Jump tests**

Immediately after the force-velocity test, participants performed a 10-min active recovery on ergocycle at a self-adjusted

low-intensity pace followed by 10 min of PR. Then, athletes followed a warm-up consisting in one set of five maximal counter movement jumps (CMJ). Jump height was estimated from the flight time measured by an infrared platform (Optojump Next system, Matsport Training, Saint Ismier, France). After 3 min of PR, athletes performed three maximal squat jumps (SJ) and three maximal CMJ on a portable force plate (PASCO PS-2142, Roseville, USA). For CMJ, participants were standing in a stationary position with body weight evenly distributed between both feet, the feet were approximately shoulder-width apart and the hips and knees were extended. Athletes were asked to keep their hands on the hips during the tests and to land back on the ground with both feet at the same time. For CMJ, they were instructed to jump vertically as high as possible after performing a countermovement (approximately 90° of knee flexion). All the SJ and CMJ values were retained for statistical analysis.

After 5 min of PR, participants were instructed to achieve the highest number of CMJ for maximum height within 1 min in order to assess an anaerobic capacity index. Data were collected thanks to the Optojump system. Athletes were instructed to land back on the ground with both feet at the same time, to bend the knees and to repeat the jumps within the set time period. A fatigue index, corresponding to the decline of jumping performances over time (i.e. the slope of the height drops), was then determined as previously described.<sup>35</sup> Finally, we calculated an index that evaluated whether participants were fully engaged without using pacing strategy at the start of the exercise<sup>35</sup>:

$$\text{Voluntary effort index (\%)} = \frac{(\overline{h(5\text{CMJ}_{1\text{ min}})})}{(h(5\text{CMJ}_i))} \times 100$$

where the numerator is the average height of the first five CMJ achieved during the 1 min test, and the denominator refers to the average height of the five CMJ performed during warm-up.

After this test, athletes performed a 10-min active recovery on ergocycle at a self-adjusted low-intensity pace.

### iPPO

On day two, participants performed an iPPO exercise. These tests were conducted between 08:00 am and 12:00 am. Athletes followed a progressive 4-min warm-up from 50 to 75W and from 70 to 100W for women and men, respectively. Then, the incremental test started at 75W and 100W for women and men respectively, with a stepwise increase of 25W for women and 30W for men every minute until exhaustion. iPPO was evaluated as sum of power output (W) at last step and duration at last step divided by 60 s × 30W or 25W for men and women, respectively. Blood lactate concentration [La] was collected 2 min after exercise using the Lactate Scout+ analyzer (EKF Diagnostic Gmhb, Barleben, Germany). The subjective perception of effort was quoted by each participant using the 6–20 rating of perceived exertion (RPE) scale.<sup>36</sup> Cardio-respiratory variables were measured breath-by-breath using a portable measurement system (MetaMax 3B-R3, Cortex Biophysics, Leipzig, Germany). Breathing flow was measured by a bi-directional digital turbine that was calibrated at the beginning of each test with a 3L syringe. Expired gases were sampled at the mouth by O<sub>2</sub> and CO<sub>2</sub> analyzers that were calibrated before each test using ambient air and standard gas (O<sub>2</sub>: 15%, CO<sub>2</sub>: 5%). Oxygen consumption ( $\dot{V}O_2$ ), CO<sub>2</sub> production ( $\dot{V}CO_2$ ), and minute ventilation ( $\dot{V}E$ ), were continuously monitored using MetaSoft Studio© studio software (5.5.2) and averaged over 5-s periods.  $\dot{V}O_{2\text{max}}$ , maximal ventilation ( $\dot{V}E_{\text{max}}$ ) and maximum heart rate ( $HR_{\text{max}}$ ) were determined with a moving average procedure of

30 s. HR was collected with a Polar heart rate monitor (Polar Electro H7, Finland).

The criterion for a maximal test were a combination of a least four of the following variables<sup>37–40</sup>: (i) plateau of  $\dot{V}O_2$ , (ii) HR > 90% of the predicted  $HR_{\text{max}}$  ( $214 \text{ bpm} - 0.8 \times \text{age}$  or  $209 \text{ bpm} - 0.8 \times \text{age}$  for men and women, respectively), (iii) respiratory exchange ratio (RER) ≥ 1.10, (iv) Borg Scale rating ≥ 18, (v) [La] > 8 mmol L<sup>-1</sup>, (vi) the athletes stopped the test despite strong verbal encouragements. Plateau of  $\dot{V}O_2$  was confirmed when  $\dot{V}O_2$  remained stable (i.e. variation less than 150 ml) during at least 30 s despite workload increase. Ventilatory threshold 1 and 2 (VT1 and VT2, respectively) were determined using Wasserman and Beaver method.

After this test, athletes performed a 10-min active recovery on ergocycle at a self-adjusted low-intensity pace.

### Ice tasks

Six hours after the iPPO test, athletes freely warmed up for 10 min on ice. Two minutes after warm-up, athletes were instructed to perform (i) a 1.5-lap all-out exercise (standing start) followed by 1 min of PR, (ii) a 3-lap all-out exercise (flying start) followed by 25 min of PR and (iii) a 7-lap exercise (flying start). In order to avoid pacing, athletes were requested to exert the maximum effort possible during each lap for the first two tests. Pacing strategy was authorized during the 7-lap exercise. Strong verbal encouragements were provided throughout the protocol by the test leaders.

### Training protocol and training load quantification

Mean training volume was about 17.6 ± 4.2 h per week. Training load on ice and non-specific training load (i.e. running, cycling, roller skating, fitness, strength training) including personal physical activity were quantified according to a method derived from that previously described.<sup>28</sup> Athletes followed 19 and 20 training sessions on ice, within TP1 and TP2, respectively. For both TPs, athletes also followed 9 training sessions of repeated sprints (including 3.7 ± 0.5 sessions of repeated sprints in hypoxia at a simulated altitude of 3500 m within TP2) and 11 strength training sessions with primarily isometric and eccentric actions.

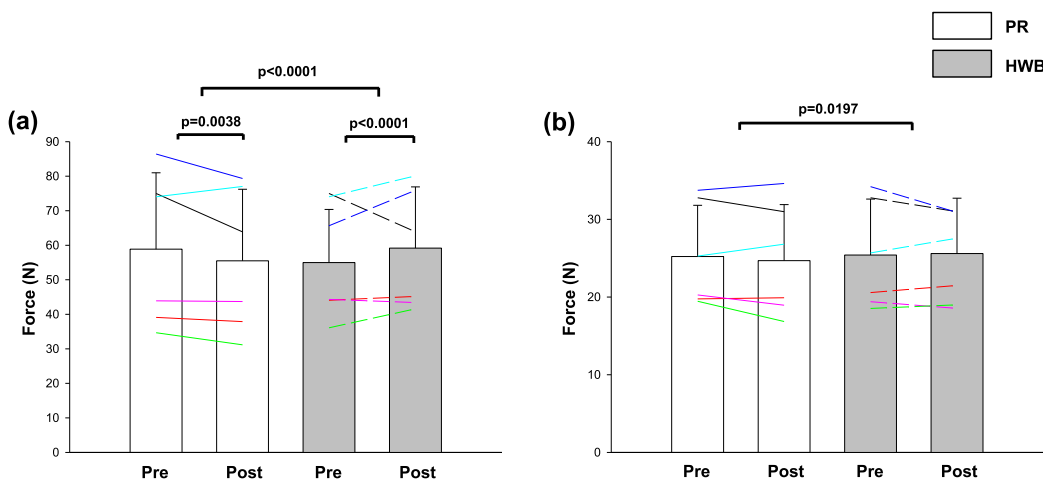
### Statistical analysis

The statistical analyses were performed using Jamovi (Version 1.1.7.0). Linear mixed models (LMM) were used to be more accurate with the specificity of our experimental design. This is a longitudinal approach that uses mixed effect modeling providing more precise estimates when data are hierarchized compared to repeated measures ANOVA. LMM flexibility makes them more appropriate for the analysis of repeated-measures data and when working with limited samples or missing data.<sup>41–43</sup> LMM have been developed to consider both the nested (i.e. multiple observations within a single participant in a given condition) and crossed (i.e. participants observed in multiple conditions) structure of the data.<sup>42,44</sup> Conditions were the fixed effects and participant was set as the random effect. Code is presented in Supplementary data 1. After inspecting residual plots, no obvious deviations from homoscedasticity or normality were present. For all the tests the level of significance was set at 0.05 and dispersion about the mean was expressed as SD. Effect sizes (d) are also provided (trivial effect d < 0.10, small effect d = 0.20, medium effect d = 0.50 and large effect d = 0.8).<sup>45</sup>

**Table 1**  
Results of the different tests prior to and following the training period with hot water bathing (HWB) or passive recovery (PR).

	PR		HWB	
	Pre-training	Post-training	Pre-training	Post-training
<b>Anthropometric characteristics</b>				
Body mass (kg)	59.6 ± 6.3	58.2 ± 4.6	60.1 ± 6.4	59.2 ± 6.3
Body mass index (a.u.)	21.0 ± 0.9	20.5 ± 1.1	21.1 ± 0.9	20.8 ± 0.8
Fat mass (%)	12.3 ± 4.8	12.6 ± 4.2	12.8 ± 4.2	12.2 ± 5.0
Lean mass (%)	82.5 ± 4.7	84.0 ± 6.7	82.0 ± 4.1	82.4 ± 4.8
Skeletal muscle mass (%)	49.5 ± 3.3	50.5 ± 4.4	49.3 ± 2.9	49.7 ± 3.5
Leg CSA (cm <sup>2</sup> )	152.9 ± 20.8	155.9 ± 18.1 *	154.8 ± 19.6	156.2 ± 19.6
KE CSA (cm <sup>2</sup> )	79.4 ± 12.4	81.2 ± 10.8 *	80.5 ± 11.8	81.4 ± 11.7
KF CSA (cm <sup>2</sup> )	29.5 ± 6.0	30.4 ± 5.2 *	30.0 ± 5.8	30.6 ± 5.6
<b>Vertical jump height (cm)</b>				
SJ	36.6 ± 8.4	36.2 ± 6.9	36.6 ± 8.2	36.7 ± 6.9
CMJ	37.8 ± 8.0	36.4 ± 6.5	37.8 ± 7.9	38.3 ± 7.7
<b>F–V relationship</b>				
Pmax (W)	1225 ± 286	1218 ± 276	1234 ± 304	1169 ± 258
Pmax (W.kg <sup>-1</sup> )	20.2 ± 3.0	20.2 ± 3.0	20.2 ± 3.0	19.2 ± 3.1
Tmax (N.m <sup>-1</sup> )	49.6 ± 4.1	51.2 ± 7.1	49.8 ± 6.8	52.4 ± 8.0
Vmax (rpm)	168 ± 21	169 ± 17	167 ± 14	166 ± 14
Topt (N.m <sup>-1</sup> )	32.4 ± 8.9	32.4 ± 6.6	31.0 ± 7.3	28.6 ± 5.1
Vopt (rpm)	119.6 ± 9.2	118.6 ± 10.8	125.4 ± 8.1	126.2 ± 11.7
<b>iPPO test</b>				
$\dot{V}E_{max}$	165.9 ± 35.0	168.7 ± 29.7	159.3 ± 36.3	162.2 ± 26.3
HR <sub>max</sub>	185.7 ± 5.0	186.2 ± 6.0	185.1 ± 7.6	184.2 ± 6.1
Time to exhaustion (s)	556.7 ± 70.2	570.0 ± 75.0	553.3 ± 77.2	560.8 ± 67.9
VT1 (% iPPO)	60.0 ± 4.8	64.3 ± 2.5	60.3 ± 4.3	59.7 ± 7.3
VT2 (% iPPO)	86.0 ± 4.2	85.8 ± 5.0	86.9 ± 4.6	82.0 ± 8.0
<b>1.5-lap all-out exercise</b>				
Time (s)	16.6 ± 0.9	16.4 ± 0.8 *	16.6 ± 0.9	16.5 ± 0.7
Mean velocity (m.s <sup>-1</sup> )	10.1 ± 0.5	10.2 ± 0.5	10.0 ± 0.5	10.1 ± 0.5
Time ½ lap (s)	7.34 ± 0.45	7.28 ± 0.41 *	7.40 ± 0.48	7.32 ± 0.39
<b>3-lap all-out exercise</b>				
Time (s)	27.0 ± 1.4	26.9 ± 1.1	27.1 ± 1.0	26.8 ± 0.7
Mean velocity (m.s <sup>-1</sup> )	12.4 ± 0.6	12.4 ± 0.5	12.3 ± 0.4	12.4 ± 0.3
<b>7-lap exercise</b>				
Time (s)	66.4 ± 3.7	66.0 ± 2.8	67.1 ± 2.6	66.3 ± 2.4
Mean velocity (%)	11.7 ± 0.6	11.8 ± 0.5	11.6 ± 0.5	11.8 ± 0.4

DATA are shown as mean ± standard deviation. CSA, muscle cross-sectional area; KE, knee extensor muscles; KF, knee flexor muscles; SJ, Squat jump (SJ); CMJ, counter-movement jump; F–V relationship, force-velocity relationship; Pmax, maximal power output; Tmax, maximal torque; Vmax, maximal velocity; Topt, optimal torque; Vopt, optimal velocity; iPPO, incremental peak power output;  $\dot{V}E_{max}$ , maximal ventilation; HR<sub>max</sub>, maximal heart rate; VT1, first ventilator threshold; VT2, second ventilator threshold. \*p < 0.05, training effect found with linear mixed models (exact p values are presented in the main text).



**Fig. 2.** Results of isometric strength tests. (a) maximal strength of knee extensors muscles, (b) maximal strength of knee flexors muscles. PR, passive recovery; HWB, hot water bathing. Significant results were found with linear mixed models. Bars represent group mean and color lines represent individual responses.



## Results

### Training loads

Training loads were not significantly different ( $p > 0.05$ ) and reached  $35417 \pm 1317$  a.u. and  $35807 \pm 1984$  a.u. for TP1 and TP2, respectively. Endurance training represented 42.6% and 39.5% of total training time for TP1 and TP2, respectively.

### Anthropometric parameters

The evolution of athletes' anthropometric characteristics is shown in Table 1. No significant effect of training was found concerning anthropometric characteristics excepted for the predicted CSA. Indeed, LMM highlighted that training with PR slightly but significantly increased the predicted CSA of total thigh ( $p = 0.0348$ ;  $d = 0.14$ ), quadriceps muscle ( $p = 0.0282$ ;  $d = 0.15$ ) and hamstring muscle ( $p = 0.0269$ ;  $d = 0.16$ ). Of note, these effects are very small according to Cohen criteria. However, no effect of HWB was observed ( $p > 0.05$ ).

### Maximal isometric strength

Results are presented in Fig. 2. According to LMM, training with PR slightly but significantly decreased maximal isometric strength in knee extensor muscles ( $p = 0.0038$ ;  $d = 0.16$ ). A significant increase was obtained with HWB ( $p < 0.0001$ ;  $d = 0.41$ ). Regarding the maximal isometric strength of knee flexor muscles, a significant effect of HWB was found ( $p = 0.0197$ ;  $d = 0.20$ ).

### SJ and CMJ

No significant effect ( $p > 0.05$ ) of both training with PR and training with HWB was found concerning vertical jump height from SJ and CMJ tests (Table 1).

### Anaerobic performance indexes

No significant effect ( $p > 0.05$ ) of both training with PR or HWB was found regarding the fatigue index, and total and mean height of jumps. In addition, no significant difference ( $p > 0.05$ ) was observed for the voluntary effort index. This suggests that athletes were similarly engaged during the different tests (Fig. 3). The pre-training values were  $95.7 \pm 6.9\%$  and  $96.2 \pm 3.7\%$  and the post-training values were  $95.9 \pm 3.9\%$  and  $97.1 \pm 5.3\%$  for PR and HWB, respectively.

### Force–velocity exercise

No significant effect ( $p > 0.05$ ) of both training with PR and training with HWB was found concerning peak power output (absolute and relative to body mass values), maximal and optimal velocity and torque (Table 1).

### iPPO

No significant effect ( $p > 0.05$ ) of training with PR was found regarding iPPO,  $\dot{V}Emax$ ,  $HRmax$ ,  $VT1$  and  $VT2$ . According to LMM,  $\dot{V}O_{2max}$  tended to be higher than pre-training after training with HWB ( $p = 0.0529$ ;  $d = 0.17$ ) for 5 on 6 athletes but no effect was observed concerning the other variables. Results are presented in Fig. 4 and Table 1.

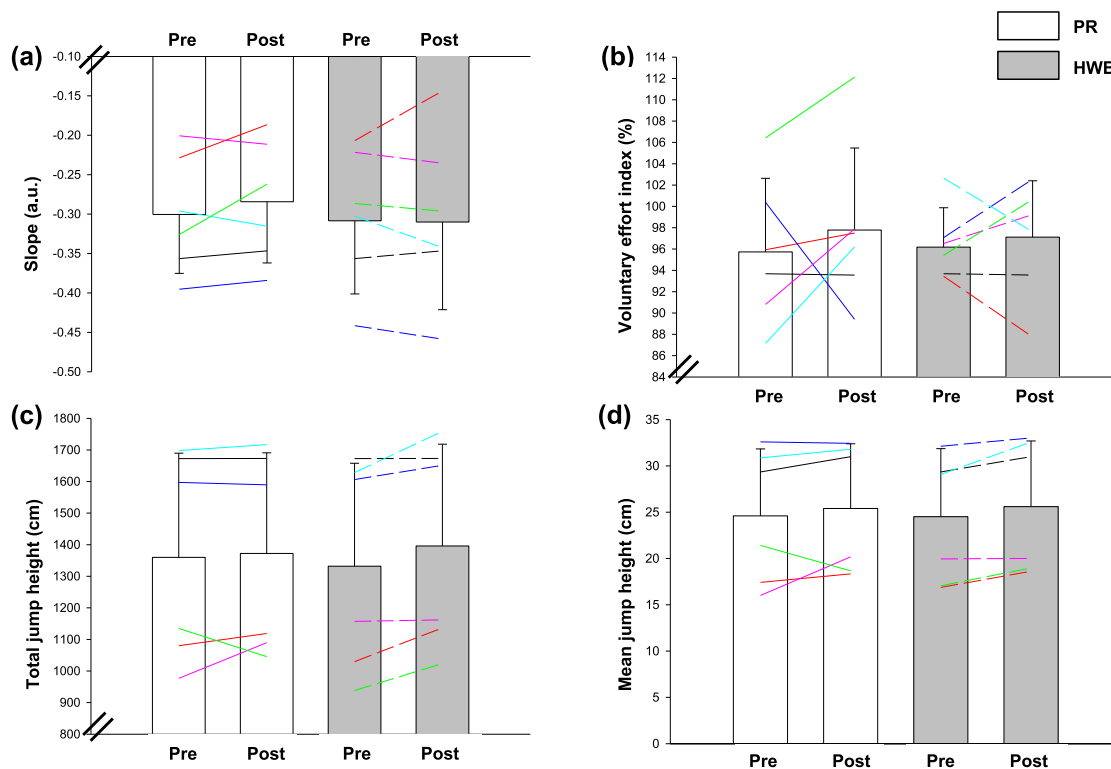
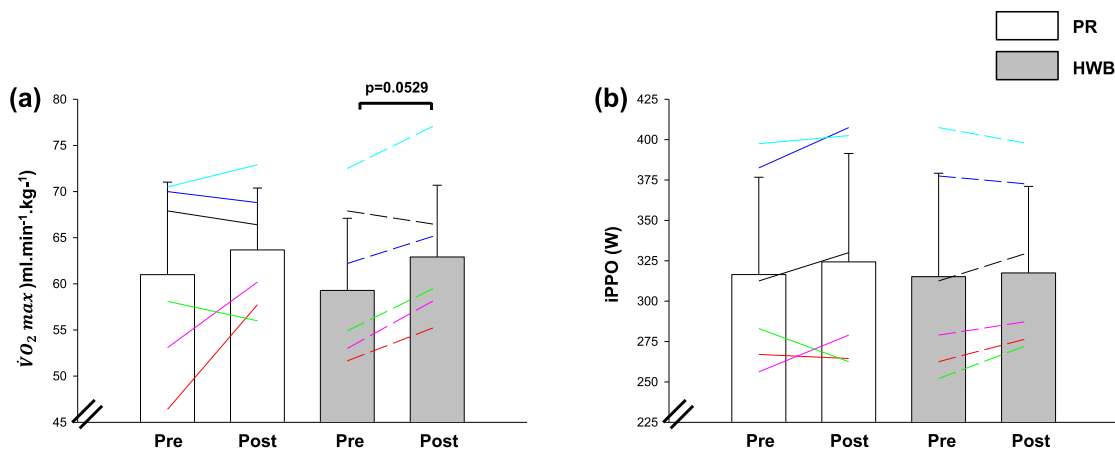


Fig. 3. Results of the fatigue index during the 1-min CMJ exercise. (a) Fatigue index calculated from jump height decline, (b) voluntary effort index, (c) total jump height, and (d) mean jump height. PR, passive recovery; HWB, hot water bathing. Bars represent group mean and color lines represent individual responses.



**Fig. 4.** Results of the incremental peak power output (iPPO) test. (a) Maximal oxygen consumption ( $\dot{V}O_2 \text{ max}$ ), and (b) aerobic peak power output. PR, passive recovery; HWB, hot water bathing.  $p = 0.0529$ , tendency for training with HWB found with linear mixed models. Bars represent group mean and color lines represent individual responses.

*Field tests on ice*

LMM showed a small but significant effect of training on both half-lap time and total time during the 1.5-lap all-out exercise ( $p = 0.0487$ ;  $d = 0.23$  and  $p = 0.0332$ ;  $d = 0.21$ , respectively). Of note, these effects are small according to Cohen criteria. There was no effect of HWB ( $p > 0.05$ ). No further effect was found regarding other field tests variables ( $p > 0.05$ ). Results are presented in Table 1.

*Estimates of fixed effects*

The residue distributions have been examined and appear satisfactory for the statistical methods used (i.e. absence of extreme data from residue distribution form). Estimates of fixed effects for all the studied variables are resumed in supplementary data 2. No effect of leg laterality was found concerning leg CSA and isometric strength of leg extensor and flexor muscles ( $p > 0.05$ ).

**Discussion**

The purpose of this counter-balanced crossover study was to compare the effects of training with HWB or PR on long term adaptations in elite athletes. Here, the effects of HWB on several variables related to performance, including field tasks on ice, were evaluated in ST athletes. According to the data, training with HWB maintains high performance level in the studied athletes and can enhance their maximal isometric force without influencing aerobic, anaerobic and field aptitudes.

In this work, the training program corresponded to a general preparation that aimed to develop various aspects of performance in ST after resuming a new season. This may partially explain the absence of training effect on several variables under PR. It is also important to note that the studied athletes already have great basal aptitudes, making more difficult to induce larger effects on performance. Both training periods (TP1 and TP2) were similar and consisted in the same training load, training volume and exercise modalities. The novel finding in this study concerns the variations of leg isometric strength. Although the training program with PR did not lead to increases in isometric strength, it was observed a positive effect of training with HWB for both knee extensor and flexor muscles. Interestingly, these results are in contrast to those that were found with CWI. Indeed, CWI has been shown to limit resistance training-induced gains of maximal isometric strength

and muscle fiber hypertrophy, without altering concentric strength.<sup>9,46</sup> The discrepancy may be explained by the fact that CWI may increase skeletal muscle protein catabolism and reduce anabolism through an inhibition of protein signaling pathways, ribosomal biogenesis and satellite cells activation.<sup>9,10,46</sup> Even if we didn't investigate cellular mechanisms underlying training adaptation in the present study, it was suggested that heat exposure significantly enhances the activity of kinases involved in protein synthesis and could enhance the training effects on muscle growth.<sup>18–20</sup> However, no significant effect of HWB was found on body composition and predicted thigh CSA. According to the data, HWB could therefore be advised if gains in muscle isometric strength are desired. However, further studies are needed to reinforce these data, especially (i) the characterization of molecular pathways involved in muscle growth, (ii) the evaluation of the effects of training with HWB in a strength specific training program.

Although there are only few reports on the effects of hot-water therapies on training adaptations, the study by Hung and co-workers recently highlighted in a crossover-study that hot-tub therapy impairs shooting performance in elite teen archers after only twice a week (every 3 days) hot-tub therapy sessions of  $2 \times 15$  min ( $40^\circ\text{C}$ ) for 2 weeks.<sup>26</sup> The authors associated these decreases in performance with impaired postural balance and hypothesized that adaptation of skin cells against hot could take away endogenous sources needing for training adaptation in teen archers. Since ST needs optimal postural adjustments among all the qualities required,<sup>28–30,32</sup> it was investigated if HWB may affect field performance during several tasks performed on ice. A very slight but significant positive effect of training was found in sprints tasks (i.e. performance in 1.5-lap all-out exercise). Importantly, chronic HWB was found not to alter performance in both exercises even if our protocol included more HWB sessions than the aforementioned study. Thus, if chronic HWB could affect postural balance according to the data from Hung et al.,<sup>26</sup> it seems not to affect performance in elite ST athletes. However, acute effects of HWB on field performance in ST warrant further investigation, especially because heat exposure could increase skin cell death and turnover that may enhance the use of carbon sources. Dehydroepiandrosterone sulfate (DHEA-S) is considered as an important endogenous source required for training adaptation.<sup>47</sup> It was hypothesized in elite teen archers that competing DHEA-S for skin adaptation after hot-tub therapy may compromise training adaptation.<sup>26</sup> Finally, long-term HWB treatment can increase maximal isometric strength but not the actual performance. In ST, athletes have to produce high power

and accelerations<sup>48</sup> and concentric strength of the leg extensors appears as a key factor that influences skating performance.<sup>32</sup> This possibly explains the absence of HWB effect on field performance (i.e. skating time or speed).

Furthermore, the results highlighted that training with HWB may be beneficial for some aerobic adaptations as suggested by the tendency of increased  $\dot{V}O_2max$  observed for 5/6 athletes. However, no significant effect of both training with PR or HWB was detected on other aptitudes (iPPO, vertical jump tests performance, anaerobic capacity index, and force velocity relationship). The sample size that could be too small to produce clear outcomes limits the conclusions. In addition, this research was conducted in elite athletes that elicit less pronounced adaptations to training than recreational athletes due to high basal aptitudes. Recreative or moderate trained people could experience higher responses. In addition, the training program administered was a generic program after resuming a new season, the results must be interpreted considering this context and the effects of HWB remain to be elucidated if the development of a specific aptitude is desired. Knowing the fact that heat stress may additionally enhance some endurance-induced mitochondrial adaptations in rodent,<sup>22</sup> the use of HWB during chronic endurance exercise also needs further attention. Furthermore, since the present study showed some beneficial effects of HWB on exercise performance, it will be advisable to compare the effects of different therapies (e.g. HWB vs cryotherapy or massage) on recovery or performance evolution in further investigations. For instance, contrast water therapy was found to present some positive effects on the acute recovery of cycling and running performance.<sup>49,50</sup> However, to the best of our knowledge, no study has investigated the effects of a regular use of this recovery method on long term adaptations to training in elite athletes.

In conclusion, the data seem indicate that four-weeks training with HWB does not impair adaptations to training in these elite ST athletes and could support positive effects on maximal isometric force and possibly on  $\dot{V}O_2max$ . Other research should be encouraged to evaluate the effects of training with HWB in specific conditions (i.e. strength or endurance training program), and to compare these effects with other recovery methods (e.g. contrast water therapy). Importantly, our knowledge on the effect of recovery methods regarding long term adaptations has to be reinforced.

Limitations: In this study, the main limitation is the small sample size. This limitation is the consequence of the difficulty to obtain elite ST speed skaters because these athletes are very rare. A larger study sample reducing type 2 error would have reinforced the conclusions and produced more clear outcomes. Furthermore, future studies are needed to compare the responses between male and female athletes. Here, the small sample size made the comparison not possible. However, LMM increased the statistic power of the study and made it possible to highlight some effects, especially the large effects. In the present study, LMM allowed to increase the precision of estimates of the observed effects. Another limitation is that there was no placebo, here it was not possible to double-blind the hot tub therapy. However, subjects were not informed about the hypothesis (i.e. if HWB was going to be positive or negative for performance). Finally, another limit could be the possible variations of ice quality during the field tests on ice. Even if quality of ice was controlled, it could influence performances and contribute to explain the small differences observed during these tests.

Practical applications: The impact of recovery on long-term adaptations to training is poorly investigated. In the current study, we investigated effects of HWB on adaptations to training in elite ST athletes. Regular training with HWB maintains high performance in these athletes. It induces additional effects on maximal

isometric strength and does not alter aerobic and anaerobic aptitudes and field performance on ice. ST is a complex coordination and high intensity sport with eccentric actions. The impact of HWB must be investigated in other disciplines that require such combination of characteristics. According to our results, we can speculate that HWB could be recommended for disciplines involving isometric or static strength such as climbing, wrestling and karate. Further studies are needed to state this hypothesis because each sport discipline has his own specificities.

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## Author contributions

Conceived and designed the experiments: AMJS, FB, TM, RC. Performed the experiments: TM, AMJS. Analyzed the data: AMJS, RS, JPA, TM. Designed the training protocol and controlled recovery: TM. Designed the tables and figures: AMJS, FB, RS, JPA. Wrote the paper: AMJS. Performed the revision of the manuscript: AMJS, JPA, RS, FB, RC. Contributed reagents/materials/analysis tools: AMJS. All the authors read the manuscript and approved the final version.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jesf.2021.01.001>.

## Conflicts of interest

The authors declare no conflicts of interest that are directly relevant to the context of this article.

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