Scand J Med Sci Sports 2015: 25 (Suppl. 1): 219–228
doi: 10.1111/sms.12392

SCANDINAVIAN JOURNAL OF
MEDICINE & SCIENCE
IN SPORTS

Low-frequency electrical stimulation combined with a cooling vest improves recovery of elite kayakers following a simulated 1000-m race in a hot environment

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Accepted for publication 17 November 2014

This study compared the effects of a low-frequency electrical stimulation (LFES; Veinoplus® Sport, Ad Rem Technology, Paris, France), a low-frequency electrical stimulation combined with a cooling vest ($LFES_{CR}$) and an active recovery combined with a cooling vest (ACT_{CR}) as recovery strategies on performance (racing time and pacing strategies), physiologic and perceptual responses between two sprint kayak simulated races, in a hot environment (~32 wet-bulb-globe temperature). Eight elite male kayakers performed two successive 1000-m kayak time trials (TT1 and TT2), separated by a short-term recovery period, including a 30-min of the respective recovery intervention protocol, in a randomized crossover design. Racing time, power output, and stroke rate were recorded for each time trial. Blood lactate concentration, pH, core, skin and body temperatures were measured before and after both TT1 and TT2 and at mid- and post-recovery intervention. Perceptual ratings of thermal sensation were also collected. $LFES_{CR}$ was associated with a *very likely* effect in performance restoration compared with ACT_{CR} (99/0/1%) and LFES conditions (98/0/2%). $LFES_{CR}$ induced a significant decrease in body temperature and thermal sensation at post-recovery intervention, which is not observed in ACT_{CR} condition. In conclusion, the combination of LFES and wearing a cooling vest ($LFES_{CR}$) improves performance restoration between two 1000-m kayak time trials achieved by elite athletes, in the heat.

Canoe sprint has been an Olympic sport since 1936 and comprises of two distinct disciplines – kayak and canoe. The international sprint canoeing competition typically comprises one to three days of races. Heats and semi-finals are often 3 h or 4 h apart with the final the following day. Depending on the strategy of the teams, many athletes compete in several events with multiple races per day in individual (C1, K1), crew (C2, K2 or C4, K4), or both, interspaced by short recovery periods (less than 2 h). Furthermore, in the last few years, the main international events in canoe sprint (Milan World Cup Series in 2014, Moscow World Championships in 2014, Zagreb European Championships in 2012, Beijing Olympic Games in 2008) regularly took place under hot and/or humid conditions, which seriously limit human performance (Kay et al., 1999; Wendt et al., 2007; Periard et al., 2014). Accordingly, it is challenging for coaches and scientists to establish competition strategies that allow athletes to regulate effort in order to achieve optimal performance. Therefore, in an attempt to overcome these intensive training and competition demands, recovery from exercise is a priority in elite canoeing as it contributes to metabolic, cognitive, and physical regeneration (Vaile et al., 2008; Crampton et al., 2011).

One of the most frequently applied recovery interventions in canoeing is active recovery, where athletes exercise at low to moderate intensities (workloads corresponding to 30–40% $\dot{V}O_{2peak}$) in an attempt to increase systemic and muscular blood flows improving oxygenation and nutrients delivery, while at the same time assisting in the removal of metabolic by-products. However, in the heat, active recovery can elicit sustained cardiovascular and thermoregulatory strains, as the muscles continue to work and therefore to produce metabolic heat (De Pauw et al., 2014). Recently, low-frequency electrical stimulation (LFES) has been investigated as an alternative to active recovery (Bieuzen et al., 2012). The physiologic rationale for using LFES during recovery from exercise is to increase blood flow in the muscles. This is achieved when LFES is applied at intensities sufficient to initiate a low-intensity, involuntary, repetitive mechanical contraction–relaxation cycle. Results from recent studies

suggest that increased systemic blood flow following LFES is beneficial to performance restoration after a short-term recovery, in a temperate environment (Bieuzen et al., 2012, 2014; Finberg et al., 2013). By being a non-active strategy, using LFES after exercise in a hot environment could limit heat development and may even enhance conductive and evaporative cooling by maximizing peripheral blood flow, and consequently, improve recovery in athletes.

Several external and internal cooling methods are also employed in elite sport to reduce thermal stress and improve recovery in-between exercise bouts in the heat. Although cold-water immersion is one of the most effective cooling strategies (Bleakley et al., 2014), it is rarely used in the field because of practical considerations. Recently, the use of cooling vests has increased and several countries have adopted this strategy as a method of reducing thermoregulatory strain in elite canoeing. Wearing a cooling vest during exercise has been shown to enhance the rate of perceived thermal comfort and physical performance in hot conditions (Hasegawa et al., 2005); however, the effectiveness of using cooling vests as a post-exercise recovery strategy has not been studied extensively (Hausswirth et al., 2012). Moreover, the effects of cooling vests on short-duration exercise performance remain inconclusive.

As is evident from earlier, acute recovery has been studied in depth, yet many questions remain unanswered. The most prevalent is the effectiveness of using mixed-method recovery intervention that can both prevent excessive heat storage and facilitate heat loss from the body as well as increasing blood flow, oxygen supply, and metabolites washout, and ultimately improve subsequent exercise performance in the heat. The combination of LFES, which prevents thermal strain and enhances blood flow, and wearing a cooling vest, which reduces thermal strain, could be an effective recovery strategy and warrants investigation.

Therefore, the aim of this study was to investigate the performance (racing time and pacing strategies), physiologic, and perceptual responses to repeated 1000-m sprint kayak races using (a) LFES, (b) active recovery combined with a cooling vest, and (c) LFES combined with a cooling vest between races in the heat. It was hypothesized that the combination of blood flow stimulation with the cooling vest between races would reduce thermal strain and improve subsequent 1000-m kayak sprint performance, in comparison with the other interventions.

Methods

Participants

Eight elite Caucasian male kayakers unacclimatized to heat participated in this study (mean ± standard deviation: age 22 ± 3 years; stature 183.3 ± 6 cm; body mass: 86.6 ± 7.3 kg; body surface area: 2.08 ± 0.1 m^2). All participants were K1, 1000-m paddlers, recruited from the French national Under 23 team, and had previously competed in the World and European Junior Championships. Data collection occurred during an international pre-competitive period in which all participants were accustomed to training up to six times per week and one to two sessions per day. Participants were informed of the possible risks and benefits of their participation in writing and an informed consent was obtained prior to data collection. The experimental protocol was conducted according to the Declaration of Helsinki statement and approved by a local ethics committee, CCP Ile-de-France XI (Ref. A006S7-S0).

Overview

Participants were familiarized with all equipment and procedures under experimental conditions before reporting to the laboratory for three separate experimental trials that were separated by a minimum of 24 h. In the 12 h prior to each testing session, participants were asked to refrain from strenuous physical exercise, caffeine and alcohol, to stay well hydrated, and to maintain a consistent dietary intake, in-line with their usual daily practice. Finally, they were asked to prepare for each testing session as they would for an important race. Each experimental trial lasted 3 h and included two 1000-m kayak time trials, TT1 and TT2, separated by a 70-min recovery period, including a 30-min recovery intervention protocol. The time recovery protocol corresponded to the mean time interval of French elite paddlers, in cases in which they are competing in different national and international races depending on the distance and the discipline. All trials were completed in a hot environment, (38.1 ± 1.1 °C, 26.4 ± 3% relative humidity, ~32 wet-bulb-globe temperature), in a temperature-controlled chamber without simulated wind condition.

Upon completion of the TT1, participants underwent a post-exercise recovery intervention administered using a randomized, repeated-measures crossover design. The randomization procedure (i.e., draw from a hat) was administered by an assistant not involved in the experiment. Recovery modalities consisted of (a) LFES; (b) active recovery combined with a cooling vest; and (c) LFES combined with a cooling vest. Performance (racing time and pacing strategies), physiologic, and perceptual responses were obtained at pre- and post-exercise and at mid- and post-recovery intervention period. During the trials, participants were allowed to ingest water and sport drink (Gatorade®, Pepsico, Colombes, France, for 100 mL: 5.9 g carbohydrates with 3.9 g sucrose, 0.13 g salt, 50 mg sodium, 47 mg chloride, 12 mg potassium, 5 mg magnesium) *ad libitum* in order to cover water and nutrients requirements.

Exercise protocol

Upon arrival to the laboratory on each testing day, participants were allowed to adjust their seat position and footrest dimensions on the kayak ergometer to simulate as close as possible their usual boat set-up. Testing sessions were performed on a kayak ergometer (Dansprint, I Bergmann A/S, Hvidovre, Denmark) set to a drag factor of 40 as per the National Australian testing protocols (Jones & Peeling, 2014). The paddle tension of the ergometer was calibrated prior to testing by standardizing the load factor of the bungee cords when they were extended to 210 cm to a tension value of 1.5 kg ± 20 g using a Kern HDB 10K10N scale (Kern & Sohn GmbH, Balingen, Germany). The paddle shaft length was fixed at 166 cm. First, participants performed a 10.7-min standardized warm-up, based on the recommendation of the French national kayak head coach and during the experiments participants wore only kayaking short. After a 10-min rest period, participants then performed a 1000-m kayak time trial. Participants were encouraged to finish exercise as fast as possible. No information with regard to time, resistance, heart rate, or cadence was provided at any time throughout the race. Only the distance to be covered

was available. Again, participants had to cover a certain amount of work as fast as possible and were free to increase or decrease their power output as desired from the outset. The second warm-up consisted of a 4.5-min paddling. After a rest period of 10-min, participants completed exactly the same kayak time trial as for the TT1.

All power outputs and stroke rates recorded from the Dansprint ergometer were captured into an Excel spread sheet via the manufacturer provided software (Microsoft Excel 2011, Microsoft Corp., Redmond, Washington, USA).

Recovery interventions

The recovery intervention period comprised a 70-min recovery period, including a 30-min recovery intervention protocol. Two 20-min transition periods were necessary to ensure all measurements before and after the recovery intervention protocol. The participants underwent the three recovery interventions, in a random manner: (a) LFES; (b) active recovery combined with a cooling vest (ACT_{CR}); and (c) LFES combined with a cooling vest ($LFES_{CR}$).

Participants in the LFES condition used an electric blood flow stimulator of the muscles (Veinoplus® Sport, Ad Rem Technology, Paris, France) for 30-min, in a seated position, with bent legs and arms. The duration and intensity settings of LFES were chosen based on pilot testing in order to obtain the same physiologic effects, based on blood lactate clearance, as the 15-min active and 15-min passive recovery combination. The stimulation was applied via four self-adhesive Veinopack 8 × 13 cm surface electrodes (Ad Rem Technology), which were replaced after each trial. One electrode was placed on the medio-central part of the calf on the left leg and the second electrode was placed symmetrically on the medio-central part of the calf on the right leg. The two others were placed in the same manner on the medio-central of the biceps brachii. The stimulation pattern delivered by Veinoplus Sport consisted of a series of rectangular pulses of low energy (< 25 μC), low voltage (50 Vpeak), with a carrier frequency of 250 Hz and impulse durations modulated from 25 to 250 μs. The specific stimulation modulation pattern of the Veinoplus Sport resulted in calf and biceps brachii muscles contractions of 60 to 90 contractions per minute during the 30-min stimulation session. The frequency of contractions automatically changed every 1-min. The device output is voltage controlled within the range of 0.5–50.0 Vp in 100 steps of 0.5 V each. During interventions, the voltage of stimulation was adjusted manually in a range of 9–18 Vp, depending on participant tolerance. The application of such stimulation voltages resulted in nearly symmetric contractions of the muscles in each leg and arm of participants. Indeed, there is a wide inter-individual difference on the voltage required to reach muscle contraction, as well as the voltage level to reach stimulation-induced pain. To limit differences among participants, a minimal threshold was fixed by the investigators corresponding to a visible contraction of the calf and biceps brachii muscles with comfortable sensation. The output impulses from Veinoplus Sport produced ~150 msec long-fused twitches of muscle contractions without pain reported by participants.

The ACT_{CR} recovery consisted of a 15-min period of paddling between 60 and 80 W on the kayak ergometer with time and power output visible and a 15-min period of a passive recovery, comfortably seated on a chair. For 30-min, participants wore a cooling vest (Cryovest®, SM Europe, La Mézière, France) composed of nine Cryopacks stored at –4 °C until use and applied on torso, back and neck. The dry weight of the vest with the inserted cooling elements was 2.2 kg.

The $LFES_{CR}$ condition involved exactly the same procedure as LFES with the addition of the cooling vest worn in the ACT_{CR}.

Measurements

Blood parameters

In order to measure blood concentration of lactate $[La^-]_b$, capillary earlobe samples (20 μL) were collected and analyzed with a Biosen Lactate analyser (Biosen C-line analyser, EKF Industrie, Elektronik GmbH, Barbelen, Germany) at rest, 3 min after both TT1 and TT2 and at mid- (15 min) and post-recovery (30 min) intervention. Additional blood samples (50 μL) were also collected from the earlobe at the same four time points and analyzed to determine serum sodium concentration $[Na^+]$, blood bicarbonate concentration $[HCO_3^-]$, blood pH, and hematocrit (Hct). Samples were collected in heparinized capillary tubes and immediately placed in the receptacle of a GC8 + cartridge for clinical chemistry analysis on an I-Stat analyzer (Abbott Point of Care Inc., Princeton, New Jersey, USA).

Thermoregulatory measures

Core temperature (T_{core}) was assessed during exercise and recovery periods via thermosensitive capsule (HQ, Inc., Thermo Pills, Palmetto, Florida, USA) ingested 4 h prior to starting the trial. Skin temperature was analyzed at four different sites (on the upper chest, lower forearm, upper thigh, and medial side of the calf) using a thermal imaging camera (ThermaCam SC 640, Flir Systems AB, Danderyd, Sweden) in accordance with the standard protocol of infrared imaging in medicine. In order to guarantee an optimal measure of skin temperature at the upper chest, the cooling vest was removed from participants for each picture taken during the protocol. Mean skin temperature (T_{skin}) was calculated according to the equation established by Ramanathan (1964) (Equation 1). Mean body temperature (T_{body}), measured prior to the initial warm-up (rest), after both TT1 and TT2, and at mid- (15 min) and post-recovery (30 min) intervention, was estimated according to the methods described by Schmidt and Bruck (1981) (Equation 2).

$$T_{skin} = 0.3 \times (T_{chest} + T_{arm}) + 0.2 \times (T_{thigh} + T_{leg}) \quad (1)$$

$$T_{body} = 0.87 T_{core} + 0.13 T_{skin} \quad (2)$$

Hydration status and sweat secretion

Urine specific gravity (USG) was assessed upon arrival to the laboratory and after both TT1 and TT2 via the provision of a mid-stream urine sample analyzed using a refractometer (PAL-10S, Atago Co., Ltd, Tokyo, Japan). Body mass loss (BML) was calculated from measures of clothed body mass prior to the initial warm-up (rest) and at the completion of TT2 using a digital platform scale (Seca 877, Seca, Hamburg, Germany) as a representative of sweat mass loss. The total amount of water and sport drink ingested was accounted for in BML calculation by adding the estimated mass of fluid consumed to the difference in rest to post-TT2 change in body mass.

Perceptual measures

Rating of perceived exertion (RPE) was recorded after each exercise on a Borg scale of 6 (*no exertion*) to 20 (*maximal exertion*) (Borg, 1998). Thermal comfort (–3 "*cold*" to +3 "*hot*") (Epstein & Moran, 2006) and sensation (–2 "*very uncomfortable*" to +2 "*very comfortable*") (Zhang & Zhao, 2008) were recorded at pre- and post-TT1 and TT2. Participants were also asked to evaluate the recovery intervention ("How do you rate the efficacy of this

Table 1. Scales used to interpret the magnitude of between-condition differences in the change for time trial performance using values of 0.3, 0.9, 1.6, 2.5, and 4.0 of the within-athlete variation (CV) as thresholds for *small*, *moderate*, *large*, *very large*, and *extremely large* differences in the change between trials

	TT (%)
CV (%)	1.0
Trivial	< 0.3
Small	0.3–0.9
Moderate	0.9–1.5
Large	1.5–2.3
Very large	2.3–3.6
Extremely large	> 3.6

CV, coefficient variation; TT, time trial.

recovery intervention?" and "How did you like this recovery intervention?") by means of a 10-point Likert scale, ranging from 1 (not at all) to 10 (very, very much) (Bieuzen et al., 2014).

Statistic analysis

Physiologic and perceptual data were compared between groups and time using nonparametric tests. Nonparametric tests were necessary (a) because of the small sample size inherent in the training level of our population (elite paddlers); and (b) because of the non normality of the data distribution revealed by the Shapiro-Wilk test. A Kruskal–Wallis matched-pairs test was completed to assess significant differences between groups and a Friedman rank test was undertaken to evaluate the statistic differences in time for each recovery modality. When a significant *F*-value in Friedmans' analysis was found, a post-hoc test with a Bonferroni correction was used to determine the between-means differences. These statistic tests were conducted using the Statistical Package for the Social Sciences (SPSS v. 20.0, IBM Corporation, Inc., Armonk, New York, USA) and the data are presented as median, the value of the lower quartile (Q_{25}) and the value of the upper quartile (Q_{75}). For these analyses, significance was accepted at $P < 0.05$.

The performance data were analyzed using the magnitude-based inference approach recommended for studies in sports medicine and exercise sciences (Hopkins et al., 2009). We used this qualitative approach (a) because of the small sample size inherent in the training level of our population (elite paddlers) and (b) because traditional statistic approaches often do not indicate the magnitude of an effect, which is typically more relevant than any statistically significant effect to infer clinical recommendations. Although no variable exhibited non-uniformity of error, the performance data from the two bouts (TT1 and TT2) were log-transformed before analysis to reduce the tendency ($P < 0.10$) of some parameters to demonstrate a skewed distribution (Hopkins et al., 2009). The magnitude of the within-condition changes, or between-condition differences in the changes, was interpreted using values of 0.3, 0.9, 1.6, 2.5, and 4.0 of the within-participant coefficient variation (CV; see Tables 1 and 2) as thresholds for *small*, *moderate*, *large*, *very large*, and *extremely large* differences in the change between the trials (Hopkins et al., 2009). Quantitative chances of higher or lower differences were evaluated qualitatively as follows: < 1%, almost certainly not; 1–5%, very unlikely; 5–25%, unlikely; 25–75%, possible; 75–95%, likely; 95–99%, very likely; > 99%, almost certain. The practical interpretation of an effect is deemed *unclear* when the magnitude of change is substantial that is the 90% confidence interval (CI) (precision of estimation) could result in positive and negative outcomes (Batterham & Hopkins, 2006). The data are reported as

Table 2. Scales used to interpret the magnitude of between-condition differences in the change for average power output and stroke rate during time trials using values of 0.3, 0.9, 1.6, 2.5, and 4.0 of the within-athlete variation (CV) as thresholds for *small*, *moderate*, *large*, *very large*, and *extremely large* differences in the change between trials

	0–100 m	100–200 m	200–300 m	300–400 m	400–500 m	500–600 m	600–700 m	700–800 m	800–900 m	900–1000 m
Average power output										
CV (%)	7%	8%	5%	3%	3%	4%	4%	5%	5%	6%
Trivial	< 2%	< 2%	< 1%	< 1%	< 1%	< 1%	< 1%	< 1%	< 2%	< 2%
Small	2–7%	2–7%	1–4%	1–3%	1–3%	1–4%	1–4%	1–4%	2–5%	2–5%
Moderate	7–12%	7–12%	4–8%	3–6%	3–5%	4–7%	4–6%	4–7%	5–8%	5–9%
Large	12–17%	12–19%	8–12%	6–8%	5–7%	7–10%	6–10%	7–11%	8–13%	9–14%
Very large	17–29%	19–31%	12–19%	8–14%	7–12%	10–17%	10–16%	11–18%	13–21%	14–23%
Extremely large	> 29%	> 31%	> 19%	> 14%	> 12%	> 17%	> 16%	> 18%	> 21%	> 23%
Average stroke rate										
CV (%)	4%	3%	3%	3%	2%	2%	3%	3%	3%	4%
Trivial	< 1%	< 1%	< 1%	< 1%	< 1%	< 1%	< 1%	< 1%	< 1%	< 1%
Small	1–4%	1–3%	1–2%	1–2%	1–2%	1–2%	1–3%	1–3%	1–3%	1–3%
Moderate	4–7%	3–5%	2–4%	2–4%	2–3%	2–4%	3–5%	3–5%	3–5%	3–6%
Large	7–10%	5–8%	4–7%	4–6%	3–5%	4–6%	5–7%	5–7%	5–8%	6–9%
Very large	10–17%	8–13%	7–11%	6–10%	5–8%	6–10%	7–11%	7–12%	8–14%	9–14%
Extremely large	> 17%	> 13%	> 11%	> 10%	> 8%	> 10%	> 11%	> 12%	> 14%	> 14%

CV, coefficient variation.

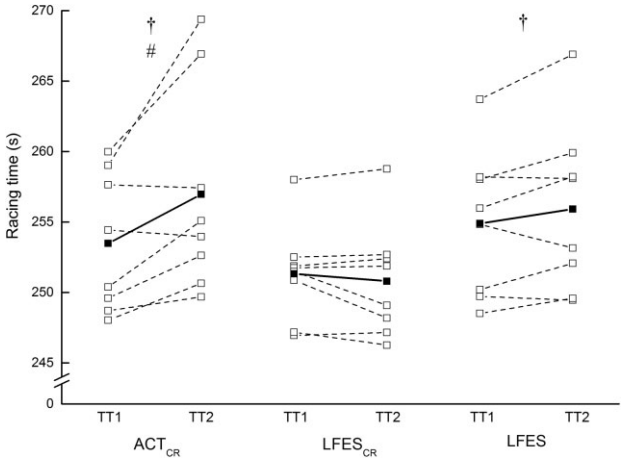

Fig. 1. Individual changes (dashed lines) and group mean changes (straigth lines) between TT1 and TT2. Between-condition difference in the change versus LFESCR: † *very likely*. Between-condition difference in the change versus LFES: # *very likely*.

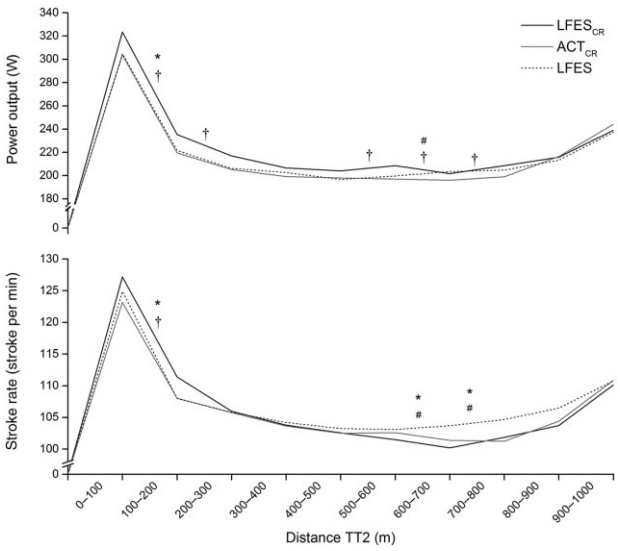

Fig. 2. Average power output and stroke rate during the second self-paced time trial (TT2). Between-condition difference in the change for LFESCR versus ACTCR, † *very likely*. Between-condition difference for LFESCR versus LFES, * *very likely*. Between-condition difference for ACTCR versus LFES, # *very likely*.

qualitative and percentage chances, the mean change effect size (ES) and the confidence interval.

Results

Performance and pacing strategy

Figure 1 details the between-condition difference in racing time variation of the TT1 and the TT2. There was *no clear* difference in racing time between all conditions during TT1. Changes in TT1 vs TT2 were –0.52 ± 0.60 s for $LFES_{CR}$, 3.49 ± 2.44 s for ACT_{CR} and 1.02 ± 0.79 s for LFES. The TT2 racing time was *very likely* faster after the $LFES_{CR}$ condition compared with ACT_{CR} [99/0/1%, ES = 1.6 (0.71; 2.44)] and LFES [98/0/2%, ES = 0.6 (0.1; 1.1)]. The TT2 racing time was *very likely* faster after the LFES condition compared with ACT_{CR} [97/0/3%, ES = 1.0 (0.1; 1.8)].

During TT1, there was *no clear* difference in pacing strategies among all conditions (i.e., power output and stroke rate). The between-condition difference in average power output and stroke rate during TT2 is presented Fig. 2. The power output during TT2 after the $LFES_{CR}$ condition was *very likely* higher than after ACT_{CR}, for the 100–300 m and 500–800 m sections [100–200 m: 99/0/1%, ES = 7.1 (2.9; 11.5); 200–300 m: 99/0/1%, ES = 5.8 (2.3; 9.5); 500–600 m: 97/0/3%, ES = 5.8 (0.97; 10.8); 600–700 m: 97/0/3%, ES = 3.0 (0.5; 5.6); 700–800 m: 99/0/1%, ES = 4.8 (2.1; 7.7)].

The stroke rate during TT2 after the $LFES_{CR}$ condition was *very likely* higher than after ACT_{CR} and LFES, for the 100–200 m section [ACT_{CR}: 99/0/1%, ES = 3.2 (1.4; 4.9); LFES: 98/0/2, ES = 3.1 (0.7; 5.5)]. The stroke rate during TT2 after the LFES condition was *very likely* higher than after $LFES_{CR}$ and ACT_{CR} for the 600–800 m section [$LFES_{CR}$: 600–700 m: 98/0/2%, ES = 3.4 (0.8; 6.1); 700–800 m: 98/0/2%, ES = 2.7 (0.8; 4.7) and ACT_{CR}: 600–700 m: 97/0/3%, ES = 2.2 (0.3; 4.1); 700–800 m: 98/0/2%, ES = 3.2 (0.9; 5.6)].

Thermoregulatory measures

The T_{core}, T_{skin}, and T_{body} values are presented in Fig. 3. There was no between-condition difference in T_{core}, T_{skin}, and T_{body} at rest and prior to the recovery intervention (post-TT1). The Friedman test revealed a significant difference in T_{body}, T_{core}, and T_{skin} between time measurements for the three conditions ($P < 0.05$). Post-hoc analysis revealed that T_{core} and T_{body} increased from the start to the end of the TT1 (average temperatures: T_{core}: 37.8 ± 0.4 °C, T_{body}: 37.4 ± 0.3 °C) and TT2 compared with baseline (rest) (average temperatures: T_{core}: 37.2 ± 0.5 °C, T_{body}: 36.9 ± 0.5 °C) for the all conditions. In the ACT_{CR} condition, the increased in T_{core} and T_{body} persists at mid-recovery and post-recovery, respectively, while these temperatures in the $LFES_{CR}$ and LFES conditions return to the initial state from mid-recovery. Analyses of T_{body} from post-TT1 measurement showed significant ($P < 0.05$) difference between time measurements with significant lower values at mid-recovery and post-recovery for the $LFES_{CR}$ only. Post-hoc analysis also revealed that T_{skin} at mid-recovery was significantly lower than post-TT1 for the $LFES_{CR}$ condition and ACT_{CR} conditions whereas T_{skin} at post-recovery was significantly lower than rest for the ACT_{CR} condition only.

Perceptual measures

RPE, thermal sensation and comfort, efficacy, and well-being recovery perceptions in the three conditions are depicted in Table 3. All participants' RPE ranged

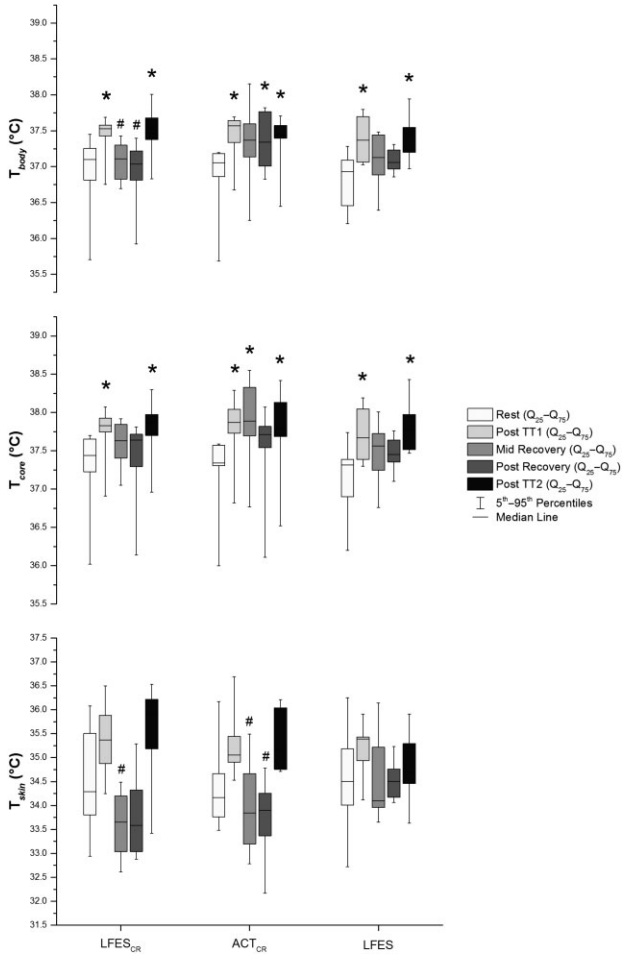

Fig. 3. Body (T_{body}), core (T_{core}), and skin (T_{skin}) temperatures during the testing session. *Significant difference from Pre ($P < 0.05$). #Significant difference from Post TT1 ($P < 0.05$).

between *very difficult* and *very very difficult* at TT1 and TT2 cessation during the whole experience (range, 17–20). The Kruskal–Wallis test revealed no significant between-condition difference in RPE ($P > 0.05$) at anytime point. The Friedman test revealed a significant difference in thermal sensation and comfort between time measurements for the three conditions ($P < 0.05$). Post-hoc analysis revealed that thermal sensation at post-recovery was significantly lower than post-TT1 for the LFES$_{CR}$ condition only. Post-hoc analysis revealed that comfort sensation at post-recovery was significantly higher than post-TT1 for all conditions.

The Kruskal–Wallis test revealed a significant less good perception of well-being from post-recovery in the ACT$_{CR}$ compared to LFES$_{CR}$ conditions. There was no significant between-condition difference in the perception of efficacy from post-recovery ($P > 0.05$).

Hydration status and sweat secretion

USG, body mass, and BML in the three conditions are depicted in Table 3. The Friedman test revealed no significant time effect in USG ($P > 0.05$). The Friedman test revealed a significant difference in body mass between time measurements for the LFES$_{CR}$ condition only ($P < 0.05$). Post-hoc analysis revealed that body mass at post-TT2 was significantly lower than rest for the LFES$_{CR}$ condition. The Kruskal–Wallis test revealed no significant between-condition difference in BML ($P > 0.05$).

Blood parameters

Examination of blood parameters is presented Table 3. The Friedman test revealed no significant time effect in [Na^+] ($P > 0.05$). A significant time effect was recorded for all conditions for pH, [La^-]$_b$ and hematocrit without significant between-condition difference. Post-hoc analysis revealed that hematocrit at post-TT1 was slightly higher than rest for the LFES$_{CR}$ condition only.

Discussion

The present study examined the effectiveness of three recovery interventions, applied during a short-term recovery period (70 min) between two kayak time trials performed in the heat, on race performance, physiologic, and perceptual responses. The main findings that can be drawn from this investigation are: (a) LFES combined with the wearing of a cooling vest (LFES$_{CR}$) resulted in a faster 1000-m time trial (TT2) compared with an active cooling intervention (ACT$_{CR}$); (b) no significant differences in [La^-]$_b$ and pH values were observed between the three interventions, at the end of the recovery intervention period; (c) only LFES$_{CR}$ intervention induced a significant decrease in body temperature and thermal sensation at post-recovery intervention; and (d) perception of well-being recovery was increased after the LFES$_{CR}$ intervention compared with the ACT$_{CR}$ condition. It is expected that these findings will help inform athletic preparations and the scientific results will be translated to an elite real-world competitive setting.

In accordance with the proposed hypotheses, our data demonstrated that the LFES$_{CR}$ condition was the most efficient recovery strategy compared with the LFES condition, and in particular, the ACT$_{CR}$ condition (Fig. 1). Compared with the active recovery strategy, LFES$_{CR}$ reduced the second 1000-m time trial by more than 3.5 s. In the last Canoe Sprint World Championships (Duisburg, 2013), Olympic Games (London, 2012) and European championships (Brandenburg, 2014), such a difference on the racing time during the Final A for K1, 1000-m boats, represented a difference between the first and fifth places in the ranking of the race. Therefore, these results outline the importance of the smallest change in real-life time trial performance. In addition to the time needed to complete the second time trial, the pacing strategy employed by the athletes is of major importance, as it is fundamental to kayak performance. It

Table 3. Blood parameters, perceptual measures, hydration status and sweat secretion measures at rest, post TT1 and TT2, and mid- and post-recovery intervention for the three groups

	Median and the value of the lower and the upper quartile (Q_{25}–Q_{75})				
	Rest	Post TT1	Mid-recovery	Post-recovery	Post TT2
Thermal sensation					
$LFES_{CR}$†	2.0 (1.0–3.0)	3.0 (2.8–3.0)	–	1.0 (0.8–1.0)‡	3.0 (2.8–3.0)
ACT_{CR} †	1.0 (1.0–2.0)	3.0 (3.0–3.0)	–	1.5 (1.0–2.3)	3.0 (3.0–3.0)
LFES†	2.0 (1.0–2.0)	3.0 (2.8–3.0)	–	1.5 (1.0–2.3)	3.0 (3.0–3.0)
Comfort sensation					
$LFES_{CR}$†	1.0 (0.5–1.3)	–1.0 (–2.0––0.8)	–	1.0 (1.0–1.0)‡	–1.0 (–1.3–0.0)
ACT_{CR}†	1.0 (0.0–1.0)	–1.0 (–2.0––1.0)	–	0.5 (0.0–1.0)‡	–1.0 (–2.0–0.0)
LFES†	1.0 (1.0–1.0)	–1.0 (–2.0––1.0)	–	1.0 (0.8–1.3)‡	–1.0 (–1.3–0.3)
Recovery efficacy					
$LFES_{CR}$	–	–	–	8.3 (7.3–8.5)	–
ACT_{CR}	–	–	–	6.9 (6.4–7.4)	–
LFES	–	–	–	7.8 (6.5–7.9)	–
Recovery well-being					
$LFES_{CR}$	–	–	–	8.7 (8.3–9.0)	–
ACT_{CR}	–	–	–	6.4 (6.2–6.9)§	–
LFES	–	–	–	7.5 (6.8–9.0)	–
RPE					
$LFES_{CR}$	–	19.0 (19.0–19.3)	–	–	19.0 (19.0–19.3)
ACT_{CR}	–	19.0 (18.8–19.0)	–	–	19.0 (18.8–19.0)
LFES	–	19.0 (19.0–19.0)	–	–	19.0 (18.0–19.0)
Urine specify gravity					
$LFES_{CR}$	1.024 (1.014–1.026)	–	–	–	1.025 (1.019–1.027)
ACT_{CR}	1.024 (1.018–1.026)	–	–	–	1.025 (1.021–1.029)
LFES	1.018 (1.017–1.025)	–	–	–	1.020 (1.018–1.022)
Body mass (kg)					
$LFES_{CR}$†	87.6 (82.1–91.9)	87.4 (82.1–91.7)	–	87.3 (82.0–92.1)	87.2 (81.9–91.6)*
ACT_{CR}	87.2 (81.9–91.3)	87.1 (81.7–91.0)	–	87.2 (81.4–91.2)	87.2 (81.3–91.1)
LFES	87.3 (81.7–91.4)	86.1 (81.5–90.4)	–	87.3 (81.0–90.3)	87.0 (81.1–90.2)
Body mass loss (kg)					
$LFES_{CR}$	–	–	–	–	1.88 (1.41–2.01)
ACT_{CR}	–	–	–	–	2.25 (1.86–2.56)
LFES	–	–	–	–	2.08 (1.95–2.29)
$[Na^+]$					
$LFES_{CR}$	142 (140–143)	143 (142–144)	143 (142–143)	142 (142–142)	143 (142–143)
ACT_{CR}	140 (140–142)	141 (139–143)	142 (141–144)	142 (141–144)	141 (140–143)
LFES	142 (140–142)	142 (139–142)	142 (140–143)	142 (141–142)	143 (140–143)
pH					
$LFES_{CR}$†	7.41 (7.38–7.43)	7.22 (7.18–7.29)*	7.39 (7.37–7.39)	7.40 (7.38–7.42)‡	7.31 (7.24–7.38)
ACT_{CR}†	7.41 (7.40–7.42)	7.20 (7.14–7.26)*	7.40 (7.38–7.43)	7.44 (7.43–7.45)‡	7.32 (7.26–7.38)
LFES†	7.40 (7.39–7.42)	7.24 (7.12–7.28)*	7.38 (7.37–7.42)	7.42 (7.40–7.43)‡	7.26 (7.21–7.31)
$[La^-]_b$					
$LFES_{CR}$†	1.18 (1.00–1.52)	12.50 (9.81–13.42)*	3.85 (3.25–4.73)	2.58 (2.02–2.70)‡	11.81 (10.50–13.13)*
ACT_{CR}†	1.19 (1.08–1.25)	11.89 (10.25–12.90)*	2.78 (1.79–3.92)	1.93 (1.12–2.44)‡	9.90 (8.91–11.80)*
LFES†	1.36 (1.06–1.55)	10.43 (9.47–12.91)*	3.71 (3.21–4.64)	2.41 (2.26–3.24)‡	10.96 (9.20–11.53)*
Hct					
$LFES_{CR}$†	47 (45–49)	50 (49–53)*	48 (44–49)	46 (44–47)	48 (47–50)
ACT_{CR}	48 (46–49)	50 (48–51)	47 (47–48)	47 (46–49)	52 (50–54)
LFES†	48 (48–49)	49 (47–51)	47 (43–49)	46 (44–47)	49 (48–52)

*Represents a significant ($P < 0.05$) difference from rest.

†Represents a significant ($P < 0.05$) time effect.

‡Represents a significant ($P < 0.05$) difference from Post TT1. All significant results were not pointed except from Rest and Post TT1 to avoid overloading the table.

§Represents a significant ($P < 0.05$) difference between $LFES_{CR}$ and ACT_{CR}.

ACT_{CR}, active recovery combined with a cooling vest; Hct, hematocrit; LFES, low-frequency electrical stimulation combined without cooling vest; $LFES_{CR}$, low-frequency electrical stimulation combined with cooling vest; RPE, rating of perceived exertion; TT, time trial.

appears that pacing strategies are dependent on the recovery method used between the two time trials. In accordance to Borges et al. (2013), 1000-m kayak races all displayed a reverse J-shaped pacing profile, with a fast start, a slower middle part and an increase in the final sprint. The minimal differences in performance and regulation of pace variability between conditions during TT1, allow us to confirm the elite status of the paddlers involved in the present study. Pacing strategies differ during TT2 as $LFES_{CR}$ resulted in a higher power output

compared with other conditions and a higher stroke rate during the first sprint, maintained during the middle part until the final stage of the second race (Fig. 2). Conversely, after LFES and ACT_{CR}, paddlers displayed an immediate decline of power output after the onset of the second exercise. This fast start strategy observed in the $LFES_{CR}$ condition has been suggested as beneficial to kayakers because of several reasons. Firstly, athletes and coaches consider positions at the front of the group early in the race to be tactically advantageous to have better control on the opponents and avoid 'wash' of the other boats (Borges et al., 2013). Secondly, the fast start strategy may also provide physiologic advantages such as improving the energy production through the aerobic pathway (Abbiss & Laursen, 2008).

In the present study, the metabolic fuel restoration and/or by-products washout do not seem to be the primary factors affecting the performance and the pacing strategies. Indeed, this study involved one repetition of 1000-m time trial, considered as short duration mainly aerobic exercise (79% aerobic, 21% anaerobic; see review of Gastin, 2001), combined with the *ad libitum* ingestion of sport drink (5.9 g carbohydrates with 3.9 g sucrose). This methodologic design enabled us to study the impact of different recovery interventions on kayaking performance in the heat without associated confounders such as dehydration (as evidenced by no significant difference in USG between conditions; Table 3) and/or glycogen depletion. The mean $[La^-]_b$ of all kayakers in this study increased first to a peak value of 11.0 ± 0.4 mmol/L after TT1, before continually decreasing until the end of the recovery intervention period, irrespective of the recovery strategy used. This mean peak value is in close agreement with the results reported by Michael et al. (2008) during laboratory and on water testing. Thus, the non-significant differences in $[La^-]_b$ and pH kinetics between the three conditions might reflect that LFES and active recovery, irrespective of the cooling vest, induced adequate blood flow to the recovering muscles allowing clearance of the accumulated blood lactate and other metabolic by-products, which can adversely affect muscle function.

Given these results, we suggest it is likely that other mechanisms apart from enhanced metabolic by-products removal from the muscle could explain the improved performance restoration after $LFES_{CR}$ recovery. An interesting finding in the current study was the differences in T_{body}, T_{core} and T_{skin} following $LFES_{CR}$, LFES and ACT_{CR} (Fig. 3). The participants in the passive interventions (i.e., LFES and $LFES_{CR}$) reduced T_{core} in a shorter period (i.e., 15 min recovery period) than participants in the ACT_{CR} condition following TT1. Active recovery implemented in a hot environment is likely to increase heat storage during low-intensity exercise as well as increasing both cardiovascular and thermoregulatory strain (Bishop et al., 2007; De Pauw et al., 2014). It has previously been demonstrated that reducing T_{core} is extremely important during recovery. Yeargin et al. (2006) suggested that lowering rectal temperature by 0.5 °C between two bouts of exercise in the heat (~27 °C) can improve 2 miles running. As an increase in T_{core} is the main determinant for initiating a thermoeffector response (sweating) (Werner, 1998) the upward trend in BML reported in the ACT_{CR} compared with LFES and $LFES_{CR}$ (Table 3) leads us to hypothesize that greater levels of heat accumulation, stimulating cutaneous vasodilatation and peripheral blood flow necessary for conductive and evaporative cooling, were experienced during ACT_{CR} (Bishop et al., 2007).

Moreover, $LFES_{CR}$ and ACT_{CR} lowered T_{skin} at mid-recovery intervention (i.e., 15 min, Fig. 3). Numerous studies (Hasegawa et al., 2005; Webster et al., 2005) have previously reported that cooling vests are an effective method of reducing T_{skin}. Although Duffield et al. (2003) observed a significant decrease of skin temperature and indicators of perceived thermal discomfort in hockey players after wearing a cooling vest for 5 min before and during the recovery periods, comparatively few studies have examined the use of cooling vests during repeated exercise bouts. Our data support these findings and suggest that cooling vests are an effective method of reducing T_{skin} and facilitating heat dissipation during exercise in the heat. The current findings also demonstrate that the reduction in T_{core} during recovery was primarily the result of the cessation of the activity and the cooling vest was only effective in reducing surface temperature.

Finally, only the $LFES_{CR}$ condition demonstrated a significant reduction of mean T_{body} at the end of the recovery intervention. Taken together, these results suggest that the non-active and cooling combination recovery (i.e., $LFES_{CR}$) was an efficient mean to impact positively the heat loss. It can be assumed that blood flow exchanges between the core and the periphery were facilitated during LFES (Glaser, 1994), thereby optimizing the cooling effect of the vest and lowering T_{body}. Therefore, the cumulative effect of non-active recovery and the cooling intervention could enhance performance and thermoregulation via greater temperature gradients between the skin and the core, indicated by a larger gradient before the start of the second time trial. In the current study, subjects did not attain high core temperatures during TT2 (~38.5 °C), indicating that aerobic exercise performance may degrade in hot environments without marked hyperthermia (De Pauw et al., 2014). The present study was mainly designed to simulate the environmental conditions athletes encounter during official competitions. However, when translating the results of the current study to the field of kayak, subtle differences between laboratory and kayaking must be considered. Indeed, kayaking causes increased air movement around the athlete, which results in faster heat dissipation by evaporation and convection. This convective cooling, which may result in an attenuated increase of

the T_{core} and T_{skin} temperature in the field, was not been taken into account in this controlled laboratory study.

The reduced thermal stress experienced after the combination of the cooling vest and the LFES intervention may partly explain how high-intensity performance have been restored during the second time trial. The reduced thermal stress may have altered motor-unit recruitment, explaining the sustained high-power output during the first part of the TT2. Indeed, neuromuscular functioning and exercise capacity are inversely associated with an elevated T_{core} temperature, as the recruitment of motor units during voluntary activation of skeletal muscle is reduced under heat stress (Cheung, 2007). Concomitantly, increasing thermal strain reduces cerebral blood flow velocity and oxygenation, also contributing to declines in motor outflow and exercise performance or to alter the perception of effort (Minett et al., 2014). Some authors have also postulated that cooling alters the activity of the central nervous system, which is linked to pacing strategies (Minett et al., 2011). Further work is necessary to determine the implications of $LFES_{CR}$ on neurophysiologic restoration.

Finally, the perceptual effects of LFES and cooling interventions have been suggested to explain performance and especially pacing strategy improvements. In the present study, we observed higher scores on recovery well-being perception scale after the $LFES_{CR}$ intervention when compared with active recovery condition (Table 3). It was also reported a better thermal sensation (Table 3) and a very likely faster completion time during the second 1000-m time trial after $LFES_{CR}$ condition. It has been proposed that the internal physiologic state, and also thermal sensation, play an anticipatory role in exercise regulation (Tucker, 2009). In addition, humans appear to be able to anticipate the intensity of heat stress they will be exposed to, in order to ensure the maintenance of homeostasis and prevent critically high temperature (Marino, 2004). As a result, the complex interactions of feedforward and feedback mechanisms appear to act in complementary ways to regulate pace in order to resist fatigue. Accordingly, we hypothesize that the combined reduction in T_{core} and T_{skin} induced by the $LFES_{CR}$ strategy before the TT2 could have been beneficial on thermal sensation and recovery perception, resulting in facilitating the regulation of pace and the maintenance of subsequent exercise performance. These observations are supported by the beneficial effect of LFES recovery regarding feeling of recovery and reported by some studies in temperate environments (Cortis et al., 2010). To a lesser extent, the addition of a cooling vest to the LFES in a hot environment appears to be beneficial to perceptions of recovery (Luomala et al., 2012). However, literature on perceptual effects of recovery modalities is rather scarce, and further investigations are required to address this paucity of research.

In summary, these findings highlighted the performance, physiologic, and perceptual benefits of the combination of LFES and wearing a cooling vest between repeated high-intensity exercise bouts in a hot environment, when athletes are adequately hydrated and have normal glycogen stores. Importantly, $LFES_{CR}$ rapidly decreased exercise-induced elevation of body temperature and improved thermal and recovery perceptions. Presumably, this hastened the recovery of power output, resulting in an efficient pacing strategy compared with ACT_{CR} and LFES recoveries.

Perspectives

The combination of LFES and the wearing of a cooling vest enhance athletic recovery and improve subsequent high-intensity self-paced sprint exercise in hot conditions. This is likely a result of reductions in core and skin temperatures during recovery. Furthermore, this may be related to some neurophysiological effect on muscle drive/activation and/or psychologic effect rather than any peripheral effect on metabolites by-products clearance throughout the recovery period. However, further research is needed to clearly evaluate these mechanisms. In addition, future research should attempt to investigate the effects of this recovery intervention in other sports, environmental conditions and in acclimatized athletes.

Key words: Post-race recovery strategy, high-intensity exercise, exercise-induced heat stress, cooling strategy, low-intensity exercise.

Acknowledgements

This study was supported by a grant of French Ministry of Sport. It was made possible by technical support from the French Federation of Canoe Kayak. Authors are especially grateful to the athletes for their effort and coaches (François During and Nicolas Maillotte) for their help and cooperation.

Conflicts of interest: The authors of this study declare that they have no conflict of interest.

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