Effect of practical precooling on neuromuscular function and 5 km time-trial performance in hot, humid conditions amongst male, well-trained runners

Running Head Title: Practical Precooling, Muscle Function and Endurance Performance

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ABSTRACT

This study investigated whether torso and thigh precooling during a warm-up effects neuromuscular function and 5 km time-trial performance in hot, humid conditions. Eight male, well-trained runners completed three randomized time-trials in 32.2 ± 0.8°C, 48.6 ± 6.7% relative humidity. A 30-min warm-up was completed with no cooling (Control), precooling via an ice vest (Vest), or ice packs covering the thighs (Packs). Before the warm-up and after the time-trial, supramaximal femoral nerve stimulation was delivered during and following maximal isometric contractions. Core and skin temperature, heart rate and perceptual ratings were recorded before, and during the warm-up and time-trial. Overall performance time was improved in Packs compared to Control (1407 ± 80 vs. 1492 ± 88 s; $P < 0.05$), but not in Vest (1444 ± 7 s; $P > 0.05$). In Packs, a higher exercise intensity ($P < 0.05$) and less cumulative time ($P < 0.01$) were evident during the last kilometer compared to Control. Maximum voluntary force, voluntary activation, muscle contractility and membrane excitability were not different after exercise or between conditions. After 10 min during the warm-up, skin temperature was lower in Vest and Packs compared to Control ($P < 0.01$). Thermal strain and body heat content change was lower in Vest and Packs, respectively ($P < 0.05$). Findings indicate that torso and thigh precooling during a warm-up reduces thermoregulatory strain. However, thigh opposed to torso precooling provides greater performance improvements. Neuromuscular function did not aid performance, indicating that transient changes in afferent feedback and muscle recruitment may enhance endurance trial performance.

Key words Ice vest, thigh precooling, endurance running, voluntary activation, thermoregulation

INTRODUCTION

Athletic competition in the heat increases physiological strain and reduces performance during self-paced, endurance exercise (12, 15). Exercising in hot, humid conditions disproportionately increases rate of heat storage, body temperature and heat illness susceptibility, subsequently decreasing force production, muscle activation and exercise intensity (23). An increase in core temperature to a critical level of 40°C and subsequent hyperthermia inhibits central nervous system function and central activation through reduced force production (15, 28). Hyperthermia increases cardiovascular strain and relative metabolic strain, and reduces oxygen supply (15). However, an increase in motor unit recruitment and work rate towards completion of prolonged exercise has been reported, regardless of heat storage rate and high core temperatures reached (13). Therefore, the application of precooling may counteract the increased physiological load and enhance subsequent performance.

Previous studies have established that precooling before exercise in hot conditions improves intermittent (7, 35) and endurance performance (11, 33, 43). Precooling may minimize thermal strain and maintain muscular recruitment, essential for optimizing performance during long-distance training and competition. External precooling techniques including ice vests or cold towels reduce skin temperature, while ice packs, cold showers, cold-water immersion or combined methods reduces skin, muscle and core temperature (22, 30, 44). However, precooling is technique-specific and duration-dependent, consequently altering heat strain, pacing and exercise performance (7, 25).

Previous research has identified performance improvements during self-paced intermittent and continuous exercise in the heat without any alterations in end-exercise physiological perturbations (2, 11, 35). Therefore, the ergogenic benefits from precooling may include the prevention of hindered central motor drive due to thermal sensory feedback (30). Precooling may improve performance through greater heat storage capacity and blunting pre-exercise core temperature to enable increased muscle recruitment and to promote the selection and maintenance of higher intensity exercise (2, 11). Further, the selection of exercise intensity may be altered by afferent feedback from peripheral signals comprising cardiovascular and thermoregulatory strain (42). However, many studies exploring precooling on self-paced endurance performance have integrated warm-up protocols that are of insufficient quality and duration before athletic competition. At present, there is little evidence (2, 36) establishing whether precooling during an active warm-up alters performance and neuromuscular function during a performance trial. Moreover, precooling techniques such as immersion and showers are not practical immediately before long-distance competition (2, 30). Portable precooling techniques that could be used at the side of a track or road before a race, consisting of ice vests, may prevent augmented heat strain (systemic effect on the upper-body) (8), while ice packs on the thighs may prevent increased muscle temperature (local effect involving direct muscle cooling) (7, 10). Passive heating increases muscle temperature and may augment the rate of acidification, causing a greater decline in force production and subsequent performance (39). Nevertheless, the use of intermittent exercise does not accurately represent the typical physiological mechanisms occurring in endurance exercise. Therefore, it is unclear whether the changes in heat strain and muscle temperature established with torso or thigh precooling will similarly influence endurance exercise performance. Moreover, previous studies comparing a single precooling technique with a control condition of no cooling have denoted that precooling with either an ice vest (5.1%) or cooling packs (6.3%) neither elicits superior or inferior changes in performance (44). Thus, it remains uncertain whether torso precooling in contrast to thigh precooling is the superlative, practical technique. Further, there is limited research examining the application of either an ice vest or cooling packs during a race-specific warm-up. With coaches and athletes needing better guidance on the usefulness of different cooling strategies before endurance running events, more evidence is required to evaluate simple, cost-effective cooling methods. Strength and conditioning professionals could also benefit in the knowledge that precooling strategies could help strength-based tasks that have a prolonged endurance element to them.

Accordingly, the aim of this investigation was to examine the effect of isolated torso and thigh precooling throughout a warm-up on neuromuscular function and 5 km time-trial performance in hot, humid conditions. It was hypothesized that torso and thigh precooling would aid running performance during a 5 km time-trial within a hot environment and minimize neuromuscular fatigue.

METHODS

Experimental Approach to the Problem

Subjects were required to visit the laboratory on four occasions with each visit separated by 2-4 days of recovery. All subjects completed a familiarization session to certify understanding with the testing equipment and procedures, and to establish optimal electrical stimulation intensities. They also performed an incremental exercise test to determine maximal oxygen uptake ($\dot{V}O_{2max}$). Then, in a randomized and counterbalanced order, three experimental trials were performed inside an environmental chamber in hot, humid conditions (32.2 ± 0.8°C; 48.6 ± 6.7% relative humidity) at similar times of day to minimize the influence of circadian variation (31). Prior to each testing session, electrical stimulation of the femoral nerve was performed during three maximal voluntary contractions (MVC) at resting baseline to assess neuromuscular function and voluntary activation (VA). A prescribed 30-min warm-up similar to Arngrïmsson et al. (2) and Stannard et al. (36) was then completed where the independent variable was either no cooling, where subjects wore a regular t-shirt with shorts containing neutral temperature packs over the thighs (Control), or precooling by wearing an Ice Vest (Vest) or frozen gel packs over the thighs (Packs). The vest or packs on the thighs were removed following the warm-up. The 5 km time-trial was then undertaken on a motorized treadmill to obtain the primary outcome dependent variable of 5 km running time. During the warm-up and time-trial, core and skin temperatures (T_{core} and $T_{sk,}$respectively), heart rate (HR), body heat content change, rating of perceived exertion, and thermal sensation were measured. Throughout the time-trial, 500 m cumulative and split times, velocity, and time to complete the 5 km were recorded. Finally, neuromuscular assessments were performed following 5 km time-trial completion.

Subjects

Eight well-trained, male club long-distance runners volunteered for the study (mean ± SD age: 34.8 ± 4.4 years; stature: 179.4 ± 4.6 cm; body mass: 72.0 ± 8.8 kg; training volume: 30.3 ± 13.7 $km \cdot week^{-1}$; maximal aerobic velocity: 17.8 ± 1.2 $km \cdot h^{-1}$; maximal oxygen uptake: 65.5 ± 3.9 $ml \cdot kg^{-1} \cdot min^{-1}$). There were three 5,000 m, two 10,000 m, one half-marathon, one marathon and one Ironman 70.3 specialists. All subjects completed more than three years long-distance training, one 5 km time-trial per year and performed 5 km in 19.5 ± 0.9 min (range: 18:22 - 21:07 min:s). Prior to testing, subjects had the experimental procedures explained to them. All subjects provided written informed consent to participate in this study, which was approved by the ethics committee at the University of Brighton and conformed to the Declaration of Helsinki 2013. Subjects completed trials during the British winter season (October to February) and were not heat acclimatized. Subjects were instructed to arrive at the laboratory in a fully hydrated state; maintain their normal diet, and replicate this before subsequent visits. They were asked to refrain from vigorous exercise 48 h, avoid alcohol for 24 h, and caffeine and food for 2 h before testing.

Procedures

Preliminary session

On arrival, data was collected comprising age, height (Detecto Scales, Detecto, Webb City, USA) and body mass (Seca 778, Seca, Germany). The subjects performed brief, isometric contractions of the knee-extensors in hot, humid conditions until they were accustomed to the equipment. Subjects were acquainted with receiving femoral nerve stimulation during these MVCs. Subjects then completed the prescribed warm-up to become accustomed with the individualized warm-up intensities, stretching and strides protocol. Afterwards, they performed an incremental exercise test to determine $\dot{V}O_{2max}$ on a treadmill (Woodway ELG, Woodway, Weil am Rhein, Germany) in a temperate laboratory environment (18-20°C, ~40% relative humidity). Following a 10-min jog at 8 $km \cdot h^{-1}$, speed was increased to 10 $km \cdot h^{-1}$ with speed increments of 1 $km \cdot h^{-1}$ every 60 s until volitional exhaustion. HR was recorded and respiratory indices were assessed breath-by-breath using the MetaLyzer Sport online gas analysis system (Cortex, Germany).

Precooling during warm-up protocol

The warm-up protocol completed before each 5 km time-trial was identical and intended to simulate stretches and distance runners covered preceding a race. Precooling occurred only during the warm-up to optimize neuromuscular performance, considered ideal for race preparation. Following neuromuscular function assessments, subjects mounted the treadmill with the precooling intervention. After collection of pre warm-up measurements, subjects performed a 5-min warm-up at their typical warm-up speed (determined during the preliminary session), followed by 10 min of prescribed static and dynamic stretching exercises. They completed a further 10-min run on the treadmill at a faster ($1.6\ \mathrm{km \cdot h^{-1}}$) pace than the initial 5 min (2, 36). Four 30-s strides at just below and just above race pace ($\pm 0.5\ \mathrm{km \cdot h^{-1}}$) were performed with 45 s of standing recovery. Subjects removed the vest or packs on the thighs and subsequent pre time-trial measures were recorded. The Vest (Arctic Heat Products, USA) and Packs (Hot-Cold Pack, Kool Pak, Poole, UK) weighed 2388 g and 2376 g, respectively. On removal from a 20°C freezer, the Vest and Packs with thermistors attached during cooling had a surface temperature of 10.7 ± 2.5°C and -16.0 ± 5.8°C, respectively (7). The Packs were secured within compartments of bespoke shorts to the anterior, lateral and posterior aspects of the thighs to completely cover the quadriceps and hamstring muscle groups. The only difference between conditions was the addition of wearing unfrozen Packs (6 for Control, 3 for Vest) during the warm-up to ensure similar energy cost of the garment compared to the Packs condition.

5 km time-trial

The 5 km time-trial was immediately commenced, with the treadmill set at 1% gradient to simulate ground running (20). Subjects increased or decreased the speed themselves, and were instructed to perform maximally over the distance. Subjects were taken out of the environmental chamber following completion of the 5 km time-trial and neuromuscular assessments, or on inability to continue or attainment of the ethics approved T_{core} limit (39.7°C). Subjects were informed on completion of every 500 m and aware that performance measures were being recorded. However, they were not provided with verbal encouragement, 500-m splits, total time elapsed during the time-trial or 5-km performance times until study completion. Reliability of the 5 km time-trial protocol in our laboratory has found a typical error of measurement of 2.5% from a heterogeneous group of fourteen physically active individuals. This is similar to the 2.0% typical error of measurement reported by Laursen et al. (21) amongst endurance-trained distance runners.

Force and EMG recordings

Knee-extensor force throughout voluntary contractions was assessed using a calibrated load cell (Model 615, Tedea-Huntleigh, California, USA). The load cell was fixed to a bespoke chair and adjusted to a height that was in the direct line of applied force for each participant. The load cell was connected to a non-compliant cuff attached around the right leg just superior to the ankle malleoli. Subjects sat upright in the chair, secured with a shoulder and waist strap, with the hips and knees at 90° of flexion (16, 34). Electromyographic (EMG) activity of the knee extensors and flexors was recorded from the vastus lateralis and biceps femoris. After the skin was shaved and swabbed with isopropyl 70% alcohol, surface electrodes (Kendall H59P, Covidien Ilc, Mansfield, MA, USA) were placed with an inter-electrode distance of 2 cm over the muscle bellies. A reference electrode was positioned over the patella. The positions of all electrodes were marked with indelible ink to ensure reproducibility of placement throughout subsequent visits. Electrodes were replaced following the time-trial. Surface electrodes were used to monitor the compound muscle action potential (M-wave) obtained by electrical stimulation of the femoral nerve (17). EMG electrodes were connected to data acquisition hardware (Bioamp Power Lab, 15T, ADInstruments, Australia) and data was viewed via specific software (Lab Chart 7.3.5, ADInstruments, Australia). Signals were amplified (ADInstruments), band-pass filtered (EMG only: 20–2000 Hz), digitized (4 kHz; ADInstruments), then acquired and later analyzed (Lab Chart 7.3.5, ADInstruments).

Neuromuscular function

Force and EMG variables were assessed inside the environmental chamber before the warm-up and immediately following the 5 km time-trial. During each MVC, subjects positioned their arms across their chest. MVC force was established from three maximal contractions (duration 5 s, 30 s recovery). Thereafter, three MVCs were performed with femoral nerve stimulation delivered during each MVC, and an additional stimulus was delivered at rest, approximately 2 s following the superimposed stimulus, to determine potentiated quadriceps twitch force ($Q_{tw,pot}$) and peripheral VA (see 'Data analysis' section; 17, 34). Subjects were provided with strong verbal encouragement during voluntary efforts. Measurements during the post time-trial neuromuscular assessments were completed within 3 min after exercise termination.

Femoral nerve stimulation

Single electrical stimuli of 1000 μs pulse width were delivered to the right femoral nerve via 50-mm diameter surface electrodes (Starburst 627SB, Tyco Healthcare Uni-Patch, Wabasha, MN, USA) using a constant-current stimulator (DS71, Digitimer Ltd, Welwyn Garden City, UK). The cathode was positioned over the nerve high in the femoral triangle, and the anode was placed midway between the greater trochanter and iliac crest (17). The site of stimulation that produced the largest resting twitch amplitude was located. Stimulation intensity began at 10 mA and was progressively increased by 10 mA until a plateau in peak twitch force was attained. The final intensity was further increased by 30% (e.g. supramaximal; mean current:

147.9 ± 20.8 mA) and maintained for subsequent sessions. Muscle contractility was assessed by measuring the amplitude of the potentiated muscle twitch evoked by motor nerve stimulation ($Q_{tw,pot}$). Membrane excitability was established by the measurement of the peak-to-peak amplitude and area of the electrically evoked M-wave (M_{max}).

Data analysis

For MVCs, data from the largest generated peak force and largest $Q_{tw,pot}$ was taken for subsequent analysis. Peripheral VA was assessed using twitch interpolation (24). In brief, the force generated during a superimposed single twitch (SIT) delivered within 0.5 s of reaching peak force during the MVC was compared with the force generated by the single twitch delivered during relaxation ~2 s after the MVC: VA (%) = [1-(SIT/$Q_{tw,pot}$] x 100. The reliability of the femoral nerve stimulation protocol for the assessment of peripheral VA for the knee extensors was determined in our laboratory (within and between day coefficients of variation: 3.9% and 5.3%, respectively).

Prior to experimental sessions, subjects provided a urine sample on arrival to the laboratory. Urine osmolality (Osmocheck, Vitech Scientific Ltd, Japan) and urine specific gravity (Hand Refractometer, Atago, Tokyo, Japan) was assessed to establish hydration status and ensure all subjects commenced exercise euhydrated (urine specific gravity: < 1.020; urine osmolality: < 700 $mOsm \cdot L^{-1}$; 6). Towel-dried nude body mass was assessed before and after exercise on a set of scales to determine nonurine fluid loss. Fluid intake was not permitted in any condition.

T_{core} (4600 Thermometer, Henleys Medical Supplies, Welwyn Garden City, UK) was monitored from a depth of 10 cm past the anal sphincter. T_{sk} was recorded using surface thermistors (Squirrel 1002, Grant Instruments, Cambridge, UK) attached under running apparel to the skin on the right side of the body on the chest, upper arm, thigh and calf as described by Ramanathan (32). T_{core} and T_{sk} were measured pre, every 10 min during the warm-up, post warm-up, and at every 1 km during the time-trial. Body heat content (H_b) change was calculated based on the equation of Jay and Kenny (19).

HR (Polar sports tester, Polar Electro, Kempele, Finland), thermal sensation (TS; eight-point Likert scale; 40) and rating of perceived exertion (RPE) according to Borg's 6-20 point scale were recorded pre, every 10 min during the warm-up, post warm-up, and at every 1 km during the time-trial.

Statistical Analyses

Data were checked for normality and sphericity was adjusted using the Huynh-Feldt method. For the dependent variables that display change across time (performance data: velocity, cumulative and split times; physiological measures: T_{core}, Tsk, H_b, HR; and perceptual ratings: RPE, TS), a two-way repeated measures ANOVA (condition x time) was used to determine the influence of the interventions within and between conditions, with Bonferroni corrected pairwise comparisons performed. Where significance was not obtained, effect size data were calculated (partial eta squared: η^2) to determine the magnitude of the interventions on performance and certain neuromuscular measures. An effect size of 0.01 was classified as a 'small', 0.06 as a 'moderate' and > 0.14 as a 'large' effect. Student's paired *t* test was used to assess baseline to post-exercise differences for body mass and neuromuscular function. Pearson's product moment correlation coefficient was calculated to establish the relationship between changes in performance time and MVC differences. Data was analyzed using a standard statistical package (SPSS version 20.0) and reported as means ± SD. Statistical significance was accepted at $P \leq 0.05$.

RESULTS

Performance

Four subjects completed all three conditions. Four subjects completed the entire time-trial in Control, and six subjects completed the time-trial in Vest and Packs. All remaining subjects terminated exercise early due to attainment of the T_{core} limit. At a distance of 3500 m, two subjects terminated time-trial completion in Control. At 4500 m, one additional subject in Control and Vest, and two subjects in Packs terminated exercise. By 5000 m, one further subject in Control and Vest terminated time-trial completion.

No significant main effects were present for cumulative or split time. There were no significant differences in cumulative time until the last kilometer, when a faster cumulative time occurred at 4000 m (Control $n = 6$, Packs $n = 8$) and 5000 m (Control $n = 4$, Packs $n = 6$) in Packs compared to Control (4000 m: 1137 ± 75 vs. 1219 ± 65 s; 6.7%; $P < 0.01$; 5000m: 1407 ± 80 vs. 1492 ± 88 s; 5.7%; $P < 0.05$; Table 1) for Packs and Control, respectively. However, a large effect was present for quicker cumulative time in Packs compared to Control ($\eta^2 = 0.37$; $P = 0.22$). Precooling via Vest (4500 m: $n = 7$; 5000 m: $n = 6$) compared to Control did not result in a significantly quicker cumulative time during the time-trial, especially at 5000 m (3.2%; 1444 ± 77 vs. 1492 ± 88 s; $\eta^2 = 0.18$; $P = 0.17$). No significant differences were observed in Packs compared to Vest (2.6%; $\eta^2 = 0.08$; $P = 0.53$).

Table 1 approximately here

There were no significant differences in split time in Packs compared to Control, however, a large effect was present for quicker split time with precooling via Packs ($\eta^2 = 0.30$; $P = 0.14$). There were no differences during the time-trial in Packs until at 1500 m, when a faster split time than the initial 500 m occurred ($P < 0.01$; Table 1). No significant differences were denoted until 3000 m, when precooling via Vest compared to Control caused a quicker split time at 3500 m ($P < 0.05$). A large effect was present for split time in Vest compared to Control ($\eta^2 = 0.14$; $P = 0.17$). No significant differences and a moderate effect size were identified in Packs compared to Vest ($\eta^2 = 0.08$; $P = 0.24$).

No significant main effects were present for mean velocity. There was a significant increment in mean velocity in Packs compared to Control at 1000, 1500 and 3500 m ($P < 0.05$; Fig 1). A large effect size was present for increased velocity in Packs compared to Control ($\eta^2 = 0.28$; $P = 0.06$). No significant differences were identified in Vest compared to Control ($\eta^2 = 0.13$; $P = 0.21$), or Packs ($\eta^2 = 0.09$; $P = 0.14$). During the last kilometer of each time-trial, change in performance time was greater in the final 500 m than the penultimate 500 m (Control: 8.3 vs. 2.0% and Packs: 4.3 vs. 0%; $P < 0.05$; Vest: 3.8 vs. 0.5%; $P < 0.01$), but was not significant between conditions.

Figure 1 approximately here

Muscle function

Baseline neuromuscular function measures did not vary across conditions. The difference in MVC force after the time-trial in Control, Packs and Vest is shown for each individual in Fig 2a. Compared to Control, an equal or greater reduction in ΔMVC force was observed in Packs in five out of eight subjects. Therefore post time-trial, ΔMVC force was not significantly reduced below baseline or between conditions

(Control: -7%; Packs -9%; and Vest: -13%; $P > 0.05$). The difference in performance time was positively correlated to MVC differences obtained pre warm-up and post time-trial in Packs compared to Control ($r = 0.73$; $P < 0.05$) but remained non-significant in Vest compared to Control ($r = 0.59$; $P = 0.12$), and Packs compared to Vest ($r = -0.21$; $P > 0.05$).

Figure 2 approximately here

After the time-trial, VA and $Q_{tw,pot}$ were not significantly different from baseline or between conditions (VA: 1, -7 and -5%; $Q_{tw,pot}$: 0, -13 and -2%; $P > 0.05$; Table 2) for Control, Packs and Vest, respectively. A greater reduction from baseline in VA was identified in Packs and Vest in four and two subjects, respectively (Fig 2b). In only two subjects, VA increased above baseline in either Control or Vest. M_{max} amplitude and area were not significantly different post time-trial or between conditions (Table 2). However, a small-moderate effect was evident for an increased M_{max} amplitude in Packs compared to Vest ($\eta^2 = 0.02$; $P = 0.31$).

Table 2 approximately here

Urine, nude body mass and heart rate

Pre-exercise hydration status did not differ between conditions for urine specific gravity (1.009 ± 0.007; 1.007 ± 0.006; 1.010 ± 0.007; $P > 0.05$) or urine osmolality

(325 ± 248; 305 ± 182; 369 ± 256 mOsm·L^{-1}; $P > 0.05$) for Control, Packs and Vest, respectively. The change in nude body mass following the time-trial, denoting nonurine fluid loss, was not significantly different post time-trial or between conditions (Control: -1.6 ± 0.4 kg; Packs: -1.5 ± 0.2 kg; and Vest: -1.4 ± 0.6 kg; $P > 0.05$).

A significant main effect was present for an increase in HR during the time-trial ($P < 0.05$), but not the warm-up. HR was not significantly different between conditions during the warm-up or time-trial ($P > 0.05$; Table 3).

Table 3 approximately here

Core and skin temperature, and H_b

No significant main effects were present for T_{core}, and T_{sk}. T_{core} was not significantly different between conditions during the warm-up or time-trial ($P > 0.05$; Fig 3a). In Packs and Vest, T_{sk} was significantly reduced after the 10th minute during the warm-up compared to Control ($P < 0.01$), but not in Packs compared to Vest (Fig 3b). In Packs, ΔT_{sk} was significantly increased post warm-up (0.65 ± 1.5°C) but remained significantly lower than Control (33.3 ± 0.8 vs. 34.8 ± 0.7°C; $P < 0.05$) but not in Vest compared to Control (33.6 ± 1.1 vs. 34.8 ± 0.7°C), or Packs compared to Vest. T_{sk} was not significantly different between conditions during the time-trial.

Figure 3 approximately here

A significant main effect was present for H_b change during the warm-up ($P < 0.05$), but not the time-trial. In Packs, H_b change was significantly lower during and post warm-up compared to Control ($P < 0.05$; Table 3). H_b change was not significantly different in Vest compared to Control, or Packs compared to Vest during the warm-up. H_b change was significantly increased post warm-up in all conditions ($P < 0.01$); however, was not significantly different between conditions during the time-trial ($P > 0.05$).

Perceptual responses

No significant main effects were present for RPE during the warm-up or time-trial. RPE was not significantly different between conditions during the warm-up or time-trial ($P > 0.05$; Table 3). A significant main effect was present for an increase in TS during the time-trial ($P < 0.05$), but not the warm-up. TS was not significantly different in Packs compared to Control, or Packs compared to Vest during the warm-up. However, TS was significantly reduced in Vest compared to Control ($P < 0.01$-0.05) until the 30th minute of the warm-up when no significant reductions were observed ($P = 0.054$). TS was not significantly different between conditions during the time-trial (Table 3).

DISCUSSION

The application of thigh precooling during a 30-min warm-up improved 5 km time-trial performance compared to the control condition, but was not improved with torso precooling. In particular, velocity was increased at 1000, 1500 and 3500 m in Packs and subsequent cumulative time improved during the last kilometer of the time-trial. Both precooling interventions did not affect voluntary force production, muscle contractility or membrane excitability. However, after 10 min of the warm-up, precooling via Vest and Packs reduced skin temperature. Further, body heat content change reduced in Packs while thermal sensation reduced in Vest during the warm-up. At the start of the time-trial, Packs reduced skin temperature.

Coinciding with previous research, precooling aids performance during endurance exercise (5, 11). Several studies have identified equivalent findings during prolonged self-paced exercise, with a 13-s improvement for a 5 km running time-trial (2), a 304-m improvement in performance for a 30 min running time-trial (5), and a 20-W increase in mean power during a 40 min cycling time-trial (11). These studies similarly identified reductions in skin temperature and perceived thermal stress. In contrast, the present study did not observe the reductions of core temperature or sweat loss, possibly due to the lack of precooling prior to exercise. Although precooling reduces core temperature and remains lower during exercise (5), cold water immersion is likely to cause a greater depth of cooling compared to the current methods. Therefore, the limited sample size is another explanation. The present data, alongside research using time-to-exhaustion exercise (43), emphasize the ergogenic benefits of external precooling for endurance exercise in the heat. Furthermore, low variability of 5 km time-trials established in our laboratory and amongst endurance-trained distance runners (typical error of measurement as a coefficient of variation: 2.5% and 2.0%, respectively) accentuates that enhanced endurance performance likely results from the precooling interventions (21). Nevertheless, few studies have explored the influence of precooling on neuromuscular function and performance during a trial among track runners. Moreover, only some studies have used precooling during an active warm-up to identify whether similar ergogenic benefits occur compared to impractical methods, such as cold water immersion.

The performance improvement apparent at the last kilometer of the time-trial in Packs may have resulted from increased exercise intensity depicted at 1000, 1500 and 3500 m. Further, the improved performance time of 48 s observed in Vest converts into a 168-m advantage at the average velocity run in Vest, which is considerable in 5000-m competition. Together, the large effects present for quicker cumulative and split time, and increased velocity following Packs, and moderate-large effects after Vest indicates the ergogenic benefits of precooling. Although, a larger sample size could confirm this implication (Control n = 4, Packs n = 6, Vest n = 6). Nevertheless, the effect of precooling induced by Packs appeared greater compared to Vest, with an improvement in 5-km performance time by 37 s. Tucker et al. (42) and Marino (22) denoted that self-paced, prolonged exercise in the heat causes a premature reduction in performance compared to thermoneutral conditions. Therefore coinciding with previous studies (2, 10), precooling promotes higher exercise intensities to be sustained during endurance exercise in the heat, despite the benefits remaining unclear.

The earlier reductions in exercise intensity observed in hot conditions may be due to reduced muscle recruitment via afferent feedback derived from the environmental condition and endogenous load (27). This may affect function of the central nervous system where this decline in skeletal muscle activation subsequently reduces exercise intensity (15). Further physiological responses may reduce muscle recruitment or ability to maintain a higher exercise intensity as apparent in the Control condition, including increased brain temperature (28), or decreased neural transmission (27). Increased core temperature to a critical level of 40°C may also reduce muscle recruitment and cause an early termination of exercise (15, 42). Nevertheless, highly trained athletes can maintain exercise intensity and produce an endspurt towards completion of an 8 km running time-trial, despite considerable heat storage and core temperature surpassing 40°C (13, 41). In the present study, an endspurt occurred approximately 1000 m before time-trial completion, even among participants terminating exercise early due to reaching the safety limit of 39.7°C. Although some subjects may be heat intolerant (29), this indicates the involvement of centrally mediated factors and/or reserve from anaerobic energy pathways.

Previously, Duffield et al. (11) reported that 20-min lower-body precooling did not alter contractile function following 40 min of self-paced cycling. In agreement, the present study identified no alterations to voluntary force production, voluntary activation or $Q_{tw,pot}$ between conditions. However, individual differences may exist in how precooling influences muscle function, as force considerably reduced or remained relatively unaltered in five subjects after the time-trial with Packs. Further, a superior decline in voluntary activation was observed with Packs and Vest amongst several subjects. Considering that fatigue resulting from the time-trial will probably supersede any effect of the precooling, the current study sought to establish the influence of precooling methods on muscle function and subsequent performance. A reduction in force production reported in the plantar flexors following 5 km running in thermoneutral conditions (14) implies that precooling minimally affects overall force generating capacity of the knee extensors. Maintained voluntary activation suggests that neural input reaching the neuromuscular junction was not impaired therefore enabling full ability to drive the motoneurons (14). Although using techniques such as transcranial magnetic stimulation may further identify the location of central fatigue. The assessment of muscle contractility and membrane excitability, of which were not altered by Packs or Vest precooling, denotes that no changes in excitation-contraction coupling occurred (1, 14). Further, no alterations of $Q_{tw,pot}$ with Packs or Vest highlights that there was an adequate quantity of formed cross-bridges between actin and myosin and their rate of attachment (1). No changes in maximum M-wave amplitude would signify that muscle excitability (ionic disturbances) was maintained (3). Since performance time improved in Packs and without alterations in neuromuscular function, it is expected that the higher sustained velocity particularly in Packs was due to the maintenance of muscle recruitment during exercise (26).

The findings from the present study indicate that a down-regulation of intensity during the performance time-trial may be related to greater thermoregulatory strain due to exercise within hot conditions. Packs appeared to ameliorate body heat content change, while similar to Arngrïmsson et al. (2), subjects perceived their thermal stress lower in Vest during the warm-up. The precooling interventions may have altered thermoregulatory strain differently, whereby the hybrid gel Vest containing ice crystals superficially cooled the skin, while the gel within Packs caused a greater depth of cooling. Further, the thigh is likely to have lesser subcutaneous fat thickness than the torso, therefore Packs may have caused more vasoconstriction than Vest. Previously used before prolonged intermittent exercise in the heat (7), Packs may generate larger thermal gradients for conductive cooling subsequently reducing the temperature of the muscle. Although muscle temperature was not measured, previous work in our laboratory has denoted that 25 min of Packs during rest reduces mean muscle temperature of a pre-determined depth by 15°C (7). Therefore, Packs may have produced a greater heat sink than Vest, explaining the lower body heat content change identified. Conflicting with Arngrïmsson et al. (2) and Cotter et al. (9) using a Vest combined with or without thigh cooling, core temperature was not significantly different in Vest or Packs during the warm-up or time-trial between conditions. However, previous studies have reported that precooling aids endurance performance despite core temperature remaining constant or even increasing (11, 43). Therefore, precooling via Packs and Vest during a warm-up may be used to reduce skin temperature and increase the difference of starting temperatures prior to commencing a time-trial in the heat. Interestingly, Arngrïmsson et al. (2) reported that the differences in skin temperature had disappeared by 3.2 km of the 5 km time-trial when differences in pacing were evident. However in the present study, all physiological and perceptual differences had dissipated by the first kilometer. Together, precooling may have enabled the selection of higher exercise intensities derived from the expectation of subsequent constraints based on the reduced physiological responses following thigh and torso precooling.

Previous research highlights that numerous models explore exercise regulation in the heat via feedback (15, 28) or feed-forward control (38). The central governor model states that the central nervous system regulates exercise intensity and skeletal muscle output through both feedback and feed-forward control to inhibit catastrophic disruptions in homeostasis (26, 37). Consistent with Castle et al. (7), these responses vary with the precooling site and dose, altering overall performance time differently as Packs was improved by 2.6% and 5.7% compared to Vest and Control, respectively. In particular, the reduced skin temperature but no changes in core temperature potentially allowed Vest to create a small heat sink (45) therefore facilitating the management of fatigue associated with heat stress. In Packs, the central governor may have processed a sufficient quantity of sensory information to alter the pacing strategy (7, 22) and increase motor unit recruitment and exercise intensity following Packs (11). Despite no significant performance differences between Packs and Vest, the selection of higher exercise intensity indicates that

Packs precooling during a warm-up may be an effective technique. Moreover, the similar RPE, thermal and cardiovascular strain during the self-paced time-trial indicates that despite working at higher intensities following Packs, subjects perceived the exercise demands and environmental condition to be similar to Vest and Control. Therefore, exercising at a higher intensity for a certain RPE may have arisen from the reduced thermoregulatory and cardiovascular strain following the thigh cooling, opposed to the identified reductions following torso cooling.

The altered physiological and perceptual responses generated from Packs and Vest may also influence force production differently. In particular, a greater reduction in force production was associated with faster performance time in Packs. Blunting the increase in thermoregulatory strain may have allowed the maintenance of higher exercise intensities and subsequently induced greater reductions in force generation due to the greater endogenous load. Further, the small-moderate effect size present for increased maximum M-wave amplitude in Packs compared to Vest indicates that thigh precooling may preserve muscle function. More specifically, completing the warm-up in the heat possibly increased muscle temperature and subsequent enzyme activity and muscle contractile properties (4), while Packs may have increased action potential propagation and adequately countered the expected post-exercise fatigue due to the cooler muscle (35).

During the warm-up in Control, wearing bespoke shorts containing neutral temperature packs ensured that changes in endurance performance resulted from precooling opposed to differing weight between conditions. While in Vest, the heat had melted the ice vest and diminished any feeling of cool sensations. Therefore, exactly half-way through the warm-up, participants wore a different ice vest to ensure that the physiological benefits associated with precooling could fully function due to a colder melting temperature (18). Interestingly, five of six subjects providing quantitative feedback reported that the ice vest was the most comfortable garment and believed to optimally aid performance and perception of the heat during the time-trial.

Similar to other studies assessing fatigue of the knee extensors (16, 17), the fatigue measurements were completed within 3 min after the termination of exercise. Peripheral voluntary activation and maximal force production have been reported to remain unchanged within 2.5 min following exercise in normoxia (16). Therefore, the present experimental design may have inadequately portrayed all elements of peripheral and central fatigue. However, the duration of the fatigue assessment following exercise remained constant for all three trials. Further, force and voluntary activation has been shown to recover during cooling from hyperthermia potentially due to a reduction in core temperature (34). Thus, the fatigue measurements were undertaken inside the environmental chamber to ensure that neuromuscular function, alongside the physiological and perceptual responses to the heat were not alleviated.

In conclusion, torso and thigh precooling during a 30-min active warm-up reduces thermoregulatory strain. Torso precooling with Vest reduces perception of thermal stress while thigh precooling with Packs reduces change in body heat content. However, precooling with Packs was the most effective technique to reduce thermoregulatory strain therefore enabling an improved selection of exercise intensities and improved performance during the last kilometer of the 5 km time-trial. Although precooling method neither improves nor inhibits neuromuscular function, it is expected that thigh precooling prevents the down-regulation of exercise intensity evident in hot, humid conditions. Future investigation should explore the use of precooling during a warm-up in the heat and the prevention of reduced exercise intensity in performance trials potentially resulting from altered sensory feedback and muscle recruitment.

PRACTICAL APPLICATIONS

For athletes competing in long-distance events undertaken within hot, humid environments, warming-up with ice packs covering the thighs compared to an ice vest does not appear to provide a superior advantage in performance. Despite a limited sample size in the present study, both practical precooling techniques offer some benefits for exercise in the heat. Further, both methods are simple to set up, inexpensive and easily transportable, therefore should be considered for use by athletes and coaches. Trialing both techniques before various training sessions and competitions may be advantageous to establish individual preferences, especially with regards to comfort. However, it seems that frozen gel packs covering the upper legs could be the most effective to blunt the rise in thermoregulatory strain. In turn, this may enable athletes to select and maintain a higher exercise intensity, crucial for optimal performance. If deciding to complete a warm-up with a precooling garment, particularly with packs, caution should be taken to ensure athletes do not select an initial pace that is too fast.

REFERENCES

1. Allen, DG, Lamb, GD, and Westerblad, H. Skeletal muscle fatigue: cellular mechanisms. *Physiol Rev* 88: 287-332, 2008.

2. Arngrïmsson, SA, Petitt, DS, Stueck, MG, Jorgensen, DK, and Cureton, KJ. Cooling vest worn during active warm-up improves 5-km run performance in the heat. *J Appl Physiol* 96: 1867-1874, 2004.

3. Bigland-Ritchie, B, Jones, DA, and Woods, JJ. Excitation frequency and muscle fatigue: electrical responses during human voluntary and stimulated contractions. *Exp Neurol* 64: 414-427, 1979.

4. Bishop, D. Warm up I: potential mechanisms and the effects of passive warm up on exercise performance. *Sports Med* 33: 439-454, 2003.

5. Booth, J, Marino, F, and Ward, JJ. Improved running performance in hot humid conditions following whole body precooling. *Med Sci Sports Exerc* 29: 943-949, 1997.

6. Casa, DJ, Clarkson, PM, and Roberts, WO. American College of Sports Medicine roundtable on hydration and physical activity: consensus statements. *Curr Sports Med Rep* 4: 115-127, 2005.

7. Castle, PC, Macdonald, AL, Philp, A, Webborn, A, Watt, PW, and Maxwell, NS. Precooling leg muscle improves intermittent sprint exercise performance in hot, humid conditions. *J Appl Physiol* 100: 1377-1384, 2006.

8. Castle, PC, Spencer, M, McNaught-Davis, P, Watt, PW, and Maxwell, NS. Quantification of heat strain during intermittent sprint exercise in male games players while under heat stress. *J Physiol* 565P: PC31, 2004.

9. Cotter, JD, Sleivert, GG, Roberts, WS, and Febbraio, MA. Effect of pre-cooling, with and without thigh cooling, on strain and endurance exercise performance in the heat. *Comp Biochem Physiol* 128: 667-677, 2001.

10. Drust, B, Rasmussen, P, Mohr, M, Nielsen, B, and Nybo, L. Elevations in core and muscle temperature impairs repeated sprint performance. *Acta Physiol Scand* 183: 181-190, 2005.

11. Duffield, R, Green, R, Castle, P, and Maxwell, N. Precooling can prevent the reduction of self-paced exercise intensity in the heat. *Med Sci Sports Exerc* 42: 577-584, 2010.

12. Ely, BR, Cheuvront, SN, Kenefick, RW, and Sawka, MN. Aerobic performance is degraded, despite modest hyperthermia, in hot environments. *Med Sci Sports Exerc* 42: 135-141, 2010.

13. Ely, BR, Ely, MR, Cheuvront, SM, Kenefick, RW, DeGroot, DW, and Montain, SJ. Evidence against a 40ºC core temperature threshold for fatigue in humans. *J Appl Physiol* 107: 1519-1525, 2009.

14. Girard, O, Millet, GP, Micallef, JP, and Racinais, S. Alteration in neuromuscular function after a 5 km running time trial. *Eur J Appl Physiol* 112: 2323-2330, 2012.

15. González-Alonso, J, Teller, C, Andersen, SL, Jensen, FB, Hyldig, T, and Nielsen, B. Influence of body temperature on the development of fatigue during prolonged exercise in the heat. *J Appl Physiol* 86: 1032-1039, 1999.

16. Goodall, S, González-Alonso, J, Ali, L, Ross, EZ, and Romer, LM. Supraspinal fatigue after normoxic and hypoxic exercise in humans. *J Physiol* 590: 2767-2782, 2012.

17. Goodall, S, Ross, EZ, and Romer, LM. Effect of graded hypoxia on supraspinal contributions to fatigue with unilateral knee-extensor contractions. *J Appl Physiol* 109: 1842-1851, 2010.

18. House, JR, Lunt, HC, Taylor, R, Milligan, G, Lyons, JA, House, CM. The impact of a phase-change cooling vest on heat strain and the effect of different cooling pack melting temperatures. *Eur J Appl Physiol* 113: 1223-1231, 2013.

19. Jay, O, and Kenny, GP. The determination of changes in body heat content during exercise using calorimetry and thermometry. *J Human Environ. System* 10: 19-29, 2007.

20. Jones, AM and Doust, JH. A 1% treadmill grade most accurately reflects the energy cost of outdoor running. *J Sports Sci* 14: 321-327, 1996.

21. Laursen, PB, Francis, GT, Abbiss, CR, Newton, MJ, and Nosaka, K. Reliability of time-to-exhaustion versus time-trial running tests in runners. *Med Sci Sports Exerc* 39: 1374-1379, 2007.

22. Marino, FE. Methods, advantages and limitations of body cooling for exercise performance. *Br J Sports Med* 36: 89-94, 2002.

23. Marino, FE, Lambert, MI, and Noakes, TD. Superior performance of African runners in warm humid but not in cool environments. *J Appl Physiol* 96: 124-130, 2004.

24. Merton, PA. Voluntary strength and fatigue. *J Physiol* 123: 553-564, 1954.

25. Minett, GM, Duffield, R, Marino, FE, and Portus, M. Volume-Dependent Response of Pre-Cooling For Intermittent-Sprint Exercise in the Heat. *Med Sci Sports Exerc* 43: 1760-1769, 2011.

26. Nummela, AT, Heath, KA, Paavolainen, LM, Lambert, MI, St Clair Gibson, A, Rusko, HK, and Noakes, TD. Fatigue during a 5 km running time trial. *Int J Sports Med* 29: 738-745, 2008.

27. Nybo, L. Hyperthermia and fatigue. *J Appl Physiol* 104: 871-878, 2008.

28. Nybo, L and Nielsen, B. Hyperthermia and central fatigue during prolonged exercise in humans. *J Appl Physiol* 91: 1055-1060, 2001.

29. Périard, JD, Caillaud, C, and Thompson, MW. The role of aerobic fitness and exercise intensity on endurance performance in uncompensable heat stress conditions. *Eur J Appl Physiol* 112: 1989-1999, 2012.

30. Quod, MJ, Martin, DT, and Laursen, PB. Cooling athletes before competition in the heat: comparison of techniques and practical considerations. *Sports Med* 36: 671-682, 2006.

31. Racinais, S. Different effects of heat exposure upon exercise performance in the morning and afternoon. *Scand J Med Sci Sports* 20: 80-89, 2010.

32. Ramanathan, NLA. A new weighting system for mean surface temperature of the human body. *J Appl Physiol* 19: 531-533, 1964.

33. Ranalli, GF, Demartini, JK, Casa, DJ, McDermott, BP, Armstrong, LE, and Maresh, CM. Effect of body cooling on subsequent aerobic and anaerobic exercise performance: A systematic review. *J Strength Cond Res* 24: 3488-3496, 2010.

34. Ross, EZ, Cotter, JD, Wilson, L, Fan, JL, Lucas, SJ, and Ainslie, PN. Cerebrovascular and corticomotor function during progressive passive hyperthermia in humans. *J Appl Physiol* 112: 748-758, 2012.

35. Skein, M, Duffield, R, Cannon, J, and Marino, FE. Self-paced intermittent-sprint performance and pacing strategies following respective pre-cooling and heating. *Eur J Appl Physiol* 112: 253-266, 2012.

36. Stannard, AB, Brandenburg, JP, Pitney, WA, and Lukaszuk, JM. Effects of wearing a cooling vest during the warm-up on 10-km run performance. *J Strength Cond Res* 25: 2018-2024, 2011.

37. St Clair Gibson, A, Lambert, EV, Rauch, LHG, Tucker, R, Baden, DA, Foster, C, and Noakes, TD. The role of information processing between the brain and peripheral physiological systems in pacing and perception of effort. *Sports Med* 36: 705-722, 2006.

38. St Clair Gibson, A and Noakes, TD. Evidence for complex system integration and dynamic neural regulation of skeletal muscle recruitment during exercise in humans. *Br J Sports Med* 38: 797-806, 2004.

39. Thornley, LJ, Maxwell, NS, and Cheung, SS. Local tissue temperature effects on peak torque and muscular endurance during isometric knee extension. *Eur J Appl Physiol* 90: 588-594, 2003.

40. Toner, MM, Sawka, MN, Foley, ME, and Pandolf, KB. Effects of body mass and morphology on thermal responses in water. *J Appl Physiol* 60: 521-525, 1986.

41. Tucker, R. The anticipatory regulation of performance: the physiological basis for pacing strategies and the development of a perception-based model for exercise performance. *Br J Sports Med* 43: 392-400, 2009.

42. Tucker, R, Marle, T, Lambert, EV, and Noakes, TD. The rate of heat storage mediates an anticipatory reduction in exercise intensity during cycling at a fixed rating of perceived exertion. *J Physiol* 574: 905-915, 2006.

43. Ückert, S and Joch, W. Effects of warm-up and precooling on endurance performance in the heat. *Br J Sports Med* 41: 380-384, 2007.

44. Wegmann, M, Faude, O, Poppendieck, W, Hecksteden, A, Fröhlich, M, and Meyer, T. Pre-cooling and sports performance: a meta-analytical review. *Sports Med* 42: 545-564, 2012.

45. White, AT, Davis, SL, and Wilson, TE. Metabolic, thermoregulatory, and perceptual responses during exercise after lower vs. whole body precooling. *J Appl Physiol* 94: 1039-1044, 2002.

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FIGURE LEGENDS

Figure. 1 Velocity during the 5 km time-trial following the 30-min warm-up in the heat with control (Control), ice vest (Vest) and frozen gel packs (Packs) precooling. † Significant difference between Control and Packs, $P < 0.01$. [a] Control ($n = 6$). [b] Control ($n = 5$), Vest ($n = 7$), Packs ($n = 6$). [c] Control ($n = 4$), Vest and Packs ($n = 6$).

Figure. 2 Individual differences in **a** maximum voluntary contraction (MVC) and **b** voluntary activation between Control, Vest and Packs precooling conditions immediately after the 5 km time-trial. Mean data and SD for the difference in the means of eight male well-trained runners are also presented.

Figure. 3 **a** Core temperature and **b** skin temperature during the 5 km time-trial following the 30-min warm-up in the heat with Control, Vest and Packs precooling. * Significant difference between Control and Vest, $P < 0.01$. † Significant difference between Control and Packs, $P < 0.01$. ‡ Significant difference between Control and Packs, $P < 0.05$. § Significant difference from the start of the warm-up in Packs, $P < 0.05$. [a] Control ($n = 6$). [b] Control ($n = 4$), Vest and Packs ($n = 6$).

Figure 1

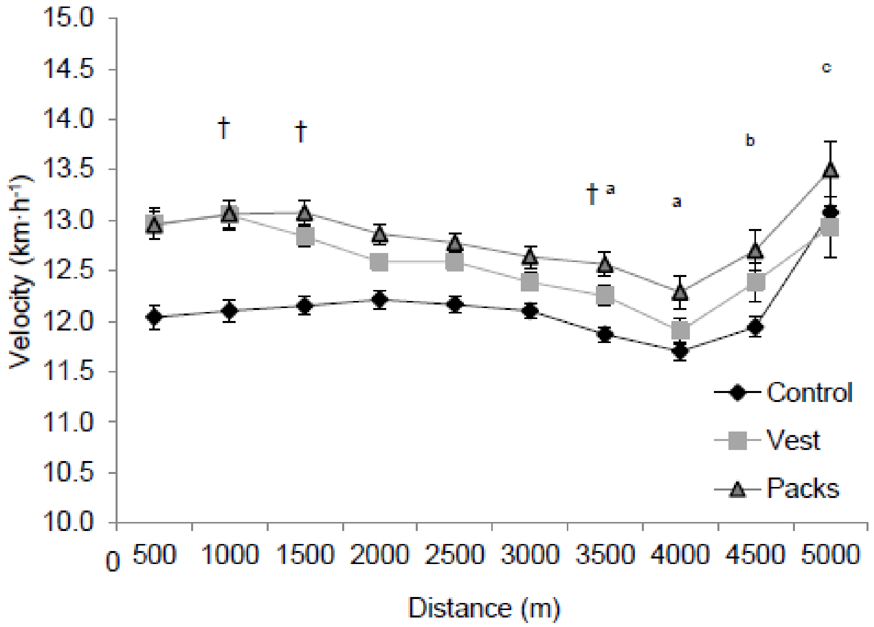
15.0
14.5
14.0
13.5
13.0
12.5
12.0
11.5
11.0
10.5
10.0
Velocity (km·h-1)
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
Distance (m)
†
†
† a
a
b
c
Control
Vest
Packs

Figure 2

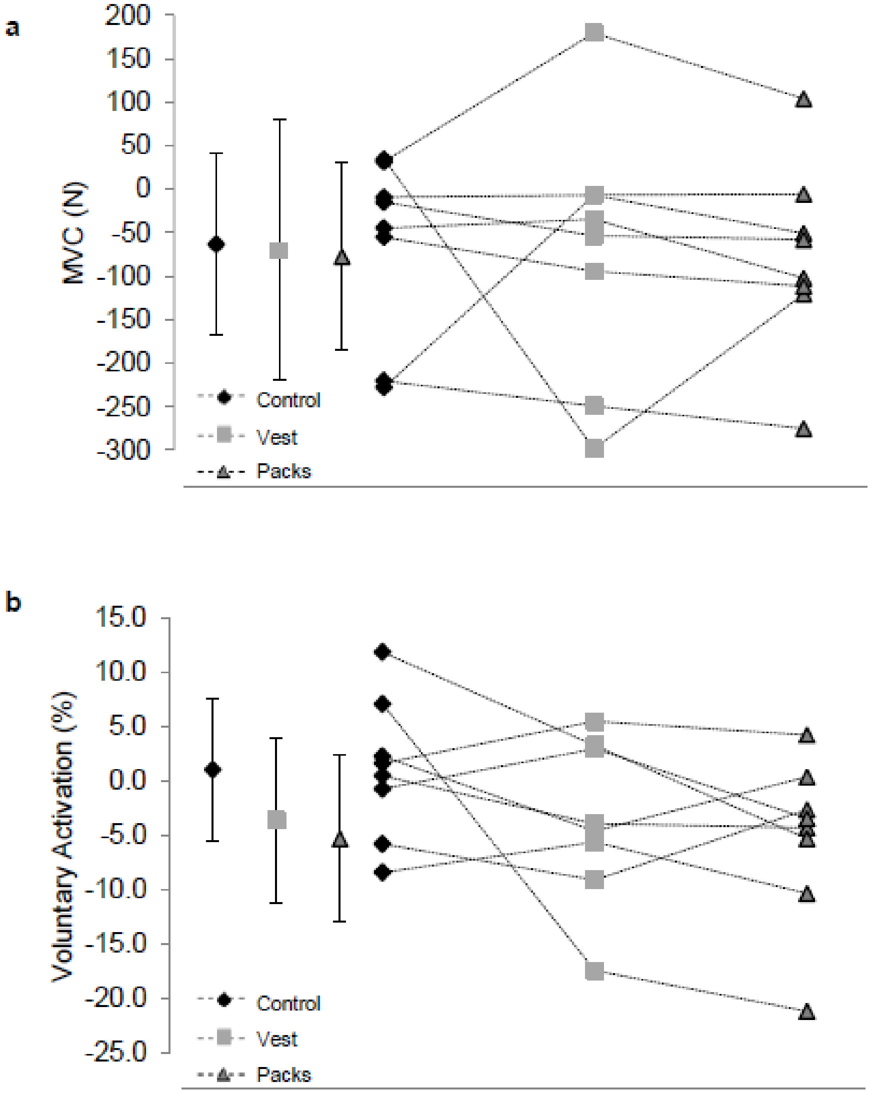
a
200
150
100
50
0
-50
-100
-150
-200
-250
-300
MVC (N)
Control
Vest
Packs
b
15.0
10.0
5.0
0.0
-5.0
-10.0
-15.0
-20.0
-25.0
Voluntary Activation (%)
Control
Vest
Packs

Figure 3

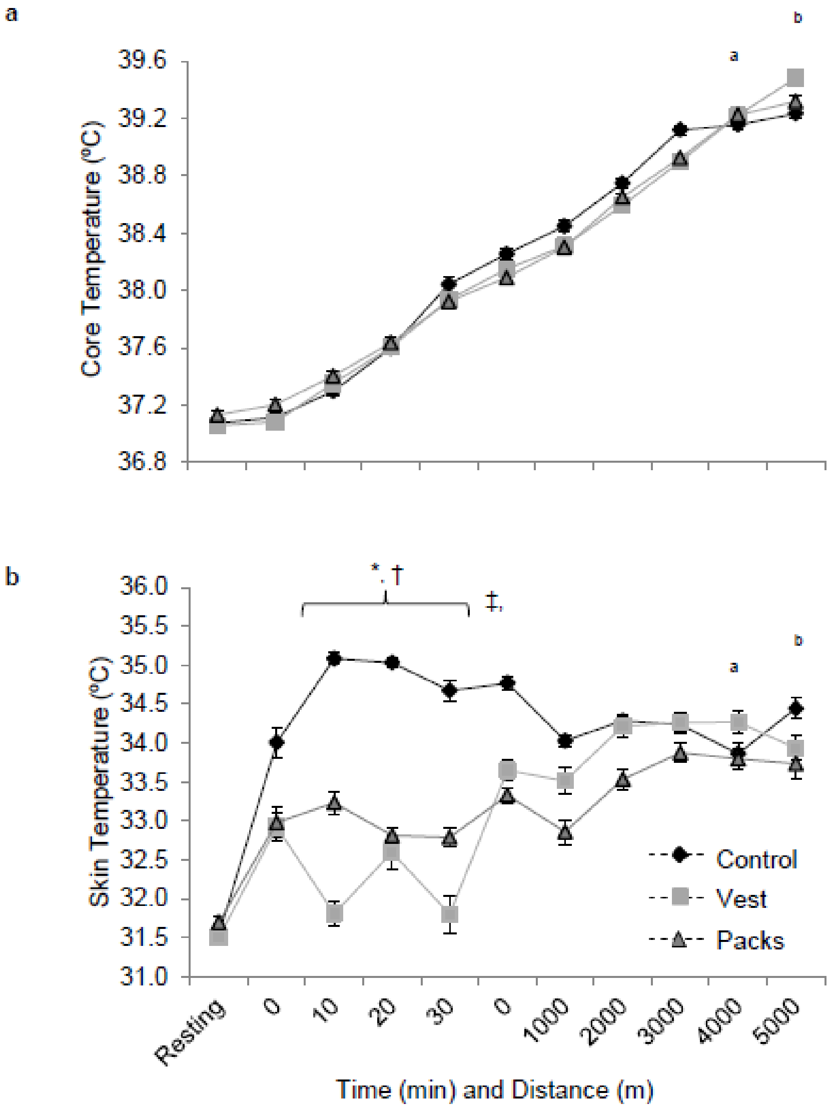
a
b
a
39.6
39.2
38.8
38.4
38.0
37.6
37.2
36.8
Core Temperature (ºC)
b
*, †
‡,
b
a
36.0
35.5
35.0
34.5
34.0
33.5
33.0
32.5
32.0
31.5
31.0
Skin Temperature (ºC)
Control
Vest
Packs
Resting
0
10
20
30
0
1000
2000
3000
4000
5000
Time (min) and Distance (m)

Table 1 Cumulative time (s) and split time (s) during the 5 km time-trial following the 30-min warm-up in the heat with Control, Vest and Packs precooling.

		500	1000	1500	2000	2500	3000	3500 [a]	4000 [a]	4500 [b]	5000 [c]
Cumulative Time (s)	Control	161 ± 15	308 ± 22	457 ± 32	604 ± 40	753 ± 47	901 ± 54	1064 ± 63	1219 ± 65	1370 ± 73	1492 ± 88
	Vest	148 ± 14	287± 27	427 ± 38	569 ± 43	712 ± 48	857 ± 54	1002 ± 60	1151 ± 58	1297 ± 62	1444 ± 71
	Packs	148 ± 14	288 ± 26	422 ± 41	565 ± 46 [#]	706 ± 54	847 ± 60 [#]	991 ± 69	1137 ± 75 [†]	1278 ± 76	1407 ± 80 [‡]
Split Time (s)	Control	161 ± 15	147 ± 12	149 ± 10	148 ± 8	149 ± 8	148 ± 8	152 ± 5	155 ± 10	152 ± 7	148 ± 7
	Vest	148 ± 14	140 ± 13	140 ± 11	143 ± 8	143 ± 7	145 ± 8	145 ± 8 **	149 ± 14	148 ± 14	144 ± 20
	Packs	148 ± 14	140 ± 12	134 ± 16 [¥ #]	143 ± 14	141 ± 9	141 ± 8	144 ± 11 [#]	146 ± 14 [#]	147 ± 18	143 ± 15

** Significant difference from Control, $P < 0.05$. [†] Significant difference from Control, $P < 0.01$. [‡] Significant difference from Control, $P < 0.05$. [#] Difference from Control, $P = 0.054$-0.065. [¥] Significant difference from 500 m, $P < 0.01$. [a] Control ($n = 6$). [b] Control ($n = 5$), Vest ($n = 7$), Packs ($n = 6$). [c] Control ($n = 4$), Vest and Packs ($n = 6$).

Table 2 Neuromuscular function before the 30-min warm-up in the heat with Control, Vest and Packs precooling, and immediately after the 5 km time-trial.

		Control	Vest	Packs
MVC	Pre	949 ± 164	936 ± 164	986 ± 102
(N)	Post	886 ± 121	866 ± 229	909 ± 93
VA	Pre	90.4 ± 4.9	91.5 ± 2.8	92.9 ± 2.3
(%)	Post	91.4 ± 4.6	87.9 ± 9.0	87.5 ± 9.3
$Q_{tw,pot}$	Pre	300 ± 35	317 ± 36	299 ± 34
(N)	Post	304 ± 61	326 ± 99	276 ± 59
M_{max} Amplitude	Pre	8.9 ± 3.3	9.1 ± 2.1	9.4 ± 3.3
(mV)	Post	9.2 ± 3.4	9.3 ± 2.3	10.5 ± 3.7
M_{max} Area	Pre	26.1 ± 50.6	48.4 ± 17.2	36.7 ± 42.2
($\mu V \cdot s^{-1}$)	Post	33.7 ± 43.3	44.2 ± 14.2	27.7 ± 47.5

Table 3 Cardiorespiratory, thermoregulatory and perceptual responses during the warm-up and 5 km time-trial in the heat with Control, Vest and Packs precooling.

		Pre Warm-Up	End of Warm-Up	0	1000	2000	3000	4000 [a]	5000 [b]
HR (beats·min^{-1})	Control	64 ± 11	156 ± 10	109 ± 16	166 ± 11	172 ± 11	173 ± 11	177 ± 11	182 ± 10
	Vest	64 ± 11	150 ± 10	114 ± 21	169 ± 10	174 ± 10	177 ± 8	176 ± 7	176 ± 11
	Packs	61 ± 8	152 ± 16	110 ± 28	169 ± 11	175 ± 7	179 ± 7	180 ± 8	183 ± 9
H_b Change (Kj)	Control	2087 ± 258	2192 ± 245	2206 ± 260 [§]	2194 ± 259	2211 ± 261	2223 ± 259	2365 ± 192	2311 ± 122
	Vest	2085 ± 242	2126 ± 258	2177 ± 258 [§]	2177 ± 260	2204 ± 262	2217 ± 269	2229 ± 275	2239 ± 156
	Packs	2090 ± 249	2146 ± 242 [‡]	2167 ± 254 [‡ §]	2156 ± 242	2186 ± 251	2204 ± 258	2214 ± 259	2226 ± 156
RPE (au)	Control		14.4 ± 1.7	9.9 ± 2.3	14 ± 1.1	15.5 ± 0.8	16.4 ± 0.5	17.0 ± 0.6	18.0 ± 0.8
	Vest		14.0 ± 1.3	10.0 ± 1.8	14.5 ± 0.9	15.5 ± 0.8	16.6 ± 0.9	17.4 ± 1.6	18.3 ± 1.1
	Packs		14.0 ± 1.5	9.8 ± 2.1	14.5 ± 1.2	16.0 ± 0.9	16.5 ± 0.9	17.8 ± 1.0	18.0 ± 1.5
TS (au)	Control	3.8 ± 0.6	6.5 ± 0.5	5.9 ± 0.7	6.3 ± 0.5	6.7 ± 0.5	6.9 ± 0.7	7.4 ± 0.4	7.5 ± 0.4
	Vest	3.9 ± 0.6	5.8 ± 1.2 [#]	5.7 ± 0.8	5.9 ± 0.8	6.5 ± 0.7	7.1 ± 0.6	7.1 ± 0.9	7.5 ± 0.4
	Packs	4.0 ± 0.4	6.1 ± 0.6	5.9 ± 0.7	6.1 ± 0.7	6.6 ± 0.8	6.9 ± 0.7	7.4 ± 0.4	7.3 ± 0.4

[‡] Significant difference from Control, $P < 0.05$. [§] Significant difference from the start of the warm-up, $P < 0.01$. [#] Difference from Control, $P = 0.054$. [a] Control ($n = 6$). [b] Control ($n = 4$), Vest and Packs ($n = 6$).