Eur J Appl Physiol (2007) 100:727–735
DOI 10.1007/s00421-007-0468-x

ORIGINAL ARTICLE

Effects of pre-cooling procedures on intermittent-sprint exercise performance in warm conditions

Rob Duffield · Frank E. Marino

Accepted: 4 April 2007 / Published online: 3 May 2007

Abstract The aim of this study was to determine whether pre-cooling procedures improve both maximal sprint and sub-maximal work during intermittent-sprint exercise. Nine male rugby players performed a familiarisation session and three testing sessions of a 2 × 30-min intermittent sprint protocol, which consisted of a 15-m sprint every min separated by free-paced hard-running, jogging and walking in 32°C and 30% humidity. The three sessions included a control condition, Ice-vest condition and Ice-bath/Ice-vest condition, with respective cooling interventions imposed for 15-min pre-exercise and 10-min at half-time. Performance measures of sprint time and % decline and distance covered during sub-maximal exercise were recorded, while physiological measures of core temperature (T_{core}), mean skin temperature (T_{skin}), heart rate, heat storage, nude mass, rate of perceived exertion, rate of thermal comfort and capillary blood measures of lactate [La$^-$], pH, Sodium (Na^+) and Potassium (K^+) were recorded. Results for exercise performance indicated no significant differences between conditions for the time or % decline in 15-m sprint efforts or the distance covered during sub-maximal work bouts; however, large effect size data indicated a greater distance covered during hard running following Ice-bath cooling. Further, lowered T_{core}, T_{skin}, heart rate, sweat loss and thermal comfort following Ice-bath cooling than Ice-vest or Control conditions were present, with no differences present in capillary blood measures of [La$^-$], pH, K^+ or Na^+. As such, the ergogenic benefits of effective pre-cooling procedures in warm conditions for team-sports may be predominantly evident during sub-maximal bouts of exercise.

Keywords Central fatigue · Heat-strain · Ice-bath · Repeat-sprint · Thermoregulation

R. Duffield (✉) · F. E. Marino
School of Human Movement, Charles Sturt University,
Panorama Ave, Bathurst, NSW 2795, Australia
e-mail: rduffield@csu.edu.au

Introduction

Training and competition for many team-sports often requires sustained exercise performance in high ambient temperatures. Under these conditions elevated core (T_{core}) and mean skin (T_{skin}) temperatures are noted, resulting in increased cardio-vascular and metabolic loads (Kozlowski et al. 1985; Morris et al. 2000), in addition to hastening neuromuscular fatigue (Kay et al. 2001) and reducing endurance (Gonzalez-Alonso et al. 1999) and intermittent-sprint (Drust et al. 2005) performance compared with normo-thermic conditions. To counter the physiological strain associated with higher environmental temperatures, pre-cooling procedures which reduce pre-exercise T_{skin} and T_{core} have been used in laboratory and field settings (Marino 2002).

Increased thermal stress has shown to excessively elevate T_{core} and subsequently reduce intermittent-sprint performance (Maxwell et al. 1999; Drust et al. 2005; Morris et al. 2005). As such, methods such as cold baths, cold ambient air and ice vests have been utilised to varying effect to delay the rise in T_{core} during prolonged duration repeated sprint efforts (Marino 2002). These procedures have improved endurance performance in exercise protocols consisting of constant-load exercise to fatigue (Lee and Haymes 1995; Hasegawa et al. 2005), total maximal work performed in a set time (Booth et al. 1997) and time to complete variable-paced efforts of set distance (Arngrímsson et al. 2004). However, minimal performance benefits have been reported by the small number of studies investigating pre-cooling and intermittent-sprint exercise (simulating team-sport activity) (Drust et al. 2000; Duffield et al. 2003; Cheung and Robinson 2004). Previous research has not shown an improvement in peak or mean power, speed or distance covered in singular (Marsh and Sleivert 1999) or repeated (Drust et al. 2000; Duffield et al. 2003; Cheung and Robinson 2004) maximal sprint efforts of 5- to 30-s in duration following pre-cooling. However, recently Castle et al. (2006) have shown some ergogenic benefits for intermittent-sprint performance following lower body pre-cooling with a 4% increase in peak power. While pre-cooling procedures are generally effective in reducing T_{core}, T_{skin} and the perceived thermal strain of intermittent-sprint exercise protocols (Mitchell et al. 2001; Sleivert et al. 2001), evidence for improved intermittent-sprint performance in warm–hot conditions following pre-cooling is limited.

Team-sport exercise patterns involve intermittent-sprint activity incorporating maximal sprints separated by activity ranging from passive stationary recovery to high-intensity work (Spencer et al. 2005). Traditionally, exercise protocols simulating team-sport exercise involve repeated maximal (2–60) non-specific cycle ergometer sprint efforts (5–30 s) interspersed with sub-maximal recovery bouts (passive–50% $\dot{V}O_{2\,max}$) over prolonged durations (30–80 min) (Duffield et al. 2003; Cheung and Robinson 2004). Exercise performance is assessed via measures of peak and mean power, while the sub-maximal exercise separating maximal efforts is normally standardised and ignored as a performance measure. Morris et al. (2005) have previously reported significantly reduced sub-maximal distances covered in 33°C compared to 17°C ambient conditions. Hence, given the improved endurance performance in completing maximal aerobic events, reported for pre-cooling procedures (Arngrímsson et al. 2004), it is surprising more research attention has not incorporated the measurement of sub-maximal exercise in the assessment of performance.

Therefore, given the often ambiguous and non-specific nature of the reported effects of pre-cooling on intermittent-sprint exercise performance, the purpose of the present study was to investigate the effect of two common pre-cooling procedures (ice-bath and ice-vest) on maximal sprint and sub-maximal work during intermittent-sprint exercise in warm conditions.

Methods

Participants

Participants were nine male, moderate to well trained, club-level rugby players with a mean ± SD age 21.4 ± 1.3 year, height 184.1 ± 5.1 cm and body mass 85.16 ± 5.56 kg. All participants gave verbal and written consent prior to engaging in testing procedures and Human Ethics clearance was granted by the Institutional Ethics Committee.

Overview

Participants performed an initial familiarisation session, followed by three testing sessions at the same time of day, separated by 5–7 days and were required to abstain from the ingestion of alcohol, caffeine and food substances 4 h prior to testing. All testing was conducted on a 20-m synthetic running track in an enclosed biomechanics laboratory. Testing was performed in warm/hot environmental conditions (32 ± 1°C and 30 ± 3% relative humidity), with heating provided by a customised gas heating system, supplemented by four electronic 2,000 W room heaters (Kambrook, Australia) placed at 5-m intervals alongside (within 1-m) the running track. Following familiarisation with all measures and procedures, participants performed three identical sessions in a randomised, counter-balanced order, with only the type of cooling intervention varying between sessions. The three sessions consisted of a control session (no cooling intervention), an ice-vest session (cooling intervention with an ice-vest) and an ice-bath session (ice bath and ice-vest). All participants were required to document their physical activity and dietary and fluid consumption in the 24 h prior to the first testing session and replicate these patterns for the following sessions and particularly to standardise fluid consumption.

Exercise protocol

Participants performed an intermittent-sprint protocol consisting of 2 × 30-min identical halves, separated by a 10-min recovery period and performed on an enclosed 20-m synthetic running track. Initially a warm-up consisting of 4 min of running along the 20-m running track with increments in running speed each minute and 5-min of passive stretching was performed. The intermittent-sprint protocol consisted of a maximal 15-m sprint every minute, separated by sub-maximal exercise of varying intensities. The maximal 15-m sprint was performed on the running track, with a 5-m space for deceleration before impact with a large high jump mat to simulate body contact and collisions that occur in many team sports. Further, during the first and last minute of each half, an extra sprint was performed, reducing the recovery to 30 s. Between each maximal sprint effort were bouts of self-paced, sub-maximal activity, consisting of hard running, jogging and walking, respectively. These sub-maximal bouts were performed up and back along the 15-m sprint track in a shuttle-run fashion. A sub-maximal exercise bout was started as soon as the participant had finished the maximal sprint and was ceased 10 s prior to the commencement of the next sprint to allow time for preparation for the ensuing sprint. Only one sub-maximal exercise mode was employed each minute and these were rotated through in the previously mentioned order to ensure correct replication of procedures. Participants were instructed prior to and given verbal support during each session to attempt to cover as much distance as possible during the hard running bouts, and jog or at a self-selected comfortable pace during the respective jogging and walking bouts.

Pre-cooling intervention

A cooling intervention was performed for 15-min prior to exercise, during the warm-up and during the 10-min half-time recovery period. Participants in the control condition sat in the 32°C temperature and within 5-m of a radiant heat source during both the initial 15-min and then 10-min half-time recovery periods with no cooling intervention. During the ice-vest session, participants wore an ice-vest (Artic Heat, Australia) while sitting in the 32°C temperature within 5-m of a radiant heat source for the 15-min pre-cooling and 10-min half-time cooling and also wore the vest during the warm-up and stretching period. The ice-vest was stored in crushed ice prior to and following use. During the ice-bath session, participants were immersed up to the suprasternal notch in a cold water bath (Custom design, CSU, Australia) at 14 ± 1°C for the initial 15-min before donning the ice-vest and performing the warm-up and stretching in the vest, and then donning the vest during the 10-min half-time recovery period while seated as per other conditions. Finally, in all conditions, participants were required to consume a measured 350 ml of water during the half-time break.

Measures

Performance

Exercise performance was assessed by measures of 15-m sprint time and distance covered during sub-maximal exercise bouts. Sprint time was measured by an infra-red timing system (Speed Light, Swift, Australia) while % decrement was calculated according to Dawson et al. (1993). Markings in 1-m increments alongside the 15-m running track allowed for an accurate measure of the distance covered on each individual sub-maximal exercise bout performed in the respective hard running, jogging and walking bouts.

Physiological measures

Before and after each testing session, nude mass was measured on a set of calibrated scales (HW 150 K, A & D, Australia) to estimate changes in body mass due to sweat loss. Heart rate was measured (Vantage NV, Polar, Finland) pre-intervention, post-intervention, pre-exercise and every 5-min throughout the exercise protocol. T_{core} was measured by a telemetric pill (VitalSense, Mini Mitter, USA) that was ingested 4–5 h prior to exercise to ensure it had passed into the Gastro-Intestinal tract. Skin temperature was measured at the sternum, chest, mid-forearm, mid-quadriceps and medial calf via telemetric patches (VitalSense, Mini Mitter, USA). T_{core} and T_{skin} were recorded pre-intervention, post-intervention, pre-exercise and every 10-min throughout the protocol from a hand-held monitor that telemetrically received core pill and skin patch measurements (VitalSense, Mini Mitter, USA). T_{skin} was calculated based on the equation of Ramanathan (1964), while heat storage was calculated based on the equation of Havenith et al. (1995). Ratings of perceived exertion (RPE) and Thermal comfort were obtained pre-intervention, post-intervention, pre-exercise, either side of the half-time break and post-exercise. A 100 µl of capillary blood was sampled from a hyperaemic ear lobe pre-intervention, post-intervention and pre- and post-halves for analysis of capillary blood lactate [La^-], pH, Potassium (K^+) and Sodium (Na^+) (ABL825 Radiometer, Copenhagen, Denmark). Finally, a 60 µl sample of capillary blood was collected pre- and post-exercise and centrifuged to separate blood plasma and analysed for hematocrit (Hct).

Statistical analysis

A repeated measures (condition × time) ANOVA was used to determine significant differences between the respective conditions (Control, Ice-vest, Ice-bath). Tukey's post-hoc HSD tests were used to determine the source of significance, which was set a priori at $P = 0.05$. Effect sizes (ES) (Cohen's *d*) were calculated to analyse potential trends in the data comparing respective cooling conditions to the control condition. An ES of <0.2 is classified as a 'trivial', 0.2–0.4 as a 'small', 0.4–0.7 as a 'moderate' and >0.8 as a 'large' effect.

Results

The results for mean ± SD 15-m sprint time, total sprint time and % decline in sprint time for the first and second half, respectively, for all conditions are presented in Table 1. No significant differences (P>0.05) and small ES were present between conditions for mean and total sprint time and % decline. The mean ± SD and total distance covered during hard running, jogging and walking exercise bouts for the first and second half and overall, respectively, for all conditions is presented in Table 2. The overall total distance covered during all sub-maximal exercise bouts were not significantly different ($P = 0.09$) for the ice-bath, ice-vest and control conditions (4865 ± 546, 4551 ± 418 and 4493 ± 403 m, respectively). No significant differences ($P > 0.05$) were noted between conditions for the mean or total distance covered in hard running ($P = 0.09$), jogging ($P = 0.50$) or walking ($P = 0.61$) either in the first or second half or overall. However, large ES data indicated a greater mean and total distance covered in the ice-bath session for hard running in both halves (ES = 0.84 and 0.86) and overall (ES = 0.88). Mean ± SD individual hard running efforts are presented in Fig. 1

Results for mean ± SD T_{core}, T_{skin} and chest temperature (T_{chest}) for all conditions are presented in Fig. 2. A significantly lower T_{core} ($P < 0.05$) was evident following the intervention, prior to the warm-up, in the ice-bath compared to the ice-vest and control condition and remained lower until the fortieth minute. Further, large ES data (ES = 1.0–1.8) indicated a lower T_{core} in the ice-bath condition following the intervention for the entire exercise protocol. No significant differences ($P > 0.05$) and moderate ES data (ES = 0.3–0.5) were evident between the ice-vest and control conditions. A significantly lower T_{skin} ($P < 0.05$) was evident following the intervention in the ice-bath compared to the ice-vest and control conditions throughout the warm-up and until the twentieth minute, with large ES data (ES = 1.0–12.0) indicating lower T_{skin} in the Ice-bath condition following the intervention for the entire exercise protocol. No significant differences ($P > 0.05$), but large ES data (ES = 0.8–1.1) were evident between T_{skin} in the ice-vest and control conditions until the twentieth minute. A significant difference ($P < 0.05$) and large ES (0.8–3.1) were evident in lower T_{chest} values in the ice-bath and ice-vest conditions compared to the control condition following cooling until the tenth minute and again after the half-time cooling procedure. No differences ($P > 0.05$) were present between the respective cooling conditions. Results for change in heat storage over the testing protocol are presented in Fig. 3. In the ice-bath condition an initial loss of body heat was noted following cooling, with a reduction in heat storage until the tenth minute ($P < 0.05$).

Mean ± SD heart rate data are presented in Fig. 4 and show a significantly lower heart rate in the ice-bath condition following the cooling intervention until the tenth minute of the exercise protocol (including the warm-up). Large ES data also indicate reduced heart rates until 15-min of the exercise protocol (ES = 0.8–1.8) and again after half-time (ES = 0.90) in the ice-bath condition. A significant difference ($P < 0.05$) in the amount of sweat loss (as measured by pre-post difference in nude body mass) was evident, with a lower change in mass in the ice-bath than control condition (1.73 ± 0.17, 1.92 ± 0.24 and 2.13 ± 0.19 kg for ice-bath, ice-vest and control conditions, respectively). The large ES data indicated both ice-bath and ice-vest conditions had a reduced sweat loss compared to the control condition.

The mean ± SD capillary blood [La^-], pH, Na^+, K^+ and Hct data is presented in Fig. 5. No significant differences ($P < 0.05$) were evident between conditions for [La^-], pH, Na^+ or K^+ throughout the exercise protocol. Large ES data (ES = 0.70) indicated lower pH values at the end of the first-half in the ice-bath condition; however, all other ES data indicated trivial to small differences. Significant differences ($P < 0.05$) were noted between the ice-bath and ice-vest respectively and control condition for the change in Hct. Attenuated changes in Hct were evident for the ice-bath (1.2 ± 0.4%) and ice-vest (1.6 ± 0.5%) compared to the control condition (2.3 ± 0.5 %).

RPE and Thermal comfort ratings throughout the protocol are presented in Table 3. No significant differences ($P > 0.05$) and small ES data (<0.4) were present between all conditions for RPE values. Significantly ($P < 0.05$) reduced Thermal comfort ratings were present in the ice-bath condition before the start of each half and in the ice-vest before the first-half compared to the control condition. Large ES (d = 1.0–3.5) were present for attenuated ratings in the ice-bath and ice-vest conditions at the start of each half.

Table 1 Mean ± SD 15-m sprint time, total sprint time for all sprints and % decline in sprint time for the first and second halves for the Control, Ice-vest and Ice-bath conditions

	Control	Ice-vest	Ice-bath
First half sprint mean (s)	2.75 ± 0.13	2.74 ± 0.18	2.72 ± 0.14
Second half sprint mean (s)	2.83 ± 0.17	2.82 ± 0.22	2.77 ± 0.16
First half sprint total (s)	90.59 ± 4.40	90.31 ± 5.96	89.81 ± 4.74
Second half sprint total (s)	93.30 ± 5.45	93.11 ± 7.22	91.26 ± 5.32
First half decline (%)	6.2 ± 1.8	7.1 ± 2.5	5.5 ± 2.5
Second half decline (%)	6.3 ± 1.9	6.2 ± 2.1	6.5 ± 2.6

No significant difference between conditions ($P > 0.05$)

Table 2 Mean and total ± SD distance covered for hard running, jogging and walking in the first and second halves respectively for the Control, Ice-vest and Ice-bath conditions

	Control	Ice-vest	Ice-bath
Mean first half hard run (m)	122.7 ± 12.5	127.0 ± 12.6	136.8 ± 14.2[a]
Mean second half hard run (m)	113.3 ± 12.0	115.9 ± 16.4	128.4 ± 15.5[a]
Mean first half jog (m)	93.8 ± 8.3	92.4 ± 10.5	95.0 ± 11.9
Mean second half jog (m)	87.2 ± 8.1	86.4 ± 10.3	91.4 ± 12.3
Mean first half walk (m)	52.2 ± 7.2	53.0 ± 7.3	55.9 ± 7.5
Mean second half walk (m)	50.4 ± 8.7	50.8 ± 5.1	53.9 ± 8.4
Total first half hard run (m)	1104.0 ± 112.3	1143.4 ± 113.5	1231.9 ± 128.6[a]
Total second half hard run (m)	1019.5 ± 107.7	1042.6 ± 147.8	1155.6 ± 139.2[a]
Total first half jog (m)	750.0 ± 66.3	740.0 ± 84.1	759.9 ± 95.0
Total second half jog (m)	697.5 ± 64.4	691.9 ± 82.7	731.3 ± 98.4
Total first half walk (m)	469.6 ± 65.2	476.9 ± 65.4	502.9 ± 67.7
Total second half walk (m)	453.3 ± 77.9	456.8 ± 46.2	484.8 ± 75.2

No significant difference between conditions ($P > 0.05$)

[a] Large effect size (>0.8) compared to control condition

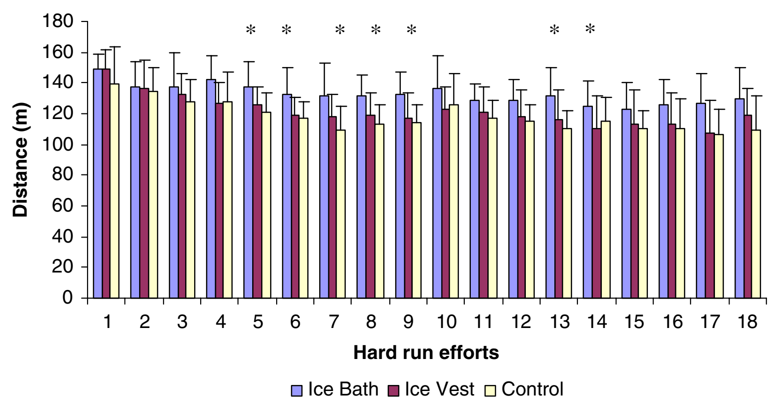

Fig. 1 Mean ± SD distance covered during individual free-paced hard running efforts through out the exercise protocol for Ice-bath, Ice-vest and Control Conditions. * Significant difference between Ice-bath and Control conditions ($P < 0.05$)

Discussion

The aim of the current study was to determine the effect of two different pre-cooling procedures on maximal sprint and sub-maximal work during intermittent-sprint exercise in warm conditions. Results for exercise performance indicated no significant differences between conditions for the time or % decline in 15-m sprint efforts or the distance covered during sub-maximal work bouts; however, large ES data indicate a greater distance covered during hard running following ice-bath cooling procedures. Physiological measures indicated lowered T_{core}, T_{skin}, heart rate, sweat loss and thermal comfort following ice-bath cooling compared with ice-vest or control conditions, with no differences present in capillary blood measures for [La$^-$], pH, K^+ or Na^+.

Similar to most previous studies investigating the effects of pre-cooling on intermittent-sprint performance in the heat, limited ergogenic effects were apparent (Drust et al. 2000; Duffield et al. 2003; Cheung and Robinson 2004). Castle et al. (2006) recently reported a 4% increase in peak power following leg cooling, but no difference in mean or total work done for any cooling procedure (bath, vest or pack) compared to a control condition. Previous prolonged intermittent-sprint protocols that have shown limited declines in sprint performance in the heat, have reported limited beneficial effects of pre-cooling (Duffield et al. 2003; Cheung and Robinson 2004). In contrast, Castle et al. (2006) demonstrated a significant decline in sprint performance in the control condition and as such reported an ergogenic influence of a cooling intervention to maintain peak power without any significant change in work done.

Exercise protocols that allow sufficient recovery (>60 s) and repletion of PCr between sprints (Bogdanis et al. 1998), with low resistance to sprint efforts may result in limited declines in performance and hence limited pre-cooling ergogenic benefits (Duffield et al. 2003). It is possible that greater resistance and durations tease out declines in sprint performance and allow for a potential ergogenic pre-cooling influence. In the present study, a moderate decline in sprint performance was evident, however, little amelioration of the decline was evident following ice-bath cooling procedures. As such, it is possible that the effects of pre-cooling on intermittent-sprint performance are minor and only manifest when the thermal and exercise stress is sufficient to induce heat strain.

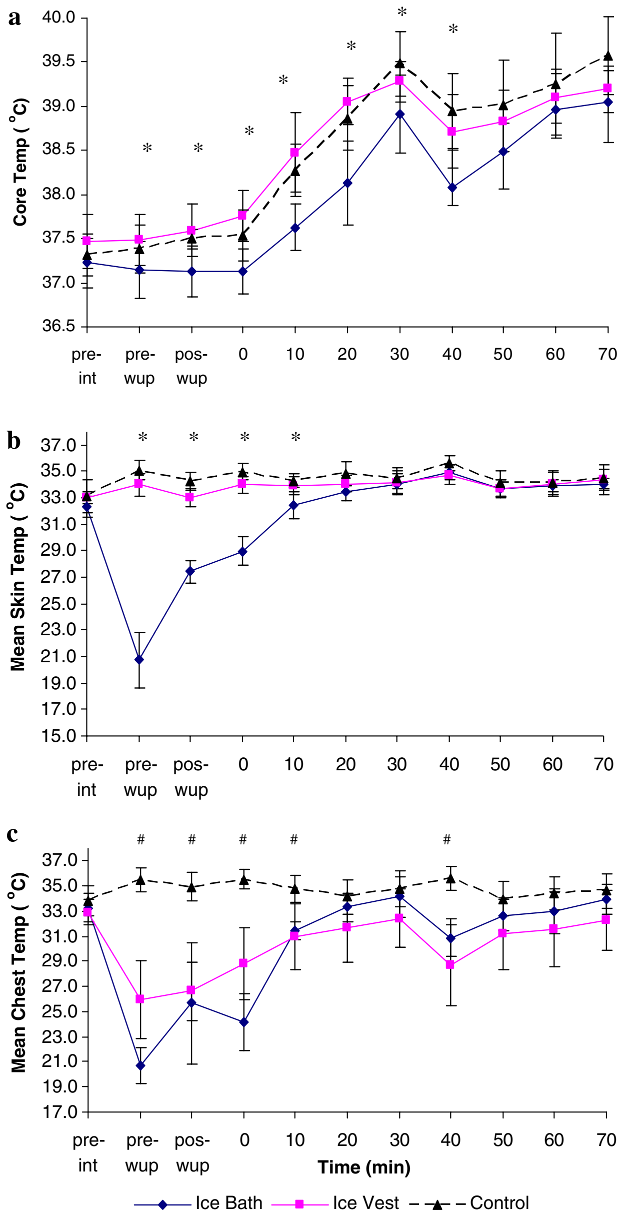

Fig. 2 **a** Mean ± SD Core temperature **b** Mean ± SD skin temperature and **c** mean ± SD chest temperature for Ice-bath, Ice-vest and Control conditions over the duration of the exercise protocol. * Significant difference of Ice-bath to Ice-vest and Control conditions respectively ($P < 0.05$). # Significant difference of both Ice-bath and Ice-vest to Control condition ($P < 0.05$)

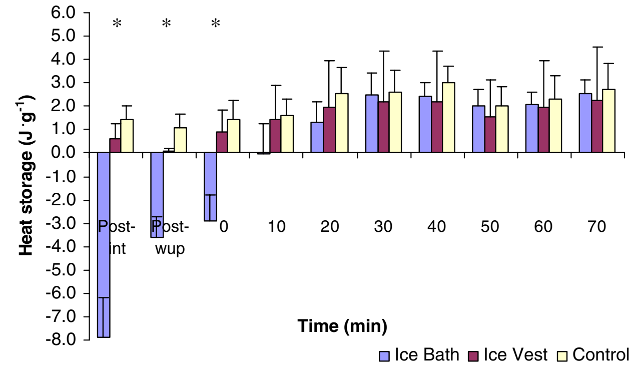

Fig. 3 Mean ± SD heat storage for Ice-bath, Ice-vest and Control conditions over the duration of the exercise protocol. * Significant difference between Ice-bath and Ice-vest and Control conditions respectively ($P < 0.05$)

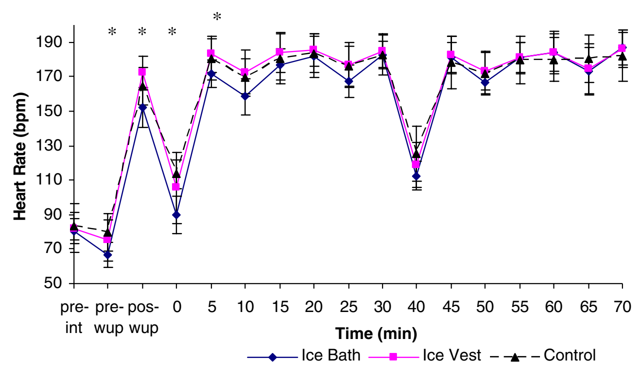

Fig. 4 Mean ± SD heart rate for Ice-bath, Ice-vest and Control conditions over the duration of the exercise protocol. * Significant difference between Ice-bath and Control conditions ($P < 0.05$)

Although limited effects of pre-cooling on sprint performance were evident, a unique aspect of the current study, which has not been previously reported in pre-cooling studies on intermittent-sprint exercise, was the measurement of free-paced distance covered between sprints. The results indicated an increased distance covered during hard-running following ice-bath pre-cooling procedures (Fig. 1). Precooling has been reported to significantly increase the distance covered in 30-min of continuous running by ~300-m (Booth et al. 1997) and decrease time to complete 5-km treadmill efforts by 13-s (Arngrímsson et al. 2004). In the current study, ice-bath cooling increased the total distance covered in the 18 respective 45-s hard-running bouts (~14-min in total) by ~200-m, which approach the distances reported by Booth et al. (1997).

The strategy of combining whole-body pre-cooling prior to warm-up to reduce T_{core} and T_{skin}, and then maintenance of cooling procedures during the warm-up (ice-vest) was effective in improving the distance covered during hard-running, compared to the less effective cooling procedures such as torso cooling alone (ice-vest). Moreover, while minimal differences were evident between conditions for distance covered in jogging and walking, respectively, the total distance covered for all sub-maximal bouts shows that the combined ice-bath and vest cooling procedure increased the distance covered by ~300–400-m compared to control or ice-bath only. Thus, while pre-cooling procedures may have limited influence on intermittent-sprint performance, pre-cooling is potentially effective in improving the sub-maximal work of team-sport athletes in

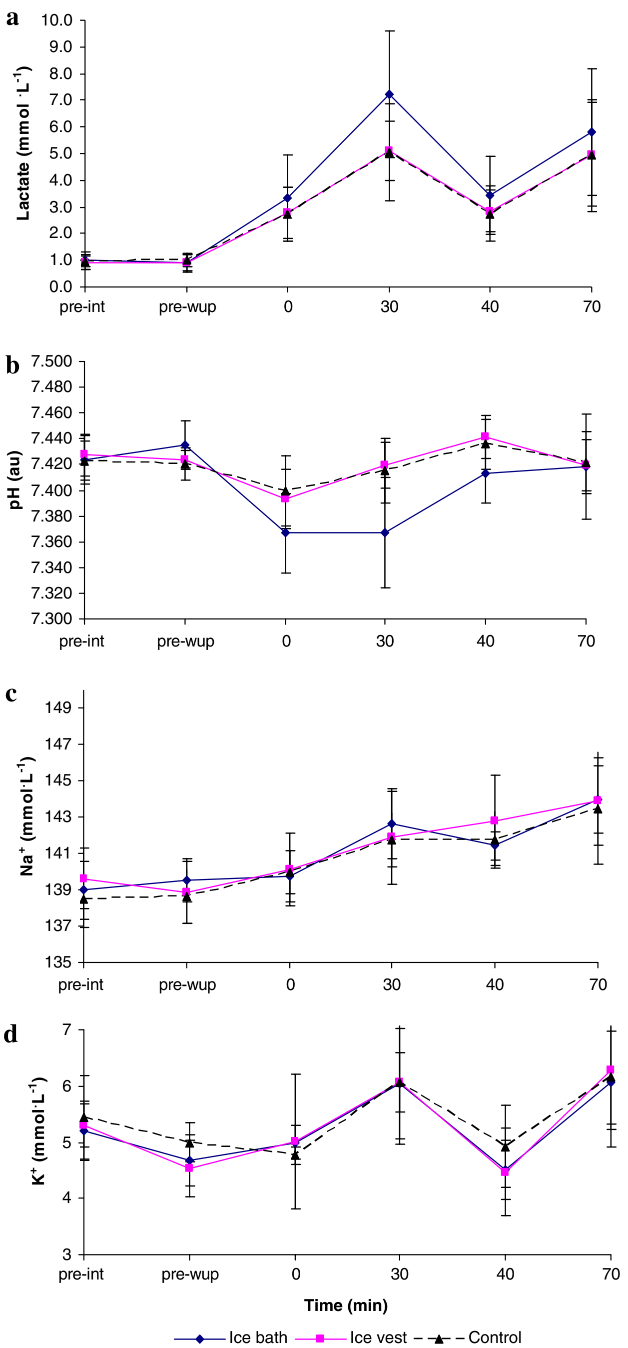

Fig. 5 **a** Mean ± SD capillary blood lactate **b** mean ± SD capillary blood pH, **c** mean ± SD capillary blood Sodium (Na^+) and **d** mean ± SD capillary blood Potassium (K^+) for the Ice-bath, Ice-vest and Control conditions

hot conditions, similar to data previously reported for endurance exercise (Booth et al. 1997; Arngrímsson et al. 2004; Hasegawa et al. 2005).

The proposition that exercise performance is reduced once T_{core} reaches either a critical level or an increment of 2°C is well documented (Gonzalez-Alonso et al. 1999). As a result, physiological mechanisms likely to assist performance improvements following pre-cooling relate to the reduction of T_{core}, T_{skin} and efficiency in heat storage and removal. In the current study, the 15-min ice-bath procedure was effective at blunting the rise in T_{core} throughout the exercise protocol. The effectiveness of cooling strategies varies with the extent and duration of cooling applied (Olshewski and Bruck 1988; Lee and Haymes 1995) and as such it is not unexpected that whole-body immersion maintained a lower T_{core} and T_{skin} compared to the torso-only cooling (only T_{chest} reduced), however, this has not been as evident in all cases (Castle et al. 2006). Increases in heat storage and T_{core} commenced from initial exposure to the warm environment in ice-vest and control conditions, yet were absent in the ice-bath condition. Several studies have indicated that there is a duration of 30–40-min before the thermal and cardio-vascular effects of pre-cooling wane (Hessemer et al. 1984; Wilson et al. 2002). Hence, the importance of maintaining the physiological advantages provided by whole-body pre-cooling until as close as possible to the start of exercise are evident, and therefore including a pre-cooling procedure during the warm-up is likely to be of benefit to performance (Arngrímsson et al. 2004; Webborn et al. 2005).

The reduced T_{skin} and reduction in stored heat in the ice-bath condition blunted the extent of the exercise-induced rise in T_{core}. In turn, a lower T_{core} is likely to be a key contributor to a delayed onset of neurally-mediated peripheral vasodilation and sweating mechanisms, respectively (Kruk et al. 1990). The delay in redistribution of cardiac output to supply cutaneous requirements for the transfer of metabolically generated heat allows the maintenance of a greater central blood volume (Gonzalez-Alonso and Calbet 2003). Further, the maintenance of a lower T_{skin} after pre-cooling results in a more efficient heat transfer gradient and reduces the requirement for evaporative sweat loss (Lee and Haymes 1995). Accordingly, the early presence of a reduced heart rate following ice-bath pre-cooling combined with an ameliorated decline in the respective post-exercise nude mass and Hct indirectly support the maintenance of a greater blood volume and more efficient thermo-regulatory control following pre-cooling; which may be of possible benefit to exercise performance.

The maintenance of a greater central blood volume will potentially reduce cardio-vascular load and provide an increased skeletal muscle blood supply (Gonzalez-Alonso and Calbet 2003) and theoretically assist muscle performance. However, given that differences in nude mass equate to a greater blood volume retention of ~ 400 ml in the ice-bath condition and differences in heart rate were only present up to the tenth min, it is apparent that these factors alone may not sufficiently explain differences in self-selected work patterns. Centrally-mediated mecha-

Table 3 Mean ± SD Rate of perceived exertion (RPE) and rating of Thermal comfort (Therm) pre-intervention (Pre-int), pre-warm up (pre-wup), post warm-up (post-wup), pre-exercise (0 min), end of first-half (30-min), end of half-time (40-min) and end of exercise (70-min) for the Control, Ice-vest and Ice-bath conditions

	Pre-int	Pre-wup	Post-wup	0-min	30-min	40-min	70-min
RPE							
Control	6.0 ± 0.0	6.0 ± 0.0	10.0 ± 2.2	7.0 ± 1.2	18.0 ± 1.4	9.1 ± 3.4	18.4 ± 1.6
Ice-vest	6.0 ± 0.0	6.0 ± 0.0	10.8 ± 1.6	7.2 ± 1.0	16.9 ± 2.7	9.5 ± 3.0	18.1 ± 1.7
Ice-bath	6.0 ± 0.0	6.0 ± 0.0	9.6 ± 2.7	7.0 ± 1.1	16.3 ± 1.8	8.9 ± 2.5	17.8 ± 2.1
Therm							
Control	4.4 ± 0.5	4.7 ± 0.7	5.7 ± 0.5	5.4 ± 0.7	7.2 ± 0.7	5.5 ± 0.9	7.1 ± 0.6
Ice-vest	4.5 ± 0.5	3.8 ± 0.7*	5.6 ± 0.5	5.0 ± 1.0	7.1 ± 0.6	4.5 ± 1.0*	6.9 ± 0.8
Ice-bath	4.4 ± 0.6	1.3 ± 0.5*	4.3 ± 0.8*	3.9 ± 0.7*	6.1 ± 1.6	3.8 ± 0.9*	7.1 ± 0.7

No significant differences ($P > 0.05$) for RPE

* Significantly different ($P < 0.05$) to Control condition for Thermal comfort

nisms resulting in a 'feed-forward' control of pacing in endurance exercise have been suggested to result in the selection of lower exercise intensities in warmer conditions or with higher T_{core} (Kay et al. 2001). Recent intermittent-sprint data (Drust et al. 2005; Castle et al. 2006) has further indicated the role of central processes in adjusting motor-unit recruitment based on both the rate of rise and absolute T_{core} per se. Previous research (Morris et al. 2000; Drust et al. 2005; Castle et al. 2006), as with the current study, have reported minimal differences in blood metabolite accumulation for intermittent-sprint exercise in hot and moderate conditions with cooling, further implicating the role of a central fatigue mechanism for the reduction in intermittent-sprint performance. In the current study, exercise was not terminated due to hyperthermia and therefore the adjustment to reduce exercise intensity was self-selected. This is indicated in the present data (Figs. 1, 2) where an increased distance covered during hard running and delayed heat storage following ice-bath cooling, suggests that subjects could perform more work for the same heat strain, especially when the rise in T_{core} was blunted. As such, it is feasible to speculate that the role of a centrally-mediated increase in work may be a result of a greater central drive to skeletal musculature in the pre-cooling condition (Kay et al. 2001; Tucker et al. 2004).

In conclusion, pre-cooling methods did not significantly improve intermittent-sprint performance; however, a combined pre-cooling strategy of an ice-bath followed by ice-vest during warm-up did indicate an effect of increasing distance covered during sub-maximal hard-running bouts. Further, the combined ice-bath and vest procedure resulted in significantly lower T_{core}, T_{skin}, heart rate, sweat loss and thermal comfort than the vest or control conditions respectively. As such, the ergogenic benefits of effective pre-cooling procedures in warm conditions for team-sports may be predominantly evident during sub-maximal bouts of exercise. Further, for maximal benefit, pre-cooling interventions should be continued until as close as possible to exercise (game) commencement.

Acknowledgments The authors gratefully acknowledge the funding of this project from a CSU Small Grant supplied by Charles Sturt University.

References

Arngrímsson SA, Petitt DS, Stueck MG, Jorgensen DK, Cureton KJ (2004) Cooling vest worn during active warm-up improves 5-km run performance in the heat. J Appl Physiol 96:1876–1874

Bogdanis GC, Nevill ME, Lakomy HKA, Boobis LH (1998) Power output and muscle metabolism during and following recovery from 10 and 20 s of maximal sprint exercise in humans. Acta Physiol Scand 163:261–272

Booth J, Marino F, Ward JJ (1997) Improved running performance in hot humid conditions following whole body precooling. Med Sci Sports Exec 29:943–949

Castle PC, Macdonald AL, Philip A, Webborn A, Watt PW, Maxwell NS (2006) Precooling leg muscle improves intermittent sprint exercise performance in hot, humid conditions. J Appl Physiol 100:1377–1384

Cheung SS, Robinson AM (2004) The influence of upper-body pre-cooling on repeated sprint performance in moderate ambient temperatures. J Sports Sci 22:605–612

Dawson B, Fitzsimons M, Ward D (1993) The relationship of repeated sprint ability to aerobic power and performance measures of anaerobic work capacity and power. Aust J Sci Med Sport 25(4):88–93

Drust B, Cable NT, Reilly T (2000) Investigation of the effects of the pre-cooling on the physiological responses to soccer-specific intermittent exercise. Eur J Appl Physiol 81:11–17

Drust B, Rassmussen P, Mohr M, Nielsen B, Nybo L (2005) Elevations in core and muscle temperature impairs repeated sprint performance. Acta Physiol Scand 183:181–190

Duffield R, Dawson B, Bishop D, Fitzsimons M, Lawrence S (2003) Effect of wearing and ice cooling jacket on repeat sprint performance in warm/humid conditions. Br J Sports Med 37:164–169

Gonzalez-Alonso J, Teller C, Anderson SL. Jensen FB, Hyldig T, Nielsen B (1999) Influence of body temperature on the development of fatigue during prolonged exercise in the heat. J Appl Physiol 86:1032–1038

Gonzalez-Alonso J, Calbet JA (2003) Reductions in systemic and skeletal muscle blood flow and oxygen delivery limit maximal aerobic exercise capacity in humans. Circulation 107(6):824–830

Hasegawa H, Takatori T, Komura T, Yamsaki M (2005) Wearing a cooling jacket during exercise reduces thermal strain and improves endurance performance in a warm environment. J Strength Cond Res 19(1):122–128

Havenith G, Inoue Y, Wyndham CH (1995) Age predicts cardiovascular, but not thermoregulatory responses to humid heat stress. Eur J Appl Physiol 70:88–96

Hessemer V, Langusch D, Bruck K (1984) Effect of slightly lowered temperatures on endurance performance in humans. J Appl Physiol 57:1731–1737

Kay D, Marino FE, Cannon J, St Clair Gibson A, Lambert MI, Noakes TD (2001) Evidence for neuromuscular fatigue during high-intensity cycling in warm, humid conditions. Eur J Appl Physiol 84(1):115–121

Kozlowski S, Brzezinska Z, Kruk B. Kaciuba-Uscilko H, Greenleaf JE, Nazar K. (1985) Exercise hyperthermia as a factor limiting physical performance: temperature effect on muscle metabolism. J Appl Physiol 59:766–773

Kruk B, Pekkarinen H, Harri M, Manninen K, Hanninen O (1990) Thermoregulatory responses to exercise at low ambient temperature performed after precooling or preheating procedures. Eur J Appl Physiol Occup Physiol 59:416–420

Lee D, Haymes E (1995) Exercise duration and thermoregulatory responses after whole body precooling. J Appl Physiol 79:1971–1976

Marino FE (2002) Methods, advantages and limitations of body cooling for exercise performance. Br J Sports Med 36:89–94

Marsh D, Sleivert G (1999) Effect of precooling on high intensity cycling performance. Br J Sports Med 33:393–397

Maxwell N, Gardner F, Nimmo M (1999) Intermittent running:muscle metabolism in the heat and effect of hypohydration. Med Sci Sports Ex 31(5):675–683

Mitchell JB, Schiller ER, Miller JR, Dugas JP (2001) The influence of different external cooling methods on thermoregulatory responses before and after intermittent exercise in the heat. J Strength Cond Res 15(20):247–254

Morris JG, Nevill ME, Williams C (2000) Physiological and metabolic responses of female games and endurance athletes to prolonged, intermittent, high-intensity running at 30° and 16°C ambient temperatures. Eur J Appl Physiol 81:84–92

Morris JG, Nevill ME, Boobis LH, MacDonald IA, Williams C (2005) Muscle metabolism, temperature and function during prolonged, intermittent, high-intensity running in air temperatures of 33° and 17°C. Int J Sports Med 26:805–814

Olschewski H, Bruck K (1988) Thermoregulatory, cardiovascular, and muscular factors related to exercise after precooling. J Appl Physiol 64(2):803–811

Ramanathan NLA (1964) A new weighting system for mean surface temperature of the human body. J Appl Physiol 19:531–533

Sleivert GG, Cotter JD, Roberts WS, Febbraio MA (2001) The influence of whole-body vs torso precooling on physiological strain and performance of high intensity exercise in the heat. Comp Biochem Physiol 128(4):657–666

Spencer M, Bishop D, Dawson B, Goodman C (2005) Physiological and metabolic responses of repeated-sprint activities. Sports Med 35(12):1025–1044

Tucker R, Rauch L, Harley YX, Noakes TD (2004) Impaired exercise performance in the heat is associated with an anticipatory reduction in skeletal muscle activation. Plugers Arch 448:422–430

Webborn N, Price MJ, Castle PC, Goosey-Tolfrey VL (2005) Effects of two cooling strategies on thermoregulatory responses of tetraplegia athletes during repeated intermittent exercise in the heat. J Appl Physiol 98:2101–2107

Wilson TE, Johnson SC, Petajan JH, Davis SL, Gappmaier E, Luetkemeier MJ, White AT (2002) Thermal regulatory responses to submaximal cycling following lower-body cooling in humans. Eur J Appl Physiol 88:67–75