Precooling and Warm-Up Effects on Time Trial Cycling During Heat Stress

Ramzi A. Al-horani; Jonathan E. Wingo; Jason Ng; Phillip Bishop; Mark Richardson

BACKGROUND: Heat stress limits endurance exercise performance. Combining precooling and warm-up prior to endurance exercise in the heat may exploit the benefits of both strategies while avoiding the potential negative consequences of each. This study tested the hypothesis that precooling combined with warm-up improves time trial cycling performance in the heat relative to either treatment alone.

METHODS: Nine healthy men completed three 16.1-km time trials in 33°C after: 1) precooling (ice slurry and ice vest) alone (PREC); 2) warm-up alone (WU); or 3) PREC plus WU (COMBO).

RESULTS: T_{re} was lower after PREC compared to WU throughout exercise and lower than COMBO for the first 12 km; COMBO was lower than WU for the first 4 km. T_{sk} during PREC was lower than COMBO and WU for the first 8 km, and lower in COMBO than WU for the first 4 km. PREC lowered pre-exercise heart rate relative to COMBO and WU (68 ± 10, 106 ± 12, 101 ± 13 bpm, respectively), but it increased similarly during exercise. Local sweat rate (SR) was lower in PREC (0.1 ± 0.1 mg · cm^{-2} · min^{-1}) than COMBO (0.5 ± 0.2 mg · cm^{-2} · min^{-1}) and WU (0.6 ± 0.2 mg · cm^{-2} · min^{-1}) for the first 4 km. Treatments did not differentially affect performance (PREC = 31.9 ± 1.9 min, COMBO = 32.6 ± 2.7 min, WU = 33.1 ± 2.9 min).

DISCUSSION: We conclude precooling alone or with warm-up mitigated thermal strain during exercise, but did not significantly improve 16.1-km cycling time trial performance.

KEYWORDS: thermoregulation, cardiovascular strain, thermal strain, self-paced exercise, body temperature.

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Aerobic exercise performance is reduced in hot conditions[19,30] because of increased cardiovascular and thermal strain.[22] Precooling prior to exercise has been shown to extend time to exhaustion[32] and distance covered in a given period of time[4,16] in hot conditions. These improvements may be related to increased heat storage capacity and attenuated cardiovascular and thermoregulatory strain as a result of lowered core (T_c) or mean skin temperature ($\overline{T}_{sk}$) prior to exercise in hot environments.[4,19] In addition, precooling has been shown to improve self-paced exercise through enhanced muscle recruitment and power output.[8,30] Despite the reputed benefits of precooling, in some situations it may be detrimental. For example, core and muscle temperatures below 37.5°C and 38°C, respectively, were linearly associated with reduced aerobic performance and peak oxygen uptake ($\dot{V}O_2$).[2]

In order to optimize muscle contractile function and $\dot{V}O_2$ kinetics—which may be reduced by precooling—prior to exercise,[3] many athletes incorporate a warm-up. Warm-up has either improved or impaired performance in association with decreased heat storage capacity.[3,32]

As such, it is reasonable that combining precooling and warm-up may result in the benefits of each strategy while avoiding the potential negative consequences of each. However, the combination of precooling and warm-up effects on exercise has only minimally been investigated, with mixed results. Many studies that found improved endurance performance with precooling did not include a warm-up session.[4] It may be that precooling fostered positive thermoregulatory responses at the expense of muscle contractile function optimization that might

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have occurred via a warm-up. In terms of studies that have combined warm-up with precooling, running time to exhaustion in the heat was improved after precooling alone relative to a trial with warm-up alone.[32] Likewise, simultaneous cooling and warm-up resulted in improved 5-km running,[1] but not cycling time trial performance in the heat[14] compared to warm-up or cooling interventions alone. None of the aforementioned studies involved reduced T_c prior to the performance test, which may explain a lack of, or small, effect of precooling given that reducing T_c has been posited as the main mechanism by which precooling enhances performance.[19]

Taken together, these studies suggest the optimal combination of precooling and warm-up remains unclear, especially for cycling. Additionally, most of the aforementioned studies were conducted on trained athletes; however, the ergogenic effect of precooling has been shown to positively impact populations with different fitness levels during self-paced cycling[5,8,16] and exercise until volitional fatigue.[12,25,28] Since many recreational athletes engage in perceived ergogenic training and competition practices, it is important to evaluate these practices in this population in order to enhance ecological validity. Accordingly, the purpose of this study was to investigate the combined and separate effects of precooling and warm-up on subsequent cycling time trial performance in a hot environment in recreationally active individuals. We hypothesized that the combination of precooling and warm-up would result in a faster performance time than either treatment alone.

METHODS

A repeated measures research design was used; subjects completed four visits to the Exercise Physiology Laboratory at the University of Alabama. The first visit involved measurement of maximal oxygen uptake ($\dot{V}O_{2max}$) using a graded cycling exercise test. The subsequent three visits involved the following treatments, in counterbalanced order: 1) precooling alone (PREC); 2) warm-up alone (WU); and 3) precooling + warm-up (COMBO). The counterbalanced treatment orders were randomly assigned to subjects. After each treatment, subjects completed a 16.1-km simulated cycling time trial in a hot environment (33°C, ~40–50% relative humidity).

Subjects

Following approval by the University's Institutional Review Board and after providing written informed consent, nine healthy, recreationally active men (performing aerobic exercise 2–3 d/wk for at least 20 min/d) volunteered to participate. Descriptive statistics (means ± SD) were as follows: age = 24 ± 5 yr; body mass = 74.7 ± 4.5 kg; height = 171.4 ± 7.7 cm; body fat estimated from skinfolds = 13 ± 5%; $\dot{V}O_{2max}$ = 43.0 ± 5.2 $mL \cdot kg^{-1} \cdot min^{-1}$. All subjects were free of any known cardiovascular, metabolic, or pulmonary disease as determined by a health history questionnaire. A power analysis revealed 8–10 subjects was necessary to detect a moderate effect (~0.5 SD) among treatments for time to completion of the 16.1-km cycling time trial, assuming power ~0.8 and correlation among the repeated measurements of time to completion ~0.9.[23] The time constraints during which data had to be collected precluded being able to control fluctuations in internal body temperature and sex hormones concomitant with the female menstrual cycle—which could have impacted the primary outcomes[11]—so women were excluded from participation.

Procedures

On the first visit, subjects reported to the laboratory 3 h postprandial but well hydrated. They were instructed to avoid consuming caffeine, alcohol, and nonprescription drugs the day before and the day of testing and vigorous exercise 2 d before testing. Upon arrival, subjects completed a 24-h history questionnaire to verify adherence to pretest instructions. Next, height and weight (BWB-800, Tanita, Tokyo, Japan) were measured, followed by body fat estimated from the sum of three skinfolds (Lange, Beta Technology, Inc., Cambridge, MD).[13] Then hydration was measured using urine specific gravity (USG); values ≤1.020 were considered adequately hydrated.[15]

Subjects then completed a graded exercise test (GXT) to measure $\dot{V}O_{2max}$ (Parvo Medics, Sandy, Utah) on an electronically braked cycle ergometer (Velotron Dynafit Pro, Racer Mate Inc., Seattle, WA) in 23°C, 40–50% relative humidity. Heart rate (HR) was monitored continuously during the GXT using a Polar telemetry transmitter unit (Polar, Stamford, CT). After a 5- to 10-min warm-up, power output was increased 25 W every 2 min until volitional fatigue. Following the GXT and ~20 min of rest, subjects completed a simulated 16.1-km cycling time trial to familiarize them with the experimental trials and to improve the reliability and reproducibility of the measurements during the subsequent trials.[35]

Subjects returned to the laboratory 3 to 4 d after the first visit for their first experimental trial. All experimental trials were conducted at the same time of day to minimize the influence of circadian rhythms on body temperature and HR. They were given the same pretest instructions as the first visit and completed the same 24-h history questionnaire as before. Then USG and seminude body mass were measured. Subjects then inserted a flexible rectal thermocouple (model RET-1, Physitemp, Clifton, NJ) ~12 cm past the anal sphincter for measurement of rectal temperature (T_{re}) and were clothed in only a cycling jersey bib shorts, socks, and shoes. Additional thermocouples (Type T, Omega Engineering, Inc., Stamford, CT) were then taped to the skin at the lateral deltoid, upper chest, quadriceps, and lateral gastrocnemius for measurement of $\overline{T}_{sk}$, according to the following equation:[24]

$$\overline{T}_{sk} = 0.3(T_1 + T_2) + 0.2(T_3 + T_4),$$

where T_1, T_2, T_3, and T_4 are lateral deltoid, upper chest, quadriceps, and lateral gastrocnemius skin temperatures, respectively. Mean body temperature ($\overline{T}_b$) was calculated from $\overline{T}_{sk}$ and T_{re} using the following formula:[17]

$$\overline{T}_b = 0.64 \cdot T_{re} + 0.36 \cdot \overline{T}_{sk}.$$

T_{re} and T_{sk} were monitored and recorded continuously at 50 Hz using a computerized data acquisition system (Biopac MP150, Santa Barbara, CA). After instrumentation with thermocouples, a plastic capsule covering 3.976 cm^2 was taped to the posterior left forearm approximately midway between the wrist and elbow in order to measure local sweat rate using a ventilated-capsule and capacitance hygrometer (Vaisala, Woburn, WA).[26,33] Whole-body sweat rate was estimated by measuring the semi-nude body mass change to the nearest 100 g. Pre-exercise body mass was measured after the subjects ingested their assigned amounts of fluid/ice-slurry and voided their bladders before they started the time trial. Postexercise body mass was measured immediately after finishing the time trial, then urine was collected for USG measurements.

For all treatments, baseline temperature and HR measurements were recorded over 10–15 min inside an environmental chamber set at 33°C, 40% relative humidity. For PREC, subjects then ingested 4 $g \cdot kg^{-1}$ body mass of carbohydrate-electrolyte beverage at 10°C over the course of 20 min, followed by ingesting 14 $g \cdot kg^{-1}$ of ice-slurry in two boluses over the course of 30 min (one bolus every 15 min).[25] During the slurry ingestion, subjects wore an ice vest (World Endurance Sports LLC, Tampa, FL) over the cycling jersey, and Elasto-Gel ice wraps (Southwest Technologies, Inc., North Kansas City, MO) were placed around the head, neck, and both legs at the level of the quadriceps.

For WU, after baseline measurements subjects ingested 14 $g \cdot kg^{-1}$ of carbohydrate-electrolyte beverage at 10°C over 30 min to match the same volume of fluid ingested during the 30 min of precooling part of PREC. Next, they completed a 20-min warm-up on the cycle ergometer, which consisted of two sets of 3 min at 25% $\dot{V}O_{2max}$, 5 min at 60% $\dot{V}O_{2max}$, and 2 min at 80% $\dot{V}O_{2max}$.[25] During the warm-up, subjects ingested 4 $g \cdot kg^{-1}$ body mass of the carbohydrate-electrolyte beverage at 10°C, matching the volume of fluid ingestion during the 20-min period before precooling in PREC.

For COMBO, the procedures were the same except both the PREC and WU were performed. Ice-slurry was ingested during both the precooling (14 $g \cdot kg^{-1}$ body mass) and warm-up (4 $g \cdot kg^{-1}$ body mass) segments, matching the volume ingested in PREC and WU. Additionally, during precooling and warm-up, an ice vest was worn over the cycling jersey and Elasto-Gel ice wraps were placed around the head, neck, and both legs at the level of the quadriceps in an effort to sustain the effect of precooling. After finishing each treatment, subjects voided their bladders and the ice vest and gel wraps were removed (if applicable), and a 16.1-km time trial was completed as quickly as possible. There was a 5-min transition time between the end of the first segment and the start of the second segment of all treatments. During exercise, a fan was placed in front of the subject at a distance that produced air velocity of 10 km/h.

During the treatments, T_{re}, $\overline{T}_{sk}$, $\overline{T}_b$, local sweat rate, and HR were recorded continuously. The simulated 16.1-km time trial was divided into four intervals of 4 km each. At the end of each interval, rating of perceived exertion (RPE), rating of thermal comfort (RTC),[29] average power output, and completion time were recorded. Experimental trials were separated by 48–72 h.

Statistical Analysis

Data are presented as mean ± SD. Data collected during exercise were averaged every 4 km. A one-way repeated measures analysis of variance (ANOVA) was used to test the significance of mean differences among the treatment conditions for time to complete the simulated time trial. For other outcomes, such as temperature measures and HR, two-way (treatment × distance) repeated measures ANOVAs were performed. In the event of significant omnibus tests, paired samples *t*-tests with a Bonferroni-adjusted alpha level to control experiment-wise error rate were performed to determine individual differences. For analyses in which the sphericity assumption was violated, the Greenhouse-Geisser adjustment to degrees of freedom was used. Data were analyzed using SPSS v. 19.0 (SPSS, Inc., Chicago, IL) and all hypothesis tests used an α level of 0.05. Effect sizes (Cohen's d) were also calculated and classified as trivial (< 0.02), small (0.2–0.6), moderate (0.6–1.2), large (1.2–2.0), and very large (>2.0).[7]

RESULTS

As expected, ambient temperatures were not different among experimental trials (33.9 ± 0.1°C, 33.8 ± 0.1°C, and 33.8 ± 0.1°C for PREC, COMBO, and WU, respectively) [$F(2, 16) = 0.6$, $P = 0.56$]. After fluid and ice-slurry ingestion, pre-exercise USG was significantly lower in WU (1.007 ± 0.005) than PREC (1.015 ± 0.008) and COMBO (1.015 ± 0.005) [$F(2, 16) = 12.5$; $P = 0.001$]. Postexercise USG was not different among treatments [1.011 ± 0.007; 1.006 ± 0.003; and 1.005 ± 0.002 for COMBO, WU, and PREC, respectively; $F(2, 16) = 3.3$; $P = 0.06$]. Body mass was not different among trials prior to treatment administration [PREC = 73.5 ± 3.7 kg; COMBO = 73.3 ± 3.5 kg; WU = 73.5 ± 3.5 kg; $F(2, 14) = 1.2$, $P = 0.3$]. Fluid and ice-slurry ingestion prior to exercise caused a gain in body mass in all treatments, but treatments were not different [PREC = 1.2 ± 0.3 kg, COMBO = 1.1 ± 0.3 kg, WU = 0.9 ± 0.3 kg; $F(2, 16) = 1.9$, $P = 0.17$]. Furthermore, exercise resulted in comparable decreases in body mass across treatments [PREC = −0.6 ± 0.1 kg; COMBO = −0.5 ± 0.2 kg; WU = −0.6 ± 0.3 kg; $F(2, 14) = 0.01$, $P = 0.9$].

As shown in **Table I**, time to complete each 4-km interval was not different among treatments [$F(1.11, 8.89) = 0.84$; $P = 0.40$ for treatment × 4-km interval interaction]. There was a main effect of treatment, but post hoc comparisons did not reveal any differences between individual treatments (all $P > 0.05$). Likewise, the one-way ANOVA comparing total performance time indicated a significant omnibus test [$F(2, 16) = 4.1$, $P = 0.04$; PREC = 3.19 ± 1.9 min, COMBO = 32.6 ± 2.7 min, WU = 33.1 ± 2.9 min], but again, post hoc comparisons did not reveal any differences (all $P > 0.05$). The results of these post hoc comparisons are consistent with the small effect sizes comparing treatments. For instance, the effect of PREC on time to completion was small compared to COMBO (d = 0.3) and WU (d = 0.5), and was small (d = 0.2) when comparing COMBO to WU. There was a trend of reduced power output over time until the final interval in each treatment, but there

Table I. Performance Time, Average Power Output, and Perceptual Responses During Each 4-km Interval of a 16.1-km Cycling Time Trial After Precooling, Warm-Up, and a Combination of Both (Mean ± SD) ($N = 9$).

TREATMENT & VARIABLE	DISTANCE (km)				
	BASELINE	0–4	4–8	8–12	12–16.1
PREC					
Time (min)	—	7.9 ± 0.4	7.9 ± 0.5	8.0 ± 0.6	7.9 ± 0.7
PO (W)	—	165 ± 18	163 ± 19	161 ± 20	162 ± 22
RPE	8 ± 3	12 ± 1*	14 ± 1*	16 ± 1*	17 ± 2*
RTC	3 ± 1†	4 ± 1*†§	5 ± 1*†§	6 ± 1*	6 ± 1*
WU					
Time (min)	—	8.0 ± 0.7	8.2 ± 0.8	8.0 ± 0.9	8.6 ± 2.0
PO (W)	—	160 ± 32	154 ± 29	150 ± 27	152 ± 27
RPE	7 ± 2	13 ± 1*	15 ± 2*	16 ± 1*	18 ± 1*
RTC	4 ± 1	5 ± 1*	6 ± 0*	6 ± 1*	7 ± 1*
COMBO					
Time (min)	—	8.1 ± 0.8	8.2 ± 0.8	8.3 ± 0.8	8.0 ± 0.7
PO (W)	—	159 ± 27	154 ± 26	152 ± 26	154 ± 26
RPE	7 ± 1	13 ± 1*	15 ± 1*	16 ± 1*	17 ± 2*
RTC	3 ± 1†	5 ± 1*	6 ± 1*	6 ± 1*	6 ± 1*

PREC = precooling treatment; WU = warm-up treatment; COMBO = combination treatment; PO = power output; RPE = rating of perceived exertion; RTC = rating of thermal comfort. *$P < 0.05$ vs. baseline, $^{\dagger}P < 0.05$ vs. WU, $^{§}P < 0.05$ vs. COMBO.

was no treatment × 4-km interval interaction [Table I; $F(6, 48) = 0.75$, $P = 0.6$]. For all 4-km intervals, the effect of PREC on power output was small (d = 0.20–0.46) compared to WU and COMBO, and trivial between WU and COMBO (d = 0.03–0.08).

Not surprisingly, baseline HR was lower after PREC than after COMBO [$t(8) = -9.1$; d = 3.01] and WU [$t(8) = -12.5$; d = 3.70] ($P < 0.005$ for both), since PREC did not involve any exercise during treatment administration (**Fig. 1**). The addition of precooling to warm-up (COMBO) did not attenuate the elevation of HR during WU [$t(8) = 1.05$; $P = 0.32$; d = 0.48]. The effect of PREC on HR ranged from moderate (d = 1.03) to small (d = 0.21) from the first to the last 4-km interval compared to WU and COMBO. Averaged across all intervals, HR was lower during PREC than during COMBO and WU [161 ± 14 vs. 167 ± 13 and 168 ± 15 bpm, respectively; $F(2, 70) = 3.7$; $P = 0.03$], but upon further inspection, differences in HR among treatments can be attributed to baseline differences that persisted during the first 4 km and do not appear to be of any practical significance.

Table I shows that like HR, RTC was lower at baseline after PREC and COMBO compared to WU [$t(8) = -6.8$, $P < 0.005$; d = 2.19 and $t(8) = 5.3$, $P < 0.005$; d = 1.70 for PREC vs. WU and COMBO vs. WU, respectively]. Values increased over time but remained lower in PREC compared to the other treatments (d > 1.20) until the second 4-km interval (d = 0.88–0.92), after which point treatments were not different. RPE values at baseline and throughout exercise were not different among treatments (all $P > 0.05$; all d = trivial to small).

As shown in **Fig. 2**, **Fig. 3**, and **Fig. 4**, before treatment administration, T_{re}, $\overline{T}_{sk}$, and $\overline{T}_b$ were not different across treatments (all $P > 0.05$). The precooling segment of COMBO and PREC resulted in lower T_{re}, $\overline{T}_{sk}$, and $\overline{T}_b$ than WU at the end of the treatments, despite the slight temperature increase that occurred during the warm-up segment of COMBO ($P < 0.005$ and d > 2.0 comparing COMBO and PREC to WU for all three variables). Additionally, PREC resulted in lower $\overline{T}_b$ and $\overline{T}_{sk}$ than COMBO [$t(8) = -6.1$, $t(8) = -3.8$; both $P < 0.005$; d = 2.15 and 2.74 for $\overline{T}_b$ and $\overline{T}_{sk}$, respectively). As expected, WU resulted in increases in all three temperature parameters relative to baseline. While the ice-slurry and ice-vest resulted in lower temperatures at the end of treatment and early in exercise in PREC and COMBO, the differences among treatments for the three temperature parameters narrowed as the exercise progressed. The effect sizes for T_{re} comparing PREC to WU and COMBO remained large-to-very large until 12 km. For $\overline{T}_{sk}$, effects for PREC and COMBO compared to WU ranged from large to very large until the second 4-km interval, and decreased to trivial thereafter.

Fig. 5 shows local sweat rate was essentially negligible during the first 40 min of treatment administration. During the warm-up phase of WU, local sweat rate increased and remained higher than both PREC [$t(8) = -9.03$, $P < 0.001$; d = 4.3] and COMBO [$t(8) = -3.7$, $P = 0.003$; d = 1.7] until the start of the time trial. Local sweat rate also was higher during COMBO than PREC [$t(8) = -2.9$, $P = 0.01$; d = 1.3] at the start of the time trial. During exercise, local sweat rate remained higher in COMBO [$t(8) = -5.9$, $P < 0.001$; d = 2.4] and WU [$t(8) = 6.4$, $P < 0.001$; d = 2.9] than PREC for the first 4 km, but thereafter treatments were not different (all $P > 0.05$). Likewise, whole-body sweat rate was not different among treatments [$1.1 \pm 0.2\ L \cdot h^{-1}$, $1.0 \pm 0.3\ L \cdot h^{-1}$, and $1.1 \pm 0.6\ L \cdot h^{-1}$ for PREC, COMBO, and WU, respectively; $F(2, 16) = 0.1$, $P = 0.9$].

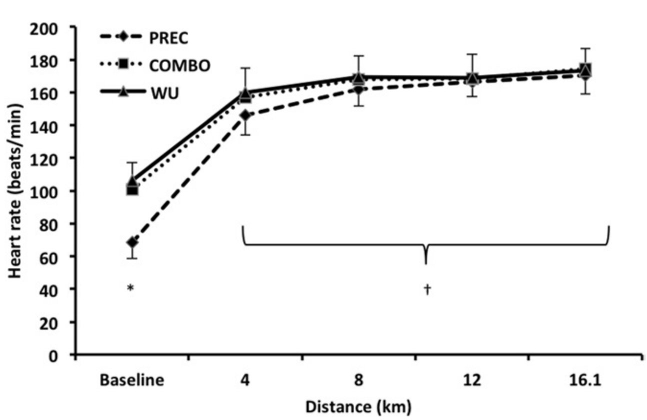

Fig. 1. Average heart rate responses (mean ± SD) every 4 km during completion of a 16.1-km cycling time trial after precooling (PREC), warm-up alone (WU), and a combination of warm-up with cooling (COMBO). SD bars for COMBO have been omitted for clarity. Baseline = time point after treatment administration just prior to the start of exercise. *$P < 0.001$ vs. COMBO and WU ($N = 9$). $^{\dagger}P = 0.03$ for the main effect of treatment on average heart rate across all intervals.

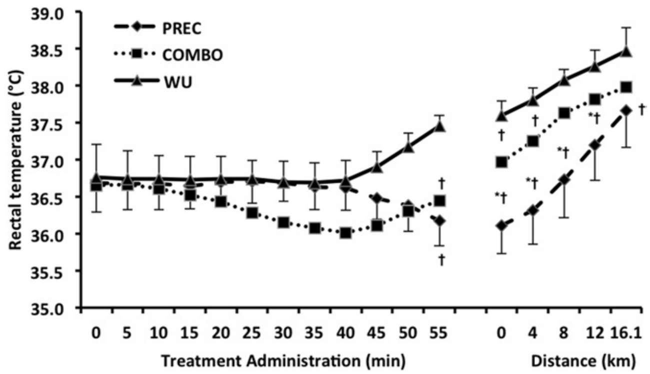

Fig. 2. Rectal temperature responses (mean ± SD) over time during precooling (PREC), warm-up alone (WU), and a combination of warm-up with cooling (COMBO), and then averaged every 4 km during completion of a 16.1-km cycling time trial. SD bars for COMBO have been omitted for clarity. *$P < 0.005$ vs. COMBO; †$P < 0.005$ vs. WU ($N = 9$).

DISCUSSION

The primary finding of the present study was that, contrary to our hypothesis, COMBO did not result in a faster cycling time trial performance, whether expressed as overall time or as time to complete each 4-km segment of the total 16.1-km distance. Despite no effect on performance, PREC and COMBO attenuated thermoregulatory strain during exercise.

The present findings regarding PREC are in contrast to some studies which have shown significant improvements in performance following ice-slurry ingestion.[12,25,34] Differences in subjects and methodology probably explain the discrepant results. For example, consumption of 14 g of ice-slurry per kg of body mass while applying iced towels improved cycling time trial performance in the heat by 1.3% compared to consumption of cold water.[25] Fluid and carbohydrate intake before and during exercise was not standardized, whereas in the present study, the volume of fluid ingestion was consistent across treatments. Furthermore, the exercise used in the Ross et al.[25] study covered ~46 km and was performed by highly trained cyclists with an average $\dot{V}O_{2max}$ of 71.6 $mL \cdot kg^{-1} \cdot min^{-1}$. In the present study, the distance covered was ~65% shorter and the subjects were recreationally active with an ~40% lower average $\dot{V}O_{2max}$. In another study, ice-slurry ingestion, compared with warmer fluid, improved 40-km cycling[12] and 10-km outdoor running time trial performances,[34] which required, on average, 45 min to complete. Regarding shorter distances, Levels et al. found no effect on performance of a 15-km cycling time trial after ice ingestion precooling[18] and Byrne found no effect of pre-exercise cold flavored water ingestion on a 30-min self-paced cycling time trial compared with a warmer control fluid.[5] The volume of exercise in the two studies mentioned above was comparable with the volume of exercise used in our study (15 km and 30 min compared to 16.1 km and ~32 min, respectively), and effects on performance were also comparable. Taken together, the studies discussed above and the present results suggest that ice-slurry may be efficacious for events of longer distances, and the overall exercise-heat stress (function of intensity and distance/duration) may require a minimal threshold in order for precooling to be effective.

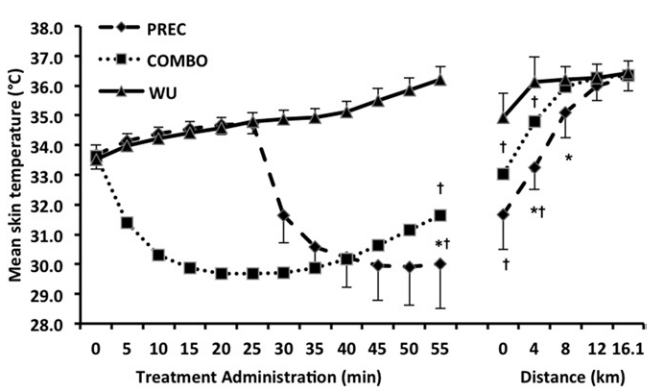

Fig. 3. Mean skin temperature responses (mean ± SD) over time during precooling (PREC), warm-up alone (WU), and a combination of warm-up with cooling (COMBO), and then averaged every 4 km during completion of a 16.1-km cycling time trial. SD bars for COMBO have been omitted for clarity. *$P < 0.005$ vs. COMBO; †$P < 0.005$ vs. WU ($N = 9$).

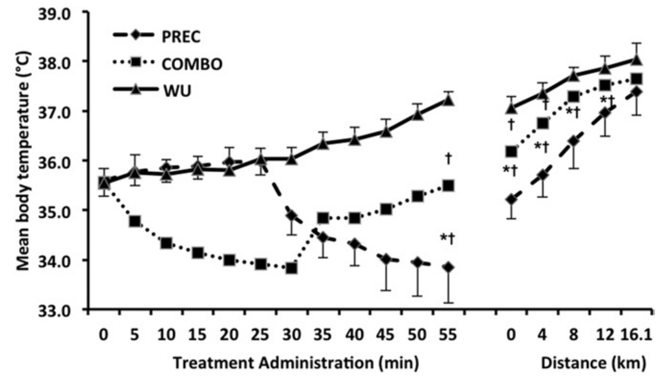

Fig. 4. Mean body temperature responses (mean ± SD) over time during precooling (PREC), warm-up alone (WU), and a combination of warm-up with cooling (COMBO), and then averaged every 4 km during completion of a 16.1-km cycling time trial. SD bars for COMBO have been omitted for clarity. *$P < 0.005$ vs. COMBO; †$P < 0.005$ vs. WU ($N = 9$).

The self-paced exercise performed in the current study does not reflect anticipatory regulation and avoidance (i.e., work rate is reduced through attenuated central drive to the skeletal muscles)[20] in order to avoid achieving a high critical T_c.[27] Power output was not reduced over time and interval times were not different across treatments. This implies that for the selected exercise distance and environmental conditions, the rate of heat storage did not mediate a work rate reduction. Similarly, power output was maintained for the first 18–25 min of 20–30 min of self-paced cycling in the heat (~30–32°C, 60–78% relative humidity).[5,10] On the other hand, during longer durations (20–40 km) of cycling time trials in higher heat stress (35°C, 60% relative humidity), power output started to decrease from 15 min or 30% of exercise duration onwards, while it was maintained throughout exercise during cool or thermoneutral trials.[22,30] It has been noted that when power output was maintained, T_c peaked around 38.5°C or less.[5,10] Conversely, significant declines in power output have been observed when T_c exceeds 38.5°C.[22,30] These findings are consistent with the present study in which the maximal T_{re} achieved during all treatments was less than 38.5°C, and the power output was maintained

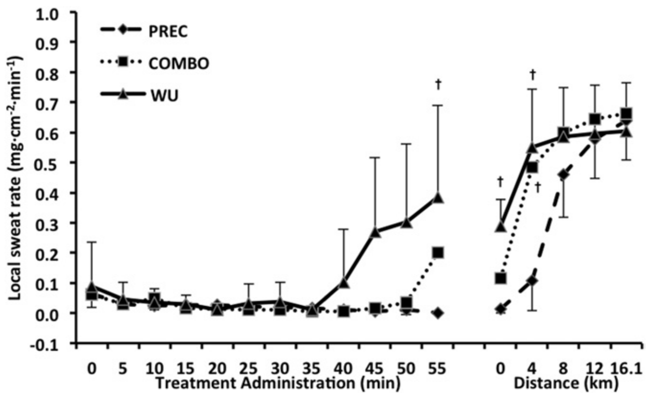

Fig. 5. Local sweat rate responses (mean ± SD) over time during precooling (PREC), warm-up alone (WU), and a combination of warm-up with cooling (COMBO), and then averaged every 4 km during completion of a 16.1-km cycling time trial. SD bars for COMBO have been omitted for clarity. $^{\dagger}P < 0.005$ vs. PREC ($N = 9$).

throughout all trials. Tyler et al.[31] reported that the effectiveness of cooling interventions, either prior to or during exercise, is dependent on the thermal strain experienced. It may be that anticipatory regulation only takes place if the thermal stress crosses a temperature threshold; however, this needs further study to be fully substantiated.

In regards to the combined effect of precooling and warm-up on cycling performance in the heat, our findings are difficult to compare to those of other studies because previous studies in this area either: 1) did not include a warm-up session following the precooling treatment;[5,12,16,28] 2) compared precooling and warm-up separately;[18,32] or 3) added a warm-up segment after all precooling treatments so the combination effect of precooling and warm-up was not investigated.[25,34] Nonetheless, in two studies that used simultaneous cooling and warm-up in the heat, one resulted in improved 5-km running performance,[1] while we previously reported no changes in 16.1-km cycling time trial performance after precooling (ice vest and/or gel wraps) during warm-up.[14] Core body temperature was not decreased below baseline at the start of exercise in either study, and no comparisons between precooling alone and the combination of precooling and warm-up were made.

The COMBO treatment of the present study was intended to elevate muscle temperature while blunting a concomitant increase in T_c. We speculate that the 20-min warm-up performed during the protocol of this study increased muscle temperature 2.5°C or more, since muscle temperature was raised 2.5°C from baseline at all depths during an intermittent warm-up for 15 min in another study.[9] The effectiveness of COMBO treatment in mitigating a rise in T_c was evident since T_{re} remained blunted during a segment of the exercise. Thus, we speculate that COMBO treatment successfully elicited the desired outcomes of elevated muscle temperature and attenuated T_c. Nonetheless, these outcomes did not result in greater performance than either treatment alone for the selected cycling distance in this recreationally active subject population.

Despite the lack of a difference in performance among treatments, body temperatures remained lower in PREC and COMBO compared to WU during various segments of the exercise. This indicates that the PREC and COMBO treatments successfully blunted thermal strain, especially early in exercise, which may have positively impacted performance had the exercise been protracted.

The magnitude of the effect of PREC on T_{re} and $\overline{T}_{sk}$ is likely the result of both the ice-slurry ingestion and the cooling vest/gel packs applied to the skin. Previous studies using external cooling (other than water immersion) without simultaneous internal cooling (ice-slurry) showed reduced skin temperature, but not core temperature.[1,14] Likewise, in another investigation, internal cooling interventions induced lower core temperature, without changing skin temperature.[28] This suggests the optimal precooling strategy may involve both internal and external methods since the combination of elevated core and skin temperatures has been shown to negatively impact aerobic exercise performance.[6] Indeed, cooling techniques that induce lower $\overline{T}_{sk}$ combined with lower T_c at the initiation of exercise maintained lower T_c for a longer duration during subsequent exercise.[8,16]

This observation of reduced local sweat rate after PREC might be explained by the temperature-dependent effect of fluid ingestion on the abdominal sudomotor receptors.[21] Morris et al.[21] found that while core and skin temperatures were similar among treatments, local sweating was inhibited with cold fluid (1.5°C) ingestion and increased with hot fluid (50°C) ingestion before and after 15, 30, and 45 min of exercise commencement. In the present study, this effect can be seen in the PREC trial where the suppressing effect of the ice slurry on sudomotor responses was transiently sustained.

As previously mentioned, recreationally active individuals, like elite athletes, often engage in what they perceive to be ergogenic training and competition practices, so it was important to test the hypotheses on this population. Based on the findings, the cooling interventions did not impact performance in this population, despite attenuation of thermoregulatory strain. We speculate that if endurance trained athletes had been studied instead, PREC and COMBO would have had a greater impact on thermoregulatory strain since endurance athletes manage their pace differently, exercise at a higher absolute intensity during competition, and thereby produce greater metabolic heat than nontrained individuals. These findings underscore the importance of testing potential ergogenic aids on the actual populations who are using them for enhanced ecological validity.

A possible limitation of this study was that with only one familiarization session, subjects could have experienced a learning effect as they progressed through the experimental trials. The reproducibility of cycling time trial performance was previously tested on competitive cyclists during three repeat bouts. Investigators found that performance time for the first trial was significantly longer than that for the second and third trials.[35] In the present study, regardless of the treatment, the completion time was not different among the first, second, and third trials. Nonetheless, there was a nonsignificant improvement in mean completion time of the third trial compared to the first and second trials, so it is possible there was a small familiarization and/or learning effect; however, the counterbalanced order should have minimized any potential effect of familiarization on the tests of our hypotheses.

Despite no statistical differences for performance time, the average time trial after PREC was on average 3.4% faster than that after WU and 2% faster than that after COMBO. This may have practical significance given that performances are often decided by a smaller margin. Given these findings, one might question the efficacy of warm-up before a short-distance cycling time trial and instead focus on precooling.

Precooling, warm-up, and combining the two did not differentially affect 16.1-km cycling time trial performance of recreationally active subjects. Nonetheless, thermoregulatory strain was lower after the treatments involving precooling compared to warm-up alone. Future studies should determine the effects of these treatments on performance of cycling events involving longer distances and heat exposure.

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REFERENCES

1. Arngrïmsson SA, Petitt DS, Stueck MG, Jorgensen DK, Cureton KJ. Cooling vest worn during active warm-up improves 5-km run performance in the heat. J Appl Physiol. 2004; 96(5):1867–1874.
2. Bergh U, Ekblom B. Physical performance and peak aerobic power at different body temperatures. J Appl Physiol. 1979; 46:885–889.
3. Bishop D. Warm up II: performance changes following active warm up and how to structure the warm up. Sports Med. 2003; 33(7):483–498.
4. Booth J, Marino F, Ward JJ. Improved running performance in hot humid conditions following whole body precooling. Med Sci Sports Exerc. 1997; 29(7):943–949.
5. Byrne C, Owen C, Cosnefroy A, Lee JKW. Self-paced exercise performance in the heat after pre-exercise cold-fluid ingestion. J Athl Train. 2011; 46(6):592–599.
6. Cheuvront SN, Kenefick RW, Montain SJ, Sawka MN. Mechanisms of aerobic performance impairment with heat stress and dehydration. J Appl Physiol. 2010; 109(6):1989–1995.
7. Cohen J. A power primer. Psychol Bull. 1992; 112(1):155–159.
8. Duffield R, Green R, Castle P, Maxwell N. Precooling can prevent the reduction of self-paced exercise intensity in the heat. Med Sci Sports Exerc. 2010; 42(3):577–584.
9. Faulkner SH, Ferguson RA, Gerrett N, Hupperets M, Hodder SG, Havenith G. Reducing muscle temperature drop after warm-up improves sprint cycling performance. Med Sci Sports Exerc. 2013; 45(2):359–365.
10. Gonzales BR, Hagin V, Guillot R, Placet V, Monnier-Benoit P, Groslambert A. Self-paced cycling performance and recovery under a hot and highly humid environment after cooling. J Sports Med Phys Fitness. 2014; 54:43–52.
11. Hessemer V, Brück K. Influence of menstrual cycle on thermoregulatory, metabolic, and heart rate responses to exercise at night. J Appl Physiol. 1985; 59:1911–1917.
12. Ihsan M, Landers G, Brearley M, Peeling P. Beneficial effects of ice ingestion as a precooling strategy on 40-km cycling time-trial performance. Int J Sports Physiol Perform. 2010; 5(2):140–151.
13. Jackson AS, Pollock ML. Generalized equations for predicting body density of men. 1978. Br J Nutr. 2004; 91:161–168.
14. Katica CP, Wingo JE, Herron RL, Ryan GA, Bishop SH, Richardson M. Impact of upper body precooling during warm-up on subsequent time trial paced cycling in the heat. J Sci Med Sport. 2017. pii: S1440-2440(17)31657-2.
15. Kavouras SA. Assessing hydration status. Curr Opin Clin Nutr Metab Care. 2002; 5(5):519–524.
16. Kay D, Taaffe DR, Marino FE. Whole-body pre-cooling and heat storage during self-paced cycling performance in warm humid conditions. J Sports Sci. 1999; 17(12):937–944.
17. Lenhardt R, Sessler D. Estimation of mean-body temperature from mean-skin and core temperature. Anesthesiology. 2006; 105(6):1117–1121.
18. Levels K, Teunissen LPJ, de Haan A, de Koning JJ, van Os B, Daanen H AM. Effect of warm-up and precooling on pacing during a 15-km cycling time trial in the heat. Int J Sports Physiol Perform. 2013; 8(3):307–311.
19. Marino FE. Methods, advantages, and limitations of body cooling for exercise performance. Br J Sports Med. 2002; 36(2):89–94.
20. Marino FE. Anticipatory regulation and avoidance of catastrophe during exercise-induced hyperthermia. Comp Biochem Physiol B Biochem Mol Biol. 2004; 139(4):561–569.
21. Morris NB, Bain AR, Cramer MN, Jay O. Evidence that transient changes in sudomotor output with cold and warm fluid ingestion are independently modulated by abdominal, but not oral thermoreceptors. J Appl Physiol. 2014; 116(8):1088–1095.
22. Périard JD, Cramer MN, Chapman PG, Caillaud C, Thompson MW. Cardiovascular strain impairs prolonged self-paced exercise in the heat. Exp Physiol. 2011; 96(2):134–144.
23. Potvin PJ, Schutz RW. Statistical power for the two-factor repeated measures ANOVA. Behav Res Methods Instrum Comput. 2000; 32(2): 347–356.
24. Ramanathan NL. A new weighting system for mean surface temperature of the human body. J Appl Physiol. 1964; 19:531–533.
25. Ross MLR, Garvican LA, Jeacocke NA, Laursen PB, Abbiss CR, et al. Novel precooling strategy enhances time trial cycling in the heat. Med Sci Sports Exerc. 2011; 43(1):123–133.
26. Schlader ZJ, Gagnon D, Lucas RAI, Pearson J, Crandall CG. Baroreceptor unloading does not limit forearm sweat rate during severe passive heat stress. J Appl Physiol. 2015; 118(4):449–454.
27. Schlader ZJ, Stannard SR, Mündel T. Exercise and heat stress: performance, fatigue and exhaustion–a hot topic. Br J Sports Med. 2011; 45(1):3–5.
28. Siegel R, Maté J, Watson G, Nosaka K, Laursen PB. Pre-cooling with ice slurry ingestion leads to similar run times to exhaustion in the heat as cold water immersion. J Sports Sci. 2012; 30(2):155–165.
29. Toner MM, Drolet LL, Pandolf KB. Perceptual and physiological responses during exercise in cool and cold water. Percept Mot Skills. 1986; 62(1):211–220.
30. Tucker R, Rauch L, Harley YXR, Noakes TD. Impaired exercise performance in the heat is associated with an anticipatory reduction in skeletal muscle recruitment. Pflugers Arch. 2004; 448(4):422–430.
31. Tyler CJ, Sunderland C, Cheung SS. The effect of cooling prior to and during exercise on exercise performance and capacity in the heat: a meta-analysis. Br J Sports Med. 2015; 49(1):7–13.
32. Uckert S, Joch W. Effects of warm-up and precooling on endurance performance in the heat. Br J Sports Med. 2007; 41(6):380–384.
33. Wingo JE, Low DA, Keller DM, Brothers RM, Shibasaki M, Crandall CG. Skin blood flow and local temperature independently modify sweat rate during passive heat stress in humans. J Appl Physiol. 2010; 109(5):1301–1306.
34. Yeo ZW, Fan PWP, Nio AQ, Byrne C, Lee JK. Ice slurry on outdoor running performance in heat. Int J Sports Med. 2012; 33(11):859–866.
35. Zavorsky GS, Murias JM, Gow J, Kim DJ, Poulin-Harnois C, et al. Laboratory 20-km cycle time trial reproducibility. Int J Sports Med. 2007; 28(9):743–748.