Exertional heat illness (EHI) remains a problem for American football players. Among secondary school athletes, American football players had the highest rate of EHI versus all other sports combined. Other recent epidemiologic data suggested collegiate football players may have a higher risk of EHI than both youth American football and high school American football players. The most serious EHI, exertional heatstroke (EHS), remains one of the leading causes of death in American football players; between 2005 and 2015, EHS was responsible for 36 documented fatalities in American football players.

American football players are a population especially prone to EHI. American football is a high-intensity sport that typically begins in the hottest part of the year (ie, August in the Northern Hemisphere). American football athletes, many of whom are physically large, are exposed to numerous EHI risk factors, such as a sudden increase in the intensity and duration of physical training in the summer, longer exposures to heat, poor heat acclimatization, and sleep deprivation during the competitive season. Moreover, American football uniforms cover approximately 70% of the body’s surface area, which reduces an athlete’s ability to dissipate environmental heat stress via evaporation. For these reasons, it is imperative that clinicians use evidence-based EHI-prevention strategies in American football.

Current EHI-prevention strategies include gradual heat acclimatization over the course of 7 to 14 days, maintaining adequate hydration during physical activity, incorporating proper work:rest ratios for exercise in the heat, and emergency preparedness. Lowering body core temperature before exercise, termed precooling (PC), with whole-body cold-water immersion (CWI) may also be an effective strategy to prevent EHS or severe hyperthermia. Precooling reduces body core temperature and improves body heat dissipation.
storage (H₂) capacity,8–10 enhances core-to-skin temperature gradients,11 and delays the onset of hyperthermia-induced fatigue.12 However, PC may have other physiological effects that could predispose athletes to EHI. For example, PC can induce vasoconstriction of cutaneous blood vessels, reduce sweat rate and skin temperature, and delay the onset of sweating by reducing body core temperature.13,14 Perceptually, PC could alter thermal comfort and thermal sensation before exercise, which may affect how hot an athlete feels during exercise or lead to the underreporting of EHI symptoms or signs (or both). Finally, some of these effects (eg, delayed sweating, cutaneous vasoconstriction, increased H₂) could alter body heat transfer, which could modify CWI cooling rates if an athlete needed emergency cooling. Therefore, before clinicians can recommend PC as an EHI-prevention strategy for American football players, clarity is needed as to whether PC affects perceptual variables related to EHI (eg, thermal sensation, environmental symptoms questionnaire [ESQ] responses) and CWI rectal temperature (Trec) cooling rates after participants become hyperthermic.

The purpose of our study was 3-fold. First, we examined how long PC delayed the onset of severe hyperthermia when participants wore American football uniforms during exercise in the heat. Second, we investigated whether PC affected Trec cooling rates after participants became hyperthermic. Third, we determined if PC affected perceptual variables such as the rating of perceived exertion (RPE), thermal sensation, and ESQ responses. We hypothesized that PC would delay hyperthermia by at least 15 minutes, postexercise CWI cooling rates would be higher with PC due to higher H₂ during exercise,15 and PC would lower RPE, thermal sensation, and ESQ responses.

METHODS

Participants

A convenience sample of 15 healthy, physically active males volunteered for testing; 3 participants were excluded because they could not tolerate the exercise protocol. Twelve men completed this randomized, crossover, counterbalanced study (Table 1). Participants were excluded from the study if they self-reported any of the following: (1) an injury that prevented them from exercising; (2) a genetic, neurologic, respiratory, gastrointestinal, or cardiovascular disease; (3) a family history of sudden cardiac death, sudden infant death syndrome, or heart abnormality identified on an electrocardiogram; (4) taking any medication that affected hydration or temperature regulation (eg, diuretic, amphetamine); (5) exercising for <30 minutes at least 3 times per week; or (6) a serious heat-related illness in the 6 months preceding data collection. Our institutional review board approved all procedures, and participants provided written informed consent before testing.

Procedures

Participants reported to the sports medicine laboratory on 2 days separated by at least 48 hours. We instructed them to avoid exercise, caffeine, and alcohol consumption for 24 hours before testing; maintain a consistent diet; drink water regularly throughout the day before and day of testing; and fast for 2 hours before testing. Participants self-reported compliance before testing each day.

On testing days, participants emptied their bladders completely. We examined their urine with a refractometer (model SUR-Ne; Atago USA Inc, Bellevue, WA) to determine if they were euhydrated (urine specific gravity <1.02). If hypohydrated, they were excused and rescheduled for a testing date at least 48 hours later. If euhydrated, we measured skinfold thicknesses at 3 sites: midquadiceps, abdomen, and chest. Participants were weighed nude to the nearest 0.1 kg (model Defender 5000; Ohaus Corp, Parsippany, NJ) and self-inserted a flexible thermistor (model 401 thermistor with YSI 4600 Precision Thermometer; Advanced Industrial Systems Inc, Prospect, KY) 15 cm past the anal sphincter. Each person donned a heart-rate (HR) monitor (Polar Electro, Lake Success, NY) across the chest and dressed in a T-shirt, undergarments, shorts, and socks.

On the PC day, they entered an environmental chamber (temperature = 39.1°C ± 0.3°C, relative humidity = 36% ± 2%), and we recorded resting Trec, thermal sensation, and ESQ responses. Then participants immersed themselves up to the neck in water (temperature = 9.98°C ± 0.04°C) for 15 minutes. We stirred the water every 2 minutes and asked them to self-report if and when they started to shiver. After PC, participants were given 10 minutes to dry themselves and change into a full American football uniform (PADS). Briefly, PADS consisted of shoes; socks; undergarments; athletic shorts; three-quarter length pants with hip, knee, tailbone, and thigh padding; a T-shirt; shoulder pads; mesh jersey; and helmet. For a complete description of PADS, we direct the reader to our prior work.16 At the end of the 10-minute period, we recorded Trec, RPE, thermal sensation, and ESQ responses.

Participants completed successive 5-minute exercise bouts with no rest between bouts until Trec reached 39.5°C. For the first 3 minutes of each 5-minute bout, participants walked on a treadmill (model 1850; Proform Performance, Logan, UT) at 4.8 km/h (3 mph). Then they ran at approximately 90% of their age-predicted maximum HR for 2 minutes. This protocol was meant to simulate the brief but high-intensity nature of American football while ensuring that participants’ Trec increased at rates comparable with those of other studies examining American football equipment.5,16,17 Heart rate was recorded every 5 minutes during exercise, and thermal sensation and RPE were recorded every 10 minutes. Once Trec reached 39.5°C, participants completed an ESQ and rated their thermal sensation. Then they removed their shoes and entered a water bath (model 4247 noncirculating 1135.6-L tub; Rubbermaid, Atlanta, GA; Table 1) while fully equipped in PADS because wearing PADS during CWI does not impair Trec cooling.16

We started a standard stopwatch as soon as participants’ feet touched the water. They were cooled until their Trec decreased to 38°C. The water bath was stirred every 2 minutes and participants self-reported if and when they started shivering. The time required to cool participants’ Trec to 38°C was recorded. Participants exited the water bath, rated their thermal sensation, and answered the ESQ a fourth time.

Participants sat in the heat for 15 minutes to recover. Then they exited the environmental chamber, removed
PADS, dried themselves fully, and removed the rectal thermistor. They were weighed nude a second time and excused. No fluids were given to participants at any time during the protocol.

The control (CON)-day procedures were the same as the PC day with 2 exceptions. First, there was no 15-minute PC intervention before exercise. Second, participants dressed in PADS before entering the environmental chamber and stood on a treadmill for 10 minutes before starting exercise.

Statistical Analysis

We calculated means and standard deviations. Data were assessed for skewness, kurtosis, and omnibus normality to ensure normal distribution. Separate dependent $t$ tests were used to determine if differences existed between conditions for CW1 $T_{rec}$ cooling rates, percentages of hypohydration, sweat rates, exercise durations, overall $H_S$ rates, and CW1 durations. Cold-water immersion $T_{rec}$ cooling rates were calculated from CW1 durations. Body $H_S$ was calculated using body mass (BM), change ($\Delta$) in $T_{rec}$, and body surface area (BSA) $^{18}$:

$$H_S = 0.965 \cdot BM \cdot \Delta T_{rec}/BSA.$$ 

Separate repeated-measures analyses of variance were used to determine if differences existed in $T_{rec}$, $H_S$, HR, RPE, or thermal sensation existed between conditions over time. When interactions were significant, we conducted Tukey-Kramer post hoc tests to identify differences between conditions at each time point. Sphericity was assessed with the Mauchly test. Geisser-Greenhouse adjustments to $P$ values and degrees of freedom were made when sphericity was violated. We used Pearson correlation coefficients to determine if body anthropomorphic values were associated with $T_{rec}$ afterdrop.

We did not examine simple main effects (eg, time) statistically, as these values did not address our research questions. Moreover, given that differences between and within participants existed for several variables between testing days (eg, exercise and cooling times), we statistically analyzed data common to all participants on each day. Significance was accepted when $P < .05$ (version 2007; Number Cruncher Statistical Software, Kaysville, UT).

RESULTS

Pretest hydration and water-bath temperatures were consistent each day (Table 1). Precooling lowered participants’ $T_{rec}$ by $0.5 \pm 0.4 ^\circ C$ by the start of exercise (Cohen d effect size $[ES] = 2.4$). Consequently, $H_S$ differed between conditions over time ($F_{2,24} = 15.8$, $P < .001$; Figure 1). Body $H_S$ before exercise and at 10 minutes into exercise was statistically lower in the PC condition ($P < .05$; ESs = 13.3 and 3.5, respectively). Similarly, the overall

**Table 1. Participants’ Demographic and Descriptive Information (Mean ± SD, n = 12)**

| Variable                          | Control Day       | Precooling Day     |
|-----------------------------------|-------------------|--------------------|
| **Demographic measurements**      |                   |                    |
| Age, y                            | 24 ± 4            | 24.0 ± 3.0         |
| Height, cm                        | 181.8 ± 8.4       | 180.0 ± 7.1        |
| Body mass index                   |                   |                    |
| Body mass pre-exercise, kg        | 78.8 ± 10.3       | 79.9 ± 10.3        |
| Body mass postexercise, kg        | 79.9 ± 10.3       | 79.9 ± 10.3        |
| Body density, g·cc$^{-1}$         | 1.07 ± 0.01       | 1.07 ± 0.01        |
| Body fat, %                       | 10.6 ± 3.9        | 10.6 ± 3.9         |
| Body surface area, m²             | 2.0 ± 0.2         | 2.0 ± 0.2          |
| **Hydration measurements**        |                   |                    |
| Pre-exercise urine specific gravity | 1.005 ± 0.004   | 1.005 ± 0.004     |
| Body mass pre-exercise, kg        | 80.1 ± 10.3       | 79.9 ± 10.3        |
| Body mass postexercise, kg        | 78.8 ± 10.3       | 79.9 ± 10.3        |
| Sweat rate, L·ha$^{-1}$           | 1.63 ± 0.54       | 1.32 ± 0.40        |
| Posttesting hypohydration, %      | 1.6 ± 0.6         | 1.8 ± 0.5          |
| **Water-bath temperature, °C**    |                   |                    |
| Before precooling                 | 9.98 ± 0.04       | 9.98 ± 0.04        |
| After precooling                  | 10.78 ± 0.07      | 10.78 ± 0.07       |
| Before postexercise cold-water immersion | 9.99 ± 0.04 | 10.00 ± 0.03     |
| After postexercise cold-water immersion | 10.67 ± 0.19 | 10.71 ± 0.22   |

$^a$ Precooling < control.

$^b$ Precooling > control. Superscripts indicate a difference between conditions ($P < .05$).
H$_S$ rate for the exercise portion of the study also differed between conditions (PC = 1.35 ± 0.29 W-m$^{-2}$-min$^{-1}$, CON = 1.87 ± 0.31 W-m$^{-2}$-min$^{-1}$; $t_{11} = 6.8, P < .001; ES = 0.4$). Participants’ BM index ($r = 0.63, P = .03$), body density ($r = -0.65, P = .02$), and percentage of body fat ($r = 0.65, P = .02$) were correlated with the $T_{rec}$ afterdrop that occurred immediately following the PC protocol. In contrast, BSA was not correlated ($r = 0.09, P = .77$). All participants (100%) self-reported shivering during the PC protocol; the average self-reported shivering onset was 3.3 ± 1.9 minutes.

We observed an interaction between time and condition for $T_{rec}$ during exercise. Although $T_{rec}$ values were comparable at baseline, PC resulted in a persistently lower $T_{rec}$ during exercise ($F_{2,26} = 38.6, P < .001$; Figure 2; ESs ranged from 2.4 to 5.4). Because PC lowered $T_{rec}$, participants exercised for 17.6 ± 3.6 minutes longer before their $T_{rec}$ reached our hyperthermic threshold of 39.5°C ($t_{11} = 17.0, P < .001$; Figure 2; ES = 1.6). Participants were more hypohydrated on PC days ($t_{11} = 2.6, P = .01, ES = 0.3$); however, sweat rates were lower with PC than CON ($t_{11} = 3.9, P = .001, ES = 0.6$; Table 1).

Heart rate also differed between conditions over time ($F_{3,29} = 21.0, P < .001$). Precooling lowered HR for the first 20 minutes of exercise ($P < .05$; Figure 3; average ES = 1.6). In contrast, RPE was similar between conditions during exercise ($F_{2,22} = 2.9, P = .07$; Figure 3).

Precooling did not affect $T_{rec}$ cooling postexercise ($F_{1,12} = 1.1, P = .32$) or CWI durations ($t_{11} = 0.2, P = .85$; Figure 2). Consequently, $T_{rec}$ CWI cooling rates were similar between conditions (PC = 0.18°C/min ± 0.06°C/min; CON = 0.20°C/min ± 0.09°C/min; $t_{11} = 0.9, P = .34$). For the postexercise CWI, 6 of 12 participants (50%) self-reported shivering on PC days with an onset of 6.4 ± 1.6 minutes. For CON, 8 participants (67%) self-reported shivering with an onset of 5.9 ± 2.3 minutes.

Thermal sensation differed between test conditions ($F_{2,26} = 21.7, P < .001$). Precooling thermal sensation scores were lower than the CON scores for the first 10 minutes during exercise ($P < .05$; Figure 4; average ES = 3.4). Interestingly, participants also indicated they felt warmer during the postexercise CWI on PC days ($P < .05$; Figure 4). Unlike thermal sensation, PC did not appear to affect ESQ responses over time ($F_{2,24} = 1.3, P = .3$; Table 2).

**DISCUSSION**

Precooling may be a useful strategy for preventing the onset of hyperthermia and, possibly, EHI. A 15-minute bout of PC before intense exercise in the heat reduced $T_{rec}$ 0.5°C and increased H$_S$ capacity by approximately 20 W/m$^2$ before exercise. Booth et al$^{10}$ and Skein et al$^{13}$ observed 0.7°C and 0.5°C decreases, respectively, in $T_{rec}$ before exercise, after similar durations of CWI. The lower $T_{rec}$ after PC in our study persisted for the duration of exercise and allowed our participants to exercise for approximately 18 minutes longer than the CON condition. Prolonged exercise times before reaching hyperthermia could be especially advantageous for American football players and offset some of the deleterious effects of wearing PADS.$^{5,6,20}$ Miller et al$^{20}$ found that $T_{rec}$ reached 39.5°C approximately 10 minutes sooner when PADS were worn instead of standard workout apparel. Similarly, Armstrong et al$^{6}$ noted that the time to volitional exhaustion was 14 minutes sooner when PADS were worn. Thus, a relatively short bout of whole-body PC may help counter some of the additional metabolic load imposed by wearing PADS, especially if the exercise session is approximately 1 hour in duration.

Our second purpose was to determine if PC affected $T_{rec}$ cooling rates once participants became hyperthermic. Before PC can be recommended as an EHS-prevention strategy, it must be shown to not interfere with the effectiveness of CWI treatment. The longer $T_{rec}$ stays above 40.5°C, the higher the likelihood of mortality and morbidity from EHS.$^7$ Despite increasing H$_S$ capacity and lowering the sweat rate, PC did not affect postexercise CWI cooling rates. On PC days, participants cooled at 0.18°C/min ± 0.06°C/min, whereas on CON days, they cooled at 0.20°C/min ± 0.09°C/min. These results support those of a similar study examining PC’s effects on CWI $T_{rec}$ cooling rates in hyperthermic men and women who did not wear PADS during exercise (our unpublished observations, 2018). We determined that PC and CON cooling rates were 0.18°C/min ± 0.14°C/min and 0.19°C/min ± 0.05°C/min, respectively. The lack of difference in CWI cooling

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*Figure 2. Rectal temperatures during exercise (left) and cold-water immersion (CWI, right) with and without precooling (mean ± standard deviation, n = 12). Data are shown for the shortest exercise and CWI durations common to all participants on both testing days. The X-axis error bars indicate the standard deviation for the final exercise (left) and CWI (right) durations. Time 0 indicates the start of exercise. a Precooling < control (P < .05). b Precooling exercise duration > control exercise duration (t$_{11}$ = 17.0, P < .001).*
rates was likely due to the transient physiological effects of PC (approximately 20 minutes) and because we used the same thermal threshold to end exercise for both conditions. Overall, $T_{\text{rec}}$ cooling rates exceeded expert recommendations for cooling rates of athletes experiencing EHS (ie, $0.155^\circ C/\text{min}$). Consequently, clinicians need not fear that PC before exercise will impair the ability to quickly lower an athlete’s $T_{\text{rec}}$ if he or she becomes severely hyperthermic.

Another advantage of PC was that it reduced physiological strain during exercise. Wearing PADS during exercise in the heat increased physiological strain (eg, increased HR and dehydration). Armstrong et al observed that HR and systolic blood pressure were higher near the end of exercise when PADS were worn during exercise in the heat. In our study, PC lowered HR by 9 to 16 beats/min during the first 20 minutes of exercise. Other researchers noted that resting HR with PC was 13% lower at the onset of exercise and 9% to 10% lower for the first 10 minutes of exercise. In our study, precooling mitigated dehydration. Consistent with other scientists, we found that PC lowered the sweat rate by 0.3 L/h compared with CON. Sweating is triggered by elevations in body temperature. Because PC lowered $T_{\text{rec}}$ before exercise, sweating was delayed, which lowered the sweat rate. Dehydration can contribute to elevations in 

Figure 3. Heart rates and ratings of perceived exertion during exercise with and without precooling (mean ± standard deviation, $n = 12$). Only measurements occurring during exercise times common to all participants on both testing days were used for statistical analysis. The end-of-exercise data point was the last heart rate and rating of perceived exertion recorded during exercise for each participant on each testing day. * Precooling < control ($P < .05$).

Figure 4. Thermal sensation before, during, and after exercise with and without precooling (mean ± standard deviation, $n = 10$). Data were mistakenly not recorded on the control trial for 2 participants; their data were removed from the statistical analysis. Only exercise times experienced by all participants on both testing days were used for statistical analysis. Scale ratings ranged from 0 (unbearably cold) to 8 (unbearably hot). A score of 4 indicated participants were comfortable. * Precooling < control ($P < .05$).

$T_{\text{rec}}$ so this may be another way PC can mitigate the onset of severe hyperthermia and physiological strain.

Precooling affected thermal sensation but not RPE or the 16-item ESQ score. Many variables affect RPE, including exercise intensity (ie, HR), age, perceived environmental conditions during exercise (hot, cold, windy, etc), and fitness level. Moreover, RPE tends to be more correlated with cardiopulmonary variables than with thermoregulatory responses. Most of these variables were consistent between trials, which may explain why we did not observe differences between conditions for RPE. The lack of difference in the ESQ scores is likely due to the number of ESQ items affected by PC and the timing of our measurements. Arguably, only 4 questions on the ESQ address variables affected by PC. Specifically, thermal perception (eg, “I feel feverish,” “I feel warm,” and “I feel goosebumps”) and coordination (eg, “My coordination is off”) may be affected because PC lowers body core temperature and skin temperature and can influence coordination. However, PC was unlikely to affect the other 12 items (eg, “I have a muscle cramp”). Therefore, the latter items may have outweighed the PC-affected items when we calculated the cumulative score. Moreover, the PC effects on body core temperature are transient (15–20 minutes), and most of our ESQ measures occurred long after PC.

Unlike the RPE and ESQ responses, PC lowered thermal sensation for the first 10 minutes of exercise in the current study. This was probably because PC lowered skin temperatures; CWI can lower skin temperatures $5^\circ C$ to $8^\circ C$. Skin temperature and the rate of skin temperature change are the primary determinants of thermal sensation. However, lower skin temperatures after CWI tend to be transient when participants complete exercise in the heat. The minor differences in thermal sensation during the postexercise CWI (approximately 1 point) likely have little clinical significance. However, anecdotally, we
believe this was because participants compared how cold they felt when with the PC with how they felt during CWI when their $T_{rec}$ was elevated.

Before implementing PC interventions, clinicians must consider 2 safety factors. The first is body core temperature afterdrop (ie, the reduction in $T_{rec}$ that occurs postcooling). This is important because afterdrop may place athletes at risk of hypothermia. Although no published PC specifications are available to ensure athlete safety, our participants’ anthropomorphic values and PC specifications resulted in a $T_{rec}$ afterdrop ranging from 0.05°C to 1.4°C by the onset of exercise. Thus, our participants’ $T_{rec}$ did not approach temperatures consistent with hypothermia (ie, $<35°C$). Knowing participants’ BMI index, body density, and percentage of body fat may be useful so that clinicians can design safe PC interventions. Other factors that may influence afterdrop are water-bath temperature, immersion duration, convective cooling frequency, and participant clothing. The highest afterdrops typically occur in smaller athletes with a low level of adiposity who wear few articles of clothing while immersed in cold water that is frequently stirred. Therefore, for safety, clinicians may consider having warming methods (eg, blankets, heaters) onsite when performing PC. The second safety consideration involves possible misconceptions that, if PC is implemented, athletes can tolerate exercise at higher intensities or for longer durations without adverse consequences. To our knowledge, no researchers have addressed whether PC reduces the EHI occurrence or contributes to the development of other injuries associated with overexertion (eg, rhabdomyolysis). Conditioning sessions, workouts, and practices should not be made more strenuous or in any other way unsafe simply because athletes undergo PC.

We acknowledge the following limitations of our study. First, similar to many prior experimental investigations of $T_{rec}$ cooling rates, our participants did not experience EHS. Second, we used HR to monitor exercise intensity. Because PC lowered HR, it is likely our participants exercised at higher intensities on PC days to comply with our instructions. We do not believe our interpretation of the data is affected by this limitation given that RPE was consistent on each day. Nevertheless, PC may delay hyperthermia for even longer durations than those reported here as exercise intensity, the primary determinant of $T_{rec}$, increases. Future researchers may wish to use other measures of exercise intensity (eg, VO$_2$) when studying PC to address this limitation. Finally, we stirred the water bath every 2 minutes to allow comparison with our prior work. For the fastest cooling, it is preferable to continuously stir the bath water to maximize conductive and convective cooling.

In conclusion, PC using whole-body CWI was effective in delaying the onset of hyperthermia in participants exercising in PADS in hot, humid conditions. Moreover, PC did not alter the effectiveness of CWI postexercise once participants were hyperthermic. Clinically, these 2 important observations may help delay the onset of EHI. Although PC did affect thermal sensation, this effect was transient and would not likely impede an athlete’s ability to perceive how hot he or she was if exercise duration was longer than 20 minutes. Because most EHI episodes occur after long periods of exercise (≥2 hours), we do not believe that PC would predispose athletes to EHI by altering thermal perception. Therefore, clinicians may wish to implement PC with other proven EHS-prevention strategies when their American football athletes exercise in the heat.

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**Table 2. Environmental Symptoms Questionnaire (ESQ) Responses Before, During, and After Exercise With and Without Precooling**

| Time            | Control | Precooling |
|-----------------|---------|------------|
| Pre-acclimation | 1.2 ± 1 | 1.9 ± 4.2  |
| Pre-exercise    | 1.3 ± 1 | 2.8 ± 3.2  |
| Postexercise    | 20.3 ± 12.9 | 22.6 ± 12.3 |
| After cold-water immersion | 7.3 ± 7.9 | 6.6 ± 5.6 |

*a The ESQ is rated on a 5-point Likert scale with scores ranging from 0 (not at all) to 5 (extreme); data from the 16 items were summed to create a cumulative score.
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Address correspondence to Kevin C. Miller, PhD, AT, ATC. School of Rehabilitation and Medical Sciences, Central Michigan University, Mount Pleasant, MI 48859. Address e-mail to mille5k@cmich.edu.