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Evidence against a 40°C core temperature threshold for fatigue in humans

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Ely BR, Ely MR, Cheuvront SN, Kenefick RW, DeGroot DW, Montain SJ. Evidence against a 40°C core temperature threshold for fatigue in humans. *J Appl Physiol* 107: 1519–1525, 2009. First published August 27, 2009; doi:10.1152/japplphysiol.00577.2009.—Evidence suggests that core temperatures of ~40°C can induce fatigue, although this may be confounded by coincident elevations in skin temperatures and maximal cardiovascular strain. In an observational field study to examine core temperature threshold for fatigue, we investigated whether running performance is impaired when rectal temperature (T_{re}) is >40°C and skin temperature remains modest. Seventeen competitive runners (7/10 women/men: 8 km best 1,759 ± 78/1,531 ± 60 s) completed 8-km track time trials in cool (WBGT ~13°C; $n = 6$), warm (WBGT ~27°C; $n = 4$), or both ($n = 7$) conditions. T_{re}, chest skin temperature, and heart rate were logged continuously; elapsed time was recorded every 200 m. Running velocity for T_{re} >40°C was compared with that for T_{re} <40°C for each runner. Changes in running velocity over the last 600 m were compared between runners with T_{re} >40°C and <40°C. Twelve runners achieved T_{re} >40.0°C with ≥600 m remaining (range 600–3,400 m). Average running velocity for T_{re} <40°C (282 ± 27 m/min) was not different from that for T_{re} >40°C (279 ± 28 m/min; $P = 0.82$). There were no differences in running velocity during the final 600 m between runners with final T_{re} >40°C or <40°C ($P = 0.16$). Chest skin temperature ranged from 30 to 34°C, and heart rate was >95% of age-predicted maximum. Our observation that runners were able to sustain running velocity despite T_{re} >40°C is evidence against 40°C representing a "critical" core temperature limit to performance.

ambient temperature; pacing; performance; body temperature

DEGRADED PHYSICAL PERFORMANCE and exhaustion can be caused by multiple physiological factors. Investigators studying the performance-limiting factors during exercise-heat stress have historically focused on the implications of the profound cardiovascular demand of simultaneously perfusing both exercising muscle and skin (15). More recently, however, focus has shifted to the impact of body temperature per se as a causative factor in the fatigue process and as an input variable for determining self-paced exercise intensity (7). This single critical factor concept is commonly invoked within the exercise science literature to explain heat stress fatigue of any variety. However, this concept ignores the multiple physiological inputs that contribute to this phenomenon.

The concept of premature fatigue in warm or hot environments as a consequence of elevated core temperature was firmly established after several studies (20, 28) demonstrated the reliable occurrence of heat stress-fatigue at a "critical" core temperature of 40°C. Importantly, this observation occurred despite varying the initial core temperature and the rate of heat storage. Furthermore, this temperature was associated with brain wave and motor neural output changes (30, 34), consistent with an interpretation that core temperature may be a safety brake for catastrophic hyperthermia (29, 32) or at least the precipice for a progressive downward performance slope (35).

Although there can be no doubt that exercise performance is made vulnerable by an elevated brain temperature (14, 29, 32), the importance (or existence) of a critical core temperature has recently been challenged (18). It is clear, for example, that temperatures of ~40°C are far lower than what is required for cellular damage (20), and there is convincing evidence that the human central nervous system can tolerate blood temperatures well in excess of 41°C for >2 h without harm (2, 11). Moreover, rectal temperatures (T_{re}) and esophageal temperatures of ≥40°C have been observed in distance runners and were apparently well tolerated for extended periods of time (3, 10, 26, 36). Unfortunately, the latter observational studies have provided no insight into whether attainment of such high core temperatures affected performance (running velocity), but it is interesting to note that, when measured, skin temperatures were also very cool (<30°C) (10, 26).

The experiments documenting an association between fatigue and the attainment of a "critical" core temperature of ~40°C were always performed under experimental conditions that produced high muscle temperatures (~41°C), high skin temperatures (~37°C), narrow core-to-skin gradients (<3°C), and substantial cardiovascular strain (heart rate >95% of age-predicted maximum) (16, 28, 30). These coexisting physiological stressors could, either alone or in combination with core temperature input, have contributed to the onset of fatigue. Gonzalez-Alonso et al. (18) have recently questioned whether attainment of a core temperature beyond 40°C would negatively affect performance under conditions where skin temperatures were lower and the accompanying demand for skin blood flow would be lessened.

A separate but related concept suggests that self-paced exercise intensity is modulated to avoid attaining a critical core temperature beyond which thermal injury (catastrophe) would occur (25, 43). In this anticipatory model, the rate of heat storage has been proposed as an input variable for autonomic or cognitive selection of exercise intensity (43). Although this idea has recently been challenged (22), to our knowledge no study has assessed whether pacing is associated with heat storage and/or absolute core temperature.

The primary purpose of this study was to test the validity of the critical core temperature hypothesis when the confounding effects of high skin temperature and narrow core to skin gradient were not present. A secondary purpose was to examine changes in self-selected pacing in relation to body temperature or the rate of heat storage. An observational field exper-

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iment with competitive distance runners was conducted as this afforded the opportunity to examine self-selected pacing and core temperature in a typical training environment. It was hypothesized that self-selected running velocity would be maintained despite core temperatures in excess of 40°C if skin temperatures remained relatively low and changes in running velocity would be independent of the rate of heat storage.

METHODS

Seventeen competitive runners (n = 10 men and 7 women) capable of completing 8 km in under 1,800 s (men) or 2,100 s (women) were recruited through local running clubs. Permission was obtained to instrument runners and to observe and log data during a scheduled 8-km time trial workout. Volunteers were provided informational briefings and gave voluntary, informed written consent to participate. Investigators adhered to AR 70-25 and U.S. Army Medical Research and Materiel Command Regulation 70-25 on the use of volunteers in research, and the appropriate Institutional Review Boards approved this study.

The time trial observations took place on four occasions: two indoor time trials in cool environmental conditions and two outdoor trials in warm environmental conditions. Volunteers ran in one (n = 10) or both (n = 7) conditions, bringing the total number of volunteer observations to 24. The location and environmental parameters for these observations were dependent on seasonal changes in venue and weather but allowed for observation over a wider range of temperatures. All trials were run on measured tracks: 400 m (outdoors, for warm conditions) or 200 m (indoors, for cool conditions). During all time trials, 200-m split times were hand recorded to the nearest second and later verified by video playback monitoring.

Before the time trial, weight was measured to the nearest 0.1 kg (Seca 770, Hanover, MD) and height was measured to the nearest 0.1 cm. Fitness was assessed by questionnaire documenting average weekly training volume in the previous 12 mo and personal best time for 8 km in the past 6 mo. Volunteers were then instrumented with a heart rate logger (Acti-heart; Mini Mitter, Bend, OR) and a skin temperature patch (Mini Mitter) placed on the subject's right chest at the mid-clavicular line, approximately half-way between the clavicle and the nipple. Once instrumented, volunteers completed a 15- to 30-min self-paced warm-up jog. After the warm-up period, volunteers inserted a telemetry pill (Jonah core body temperature capsule, Mini Mitter) as a suppository 8–10 cm beyond the anal sphincter. Although telemetry pills are a convenient solution to monitoring core body temperature in the field (e.g., Ref. 3), their well-described limitations (4, 19) inspired a suppository solution that ensured a true T_{re} (23). Skin temperature and T_{re} readings were logged telemetrically on a monitor (Vitalsense monitor, Mini Mitter), which each volunteer wore around their waist in an elastic belt. Immediately after completion of the time trial, volunteers were asked to rate the intensity of their effort in the time trial on a scale of 1 to 10.

T_{re}, chest skin temperature (T_{sk}), and heart rate were logged continuously during the time trial, and values corresponding to the forty 200-m segments were extracted. A core-to-skin temperature gradient was calculated by subtracting T_{sk} from T_{re} at each 200 m. Running velocity was calculated by dividing the distance run (200 m) by the time it took to cover the distance (seconds) for all 40 segments. An average running velocity was calculated from the mean of all 200 m splits. A percent change in running velocity was calculated for each 200 m by the following equation: (true running velocity − average running velocity over the 8 km)/(average velocity) × 100. A positive percent change represents a segment that was slower than average pace, and a negative percent change represent a faster than average segment. Variation in running velocity was assessed by calculating a coefficient of variation [CV; (SD/mean) × 100] from the first 37 200-m segments for each runner and then reporting the group average CV.

Mean body temperature was calculated using weighted coefficients for T_{re} and T_{sk} [body temperature = $0.8(T_{re}) + 0.2(T_{sk})$], and rate of heat storage (Q_c) was calculated using thermometry [Q_c = mean body temperature × body mass in kg × 3.47; ΔQ_c between time T_0 and T_1 = $Q_{cT1} - Q_{cT0}$] as in previous analyses (43). Changes in the rate of heat storage were analyzed for correlation with changes in normalized pace per 800 m (10% of time trial distance) by the following equation for the ten 800-m segments: (true running velocity − average running velocity over the 8 km)/average velocity × 100.

The last 600-m segment was analyzed separately on the basis of research identifying that an "end spurt" occurs when a task is 90–95% complete, irrespective of length of task (5, 6, 13, 31). Additionally, it was estimated, using ordinary heat balance calculations, that T_{re} would reach 40°C by 7,400 m in most of the runners. To examine the end spurt, running velocity during the last 600 m (last 7.5%) was compared with the average running velocity over the initial 7,400 m.

Statistical analysis. Of primary interest in this study was the simple comparison of an individual's running velocity when T_{re} was above and below 40°C. Mean running velocities were compared for the entire period, wherein each volunteer fell in the range of T_{re} <40°C and T_{re} >40°C, as well as when T_{re} was ≥40°C in all runners (final 600 m) relative to mean running velocity (0–7,400 m) using paired-sample t-tests for all runners with a final T_{re} of >40°C. Changes in running velocity per 800 m were compared with changes in the rate of heat storage and analyzed in each environment using a Pearson product moment correlation analysis. The importance of any change in running velocity, independent of P value, was assessed in relation to the within-subject CV for running velocity (0–7,400 m) described above. Changes in running velocity within this zone were considered unimportant (typical noise). Because a finding of no difference is one outcome that would support our hypothesis, care was taken to avoid a type II error in association with small statistical power. Using conventional alpha (0.05) and beta (0.20) assumptions, we estimated that 16 runners would provide sufficient power (42) to detect a meaningful difference in running velocity equal to or greater than the CV, which was estimated from the first group of seven runners at 2–3%. This is equal to a change in running velocity of ~6 m/min. Linear regression was also used where indicated. The results were analyzed using Sigma Stat 3.0 software (Systat, Point Richmond, CA). No analytical comparisons were made between cool and warm condition trials. Descriptive data are presented as means ± SD unless noted otherwise.

RESULTS

Four separate time trials took place: two trials in cool (indoor; 7 men and 6 women) and two trials in warm (outdoor; 6 men and 5 women) conditions. Group characteristics for both conditions were similar for age, body size, fitness, and training status (Table 1). All volunteers completed the time trials within the allotted time in both environments (<1,800 s for men; <2,100 s for women). Seven volunteers ran in both cool and warm trials. The seven runners were treated as unique subjects in each environment as the trials were separated by several months and changes in the competitive racing season, fitness, heat acclimatization, and hydration status could not be controlled, thus invalidating a sound within-subject comparison. Furthermore, only two volunteers who completed both trials obtained T_{re} >40°C in both environments, limiting within-subject comparisons in the primary analysis.

Environmental conditions were similar for the two cool trials (wet bulb globe temperature of ~13°C; Table 2) and the two warm trials (wet bulb globe temperature of 26–28°C, Table 2). Finishing times in cool [mean (range)] were 1,657 s (1,470–1,922) and 1.5 ± 1.9% slower than the runners current 8 km

Table 1. *Demographics*

	Cool		Warm	
	7 Men	6 Women	6 Men	5 Women
Age, years	28±3	28±2	30±2	27±2
Weight, kg	69.5±7.5	55.8±2.7	70.9±5.5	56.8±2.1
Height, cm	178.4±4.2	165.4±4.6	179.6±4.0	166.0±4.2
8-km or 5-mile best time, s	1501±37	1787±82	1562±63	1726±66
Weekly training volume, km	141±40	96±16	114±22	109±13

Values are means ± SD.

best (defined as personal best time for 8 km in the previous 6-mo period). In warm conditions, finishing times averaged 1,768 s (1,526–1,985) and 7.9 ± 5.4% slower than the runners current 8 km best. Despite slower finishing times, volunteers in warm conditions, as in cool, had an average final heart rate over 95% of age-predicted maximum (Table 3), indicating a near-maximal effort. Ratings of effort (scale of 1–10) also indicated a high level of intensity in both conditions (cool: 8.2 ± 0.7; warm: 8.0 ± 1.0). Physiological responses (heart rate, core temperature, skin temperature, core-to-skin gradient) are summarized in Table 3 and Fig. 1. Heart rates were very similar between trials; however, T_{re}, T_{sk}, and the core-to-skin temperature gradient were markedly different.

In cool conditions, volunteers maintained an even pace throughout the 8-km time trial (Fig. 2) as their running velocity varied 2.4% (1.7–3.2%) from 0 to 7,400 m. Regression analysis of running velocity from 0 to 7,400 m indicated a flat slope for cool and a slight, but significant ($P < 0.05$), linear slowing trend for warm conditions (−24 m/min over 7,400 m) (Fig. 2, *top*). The linearity of this relationship suggests that pace changes occurred independent of core temperature. Therefore, use of the average pace over 0–7,400 m in both environments was considered an accurate average for fair comparison to the last 600 m (end spurt). Runners in cool conditions were able to produce an end spurt in the final 600 m of the time trial, accelerating their running velocity 3.6 ± 3.9% ($P = 0.006$) compared with their running velocity from 0 to 7,400 m. Running pace was slightly more variable in the warm trial as the CV of running velocity was 3.4% (2.0 to 5.2%) and runners were able to accelerate slightly in the final 600 m compared with their average pace from 0 to 7,400 m (Fig. 2; $P = 0.18$).

Heat storage, calculated using thermometry, peaked within the first 3,200 m in both warm and cool conditions and then stabilized or slowly declined through the duration of the time trials (Fig. 3). Changes in running pace per 800 m followed a similar trend as pace per 200 m in each environment and were not related to changes in heat storage (cool: $r = -0.003$;

Table 2. *Range of weather conditions for two cool (indoor) and two warm (outdoor) trials*

	Cool	Warm
Dry bulb temperature, °C	16.7–17.8	29.5–30.2
Wet bulb temperature, °C	10.8–11.0	24.3–24.3
Globe temperature, °C	17.2–17.8	31.3–38.3
Wet bulb globe temperature, °C	12.8–12.9	26.2–27.7

WBGT, wet bulb globe temperature.

Table 3. *Physiological responses in cool and warm environments*

	Cool	Warm
Mean T_{sk}, °C	30.3 (27.8–32.7)	34.3 (32.5–36.5)
Mean core-to-skin gradient, °C	8.5 (6.0–11.0)	5.2 (3.5–6.8)
Peak heart rate, beats/min	186 (177–196)	186 (175–195)
Peak heart rate, %	97 (92–105)	97 (93–101)

Values are means (range in parentheses).T_{sk}, chest skin temperature.

warm: $r = 0.128$; $P > 0.05$). In cool conditions, running velocity was stable or accelerated slightly when heat storage was highest. In warm conditions, pace declined most rapidly while heat storage was stable (Fig. 3).

Twenty-three of the 24 runners reached peak T_{re} in excess of 39.5°C [mean (range) for cool: 39.84°C (39.39–40.28); mean (range) for warm: 40.32°C (39.67–40.89)]. In cool conditions, 3 of the 13 runners achieved final T_{re} >40.0°C, whereas 9 of 11 volunteers in warm conditions obtained T_{re} >40.0°C during the time trial. The absolute rise in T_{re} during exercise was similar in both environments (cool: 2.12 ± 0.30°C; warm:

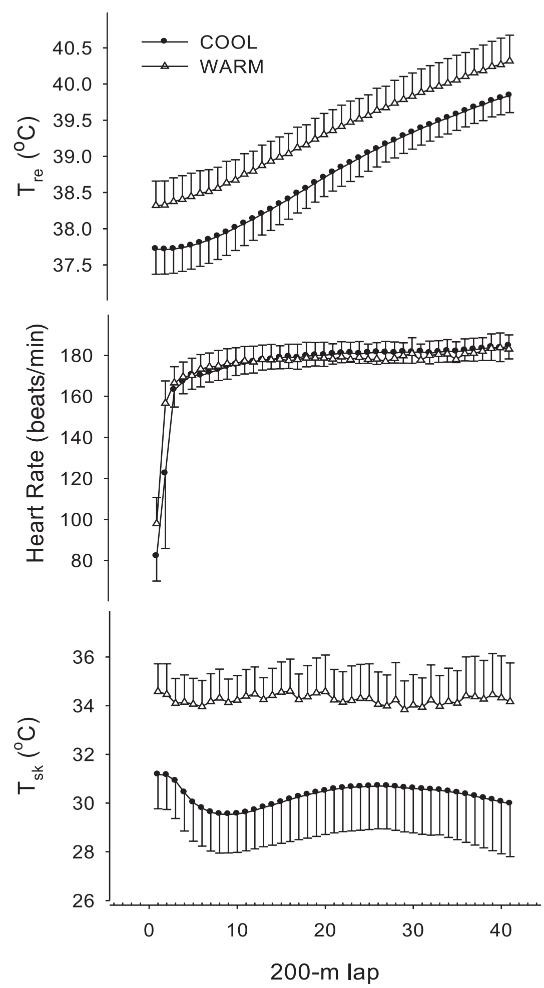

Fig. 1. Rectal temperature (T_{re}), heart rate [in beats/min (b/min)], and chest skin temperature (T_{sk}) per 200-m segment in cool and warm conditions. Values represent means ± SD.

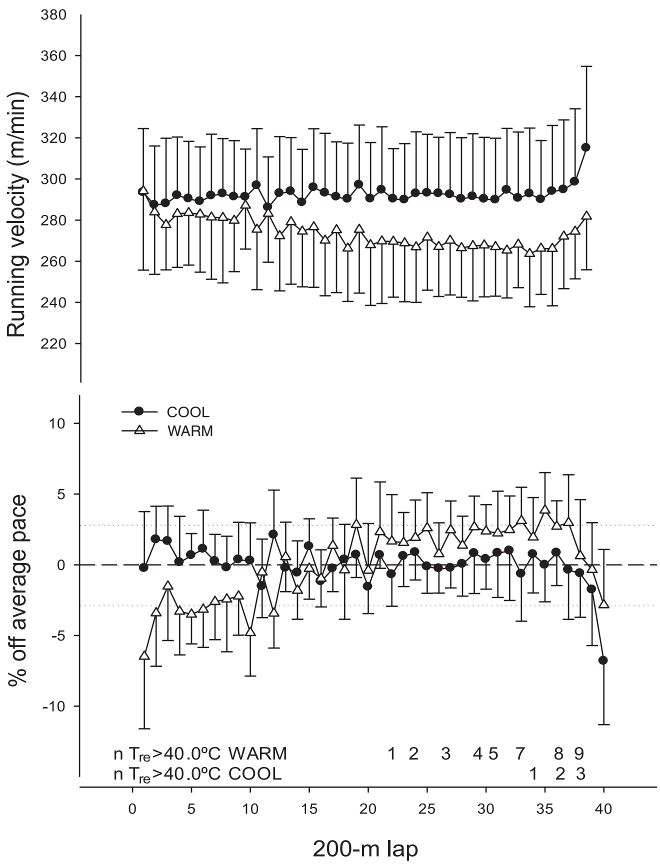

Fig. 2. Running velocity (*top*) and normalized pace (*bottom*) per 200-m segment in cool and warm conditions (see text for description). Dashed line represents an even pace; dotted lines represent the cumulative coefficient of variation (CV) for all trials. The cumulative number of volunteers with core temperatures exceeding 40°C in each environment is shown at the base of the graph. Values represent means ± SD.

2.00 ± 0.23°C; Fig. 1). Higher peak T_{re} in warm conditions was due to 0.60°C higher initial starting temperatures in warm (38.32 ± 0.34°C) compared with cool conditions (37.72 ± 0.35°C) (Fig. 1).

Figure 4 presents the impact of T_{re} on running pace over the final 600 m relative to the average lap-by-lap CV of running velocity for all runners collapsed across environments (2.85 ± 0.88%). In cool conditions, five runners ran the final 600 m faster than the CV, and four were within the CV when T_{re} was <40°C. Few runners achieved T_{re} >40°C in cool conditions, but, of those who did, two ran the final 600 m faster than the CV, and one was within the CV. In warm conditions, only two runners did not reach T_{re} >40°C (1 faster than CV, 1 within). Of the remaining nine runners who did exceed T_{re} of 40°C, two were faster than the CV and seven were within the CV. Therefore, no runner in either environment slowed beyond the normal variation in running velocity over the final 600 m when T_{re} was <40°C or >40°C (Fig. 4).

Because some runners attained T_{re} ≥40°C earlier than others during the time trial [mean (range) of distance covered with T_{re} ≥40°C: 1,650 (600–3,400) m], consideration was given to the affect that this may have had on pace before the final 600 m. Given that the cumulative time spent with an elevated T_{re} may be more indicative of strain and fatigue than the absolute T_{re} (21), the running velocity of each runner was compared for the entire duration when their T_{re} <40°C and when their T_{re} >40°C. As illustrated in Fig. 5, the mean running velocities were similar (P = 0.82), averaging 282 ± 27 m/min under 40°C and 279 ± 28 m/min when T_{re} was >40°C. When the second trials for the two volunteers who reached peak T_{re} >40°C in both cool and warm trials were eliminated from the data set, the statistical outcomes were unchanged (P = 0.72). When these two trials were removed from the data set, the mean running velocities averaged 276 m/min when T_{re} <40°C and 272 m/min when T_{re} >40°C.

DISCUSSION

To test our hypothesis that attainment of a critical core temperature (≥40°C) would not slow running velocity when skin temperatures remained modest, we observed highly trained runners competing in an 8-km training time trial in environmental conditions favorable for heat exchange. The race distance was selected as it was short enough to minimize potential confounders such as substrate depletion, significant dehydration, and loss of motivation, which may independently alter pace or work in concert to magnify the effects of hyperthermia. Importantly, the 8-km running time trial was long enough to test our hypothesis, as 12 of 24 participants exceeded 40°C during the trial, and T_{sk} results were stable at ~30

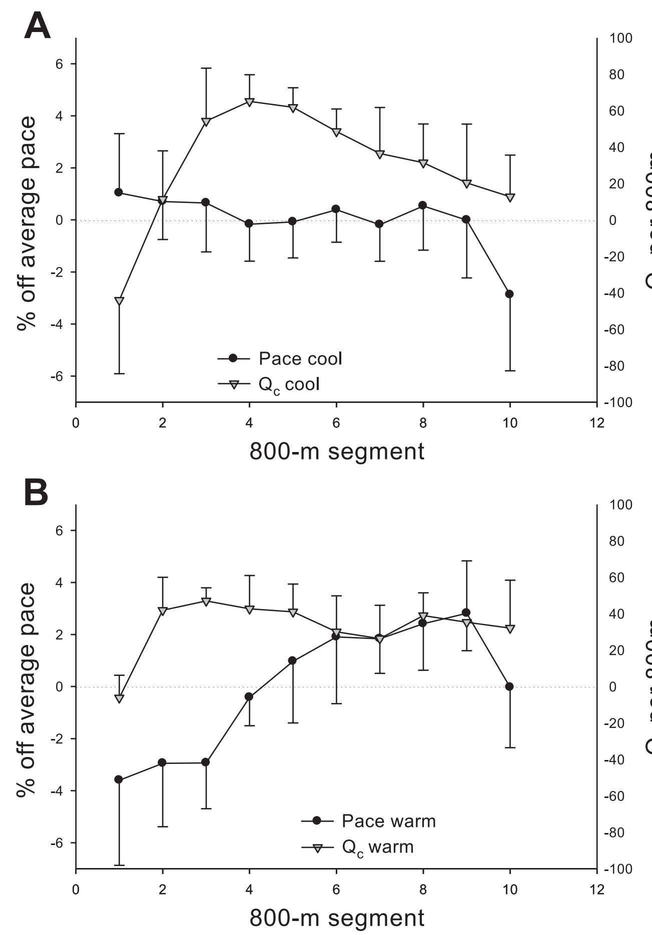

Fig. 3. Normalized pace per 800 m and rate of heat storage per 800 m in cool (*A*) and warm (*B*) conditions. Negative values represent a faster than average running velocity and a net heat loss; positive values represent a slower than average running velocity and a net heat gain.

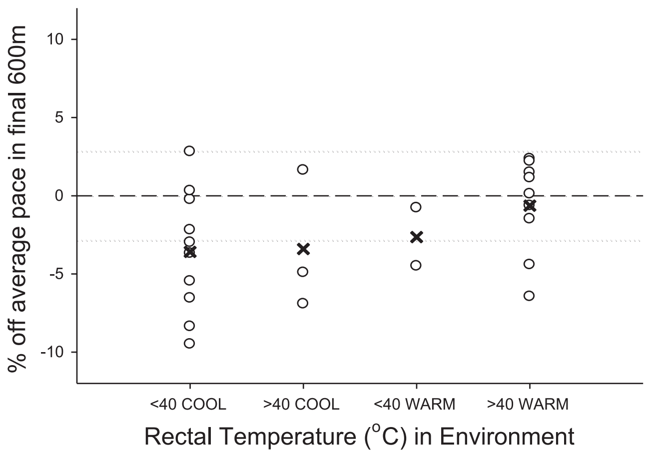

Fig. 4. Pace changes in the final 600 m (7,400–8,000 m), compared with the average pace in 0–7,400 m for each individual. Subjects are grouped by environment and T_{re} (under or over 40°C). Means for each group are displayed as a large X. Dashed line at center represents no change in pace between 0–7,400 m and final 600 m; dotted lines above and below represent the CV (typical noise; 2.85%) for all trials combined.

and 34°C in cool and warm conditions, respectively. The volunteers were ideally suited to the time trial task, as they regularly participated in workouts and competitions of similar length and intensity, which increased the likelihood that changes in running velocity were attributable to elevated T_{re} or rate of change in body temperature vs. other confounding variables.

The primary finding of this study is that T_{re} >40°C was not associated with a degradation in performance in an 8-km time trial. In the highly fit and trained population studied, T_{re} >40°C did not alter running velocity in any manner indicative of fatigue (Figs. 4 and 5). In fact, most of the runners were able to accelerate in the final 600 m despite having T_{re} between 39.4 and 40.9°C (Fig. 4). Thus these data directly refute the idea that core temperatures approaching 40°C represent a threshold where fatigue is imminent.

Our findings are consistent with limited observations of well-trained athletes participating with apparent success in athletic events despite the presence of core temperatures in excess of 40°C (3, 10, 26, 36). A common feature of these studies and the present study is that the observations were made under environmental conditions where reliance on skin blood flow to transfer body heat from the body core to the periphery was relatively low consequent to modest skin temperatures (30–34°C) and large core-to skin temperature gradients (5–8°C; Table 3). With presumably less blood in the skin than shown in studies with similar core but higher skin temperatures (16, 28, 30), cardiovascular reserves were likely maximized by a larger central blood volume (17, 24, 27, 33, 37) and allowed sustainment of a high level of aerobic performance, especially in cool conditions (1). Indeed, elevated skin temperatures alone may reduce short-duration endurance exercise performance (15-min effort) in the heat by 15–20% (12). The absent criticality of a 40°C core temperature on performance is thus apparent when skin temperatures are relatively low. These findings support the consensus that fatigue from heat strain is a multifaceted, integrated phenomenon that is highly contingent on circumstances (8, 9, 15, 18, 35, 40).

Although the results of this study support the conclusion that core temperatures of ~40°C do not represent a threshold beyond which fatigue is imminent, the use of T_{re} was anatomically dissimilar from the esophageal temperatures used in the seminal experiments (16, 28) establishing the critical core temperature hypothesis. On one hand, T_{re} results are slightly higher (but <0.20°C) than esophageal temperatures at steady state across a range of exercise intensities (39, 41). Because esophageal temperature is the best noninvasive measure reflecting true blood temperature (41), 40°C temperatures measured at the rectum may represent an overestimate. However, the larger heat capacity of the rectum relative to the esophagus creates a slower response that typically takes 25–40 min to reach its peak (38, 41). In the present study, the average duration of the time trials was 27–30 min, and there was no plateau in T_{re} (Fig. 1). Thus is it equally plausible and more likely that the T_{re} reported herein actually underestimated the temperature of the blood perfusing the brain. Had esophageal temperatures somehow been measured in this field setting, the conclusions would have been similar.

The rate of heat storage has been examined as a means of explaining acute changes in pace in anticipation of a critical core temperature (25, 43). Although this idea has recently been challenged (22), it was investigated as a plausible explanation for the slight slowing trend observed in the warm environment. Because T_{re} lags behind esophageal temperature and is less reflective of minute-by-minute circulating blood (and brain) temperature (38, 41), mean body temperature calculations using a two-compartment model (core and shell; rectal and skin) and thermometric heat storage have been questioned as accurate, real-time reflections of body temperature (22). However, calculations were kept consistent with previous work (43) to make a fair comparison. No correlation was found between changes in the rate of heat storage and changes in pace, as runners appeared able to accelerate despite high rates of heat storage in both warm and cool conditions. Any slowing of running pace in warm conditions occurred independent of elevated core temperature or a high rate of heat storage. Although various physiological and psychological inputs may influence pace as both feedforward and feedback mechanisms

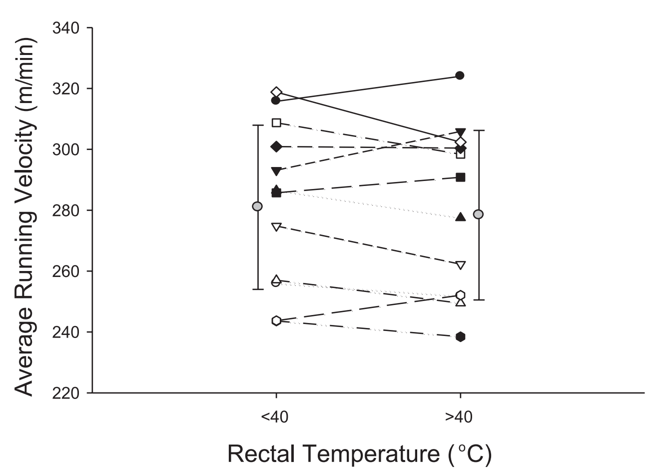

Fig. 5. Running velocity for each individual (n = 12) when T_{re} is <40°C (representing 32 ± 5 200-m segments) and T_{re} is >40°C (representing 8 ± 5 200-m segments). Means ± SD for T_{re} group are represented just outside individual plots.

(25, 44), the simplest and most plausible explanation for the overall slower finishing times and moderate deceleration trend in warm conditions can be explained by the reductions in peak oxygen consumption experienced in warm to hot environmental conditions (1, 45).

In conclusion, there were no observed changes in running velocity in well-trained athletes when a T_{re} of 40°C was attained. In fact, several runners were able to accelerate at the end of the task despite a T_{re} above the critical limit. Additionally, the rate of heat storage during exercise did not appear to mediate any pace changes in either warm or cool environments. These outcomes are unique evidence against both changes in heat storage regulating pace in an anticipatory manner and core temperature criticality per se. Combined with the larger body of heat stress fatigue literature, the data suggest that heat stress fatigue is not an all or none phenomenon but is better explained as a continuum (9) with dependent complex interplay from multiple physiological systems (8, 15, 18, 35, 40).

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