REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
2009

2. REPORT TYPE
Journal Article-High Altitude Medicine & Biology

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Aerobic Performance is Degraded, Despite Modest Hyperthermia, In Hot Environments

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
B.R. Ely, S.N. Cheuvront, R.W. Kenefick, M.N. Sawka

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Thermal and Mountain Medicine Division
U.S. Army Research Institute of Environmental Medicine
Natick, MA 01760-5007

8. PERFORMING ORGANIZATION REPORT NUMBER
M09-24

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Same as #7 above

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Environmental heat stress degrades aerobic performance; however, little research has focused on performance when the selected task elicits modest elevations in core body temperature (<38.5ºC). Purpose: To determine the effect of environmental heat stress, with modest hyperthermia, on aerobic performance and pacing strategies. Methods: After a 30-min cycling preload at 50% VO2peak, eight euhydrated men performed a 15-min time trial on a cycle ergometer in temperate (TEMP; 21ºC, 50% RH) and hot (HOT; 40ºC, 25% RH) environments. Core and skin temperature (Tc and Tsk, respectively) and HR were continuously monitored. Performance was assessed by the total work (kJ) completed in 15 min. Pacing was quantified by comparing the percent difference in actual work performed in each of five 3-min blocks normalized to the mean work performed per 3-min block. Pace over the final 2 min was compared with the average pace from minutes 0 to 13 for end spurt analysis. Results: Tc and HR rose continually throughout both time trials. Peak Tc remained modestly elevated in both environments [mean (range): HOT = 38.20ºC (37.97–38.42ºC); TEMP = 38.11ºC (38.07–38.24ºC)], whereas Tsk was higher in HOT (36.19 T 0.40ºC vs 31.14 ± 1.14ºC), and final HR

15. SUBJECT TERMS
CORE TEMPERATURE, HEAT STRAIN, PACING, END SPURT

16. SECURITY CLASSIFICATION OF:

a. REPORT	b. ABSTRACT	c. THIS PAGE
Unclassified	Unclassified	Unclassified

17. LIMITATION OF ABSTRACT

18. NUMBER OF PAGES
6

19a. NAME OF RESPONSIBLE PERSON
Brett Ely

19b. TELEPHONE NUMBER *(Include area code)*
508-233-4134

Reset

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

Aerobic Performance Is Degraded, Despite Modest Hyperthermia, in Hot Environments

BRETT R. ELY, SAMUEL N. CHEUVRONT, ROBERT W. KENEFICK, and MICHAEL N. SAWKA

US Army Research Institute of Environmental Medicine, Natick, MA

ABSTRACT

ELY, B. R., S. N. CHEUVRONT, R. W. KENEFICK, and M. N. SAWKA. Aerobic Performance Is Degraded, Despite Modest Hyperthermia, in Hot Environments. *Med. Sci. Sports Exerc.*, Vol. 42, No. 1, pp. 135–141, 2010. Environmental heat stress degrades aerobic performance; however, little research has focused on performance when the selected task elicits modest elevations in core body temperature (<38.5°C). **Purpose**: To determine the effect of environmental heat stress, with modest hyperthermia, on aerobic performance and pacing strategies. **Methods**: After a 30-min cycling preload at 50% $\dot{V}O_{2peak}$, eight euhydrated men performed a 15-min time trial on a cycle ergometer in temperate (TEMP; 21°C, 50% RH) and hot (HOT; 40°C, 25% RH) environments. Core and skin temperature (T_c and T_{sk}, respectively) and HR were continuously monitored. Performance was assessed by the total work (kJ) completed in 15 min. Pacing was quantified by comparing the percent difference in actual work performed in each of five 3-min blocks normalized to the mean work performed per 3-min block. Pace over the final 2 min was compared with the average pace from minutes 0 to 13 for end spurt analysis. **Results**: T_c and HR rose continually throughout both time trials. Peak T_c remained modestly elevated in both environments [mean (range): HOT = 38.20°C (37.97–38.42°C); TEMP = 38.11°C (38.07–38.24°C)], whereas T_{sk} was higher in HOT (36.19 ± 0.40°C vs 31.14 ± 1.14°C), and final HR reached ~95% of age-predicted maximum in both environments. Total work performed in HOT (147.7 ± 23.9 kJ) was ~17% less ($P < 0.05$) than TEMP (177.0 ± 25.0 kJ). Pace was evenly maintained in TEMP, but in HOT, volunteers were unable to maintain initial pace, slowing progressively over time. A significant end spurt was produced in both environments. **Conclusions**: During a brief aerobic exercise time trial where excessive hyperthermia is avoided, total work is significantly reduced by heat stress because of a gradual slowing of pace over time. These findings demonstrate how aerobic exercise performance degrades in hot environments without marked hyperthermia. **Key Words:** CORE TEMPERATURE, HEAT STRAIN, PACING, END SPURT

Aerobic exercise performance is degraded by environmental heat stress when studied in both laboratory (1,12,35) and field settings (8). Although numerous physiological mechanisms can contribute to heat stress-related performance degradation (21,26), there has been an emphasis in the sports medicine literature on a "critical core temperature" mediating this degradation. Sports medicine scientists often identify an elevated core temperature (>39°C) as a primary determinant of fatigue during exercise in hot environments (as reviewed by Cheung and Sleivert [6] and Nybo [21]). A complement to this idea is that athletes use an anticipatory control mechanism during exercise to ensure maintenance of T_c by making compensatory adjustments in work rate to regulate the rate of heat storage (20,32,34). However, other well-established physiological mechanisms such as increased cardiovascular strain resulting from the maintenance of high skin blood flow (14,23,25) may also explain the observed degradation in performance independent of core temperature. Most studies documenting performance degradation in the heat have elicited marked hyperthermia during the heat stress trials (7,12,22,35), and only one study has demonstrated reduced performance with modest hyperthermia (1) but their control condition was very cool.

One way to better understand the overall performance decrement from heat stress is to examine self-selected pacing strategy. Few studies have looked at the pacing of aerobic exercise performance in the heat. Although there are various successful pacing strategies in temperate conditions (2,10,15), the addition of environmental heat stress may alter physiological responses and perception of effort during exercise (32–34), thus altering an otherwise *a priori* strategy (30). It is believed that the performance decrement associated with aerobic exercise in the heat may come from either an early modification of work output or an inability to maintain a desired work output over time (9). Multiple factors may play a role in perception of effort and compensatory work rate adjustments (as reviewed by St Clair Gibson et al. [28] and Tucker and Noakes [33]). In the

Address for correspondence: Brett R. Ely, M.S., Thermal and Mountain Medicine Division, US Army Research Institute of Environmental Medicine, Kansas St, Natick, MA 01760; E-mail: brett.ely@us.army.mil.

Submitted for publication February 2009.
Accepted for publication May 2009.

0195-9131/10/4201-0135/0
MEDICINE & SCIENCE IN SPORTS & EXERCISE®

DOI: 10.1249/MSS.0b013e3181adb9fb

final stages of exercise, if peak power or muscle activity is affected by the heat (2), final sprinting ability or end spurt is likely to also be compromised.

An important factor that must be taken into consideration when studying the impact of environmental heat stress on aerobic exercise performance is the duration of the task. The magnitude of the effect of heat stress appears to be greater during long-duration activities (8,12), whereas smaller performance decrements (10% or less) are noted in shorter duration aerobic exercise tasks in warm-to-hot conditions (1,34). Larger decrements during more prolonged tasks may be explained by multiple and additive fatigue factors (i.e., dehydration, hyperthermia, accelerated substrate depletion); thus, studying a shorter aerobic exercise task might afford a less confounded examination of the independent effects of heat stress on performance and pacing.

The purpose of this study was to determine the effect of environmental heat stress with modest hyperthermia (body core temperature <38.5°C) (24) on aerobic exercise performance and pacing in moderately fit subjects during a brief aerobic exercise task. The use of a shorter aerobic exercise task (15 min) allowed for study of the impact of heat stress on performance and pacing without the associated confounders previously mentioned (e.g., dehydration, glycogen depletion). It was hypothesized that aerobic exercise performance would be degraded with heat stress, and this decline would come from subjects adopting a slower pace from the outset (9). Findings of this investigation will be important in the determination of the effect of heat stress, independent of marked hyperthermia, on performance and pacing strategy during aerobic exercise in a hot environment.

METHODS

Subjects. Eight healthy, non–heat-acclimated male volunteers (mean ± SD: age = 22 ± 4 yr; height = 175.9 ± 5.6 cm; weight = 74.9 ± 7.4 kg; $\dot{V}O_{2peak}$ = 46.0 ± 4.8 $mL \cdot kg^{-1} \cdot min^{-1}$) participated in this study and completed all phases of experimentation. Volunteers were provided informational briefings and gave voluntary informed written consent to participate. Investigators adhered to AR 70–25 and US 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.

Preliminary procedures. Two weeks of preliminary testing were completed in a temperate environment (20–22°C) before the experimental trials. $\dot{V}O_{2peak}$ was measured in all volunteers using an incremental cycle ergometer (Lode Excalibur Sport, Lode, Groningen, the Netherlands) protocol with continuous gas exchange measurements (True-Max; ParvoMedics, Sandy, UT). Volunteers cycled at a cadence of 60 rpm as workload increased by 20 W every minute until volitional fatigue. The maximal workload achieved was used to calculate a setting to elicit 50% $\dot{V}O_{2peak}$, which was validated with subsequent familiarization rides. The workload at 50% $\dot{V}O_{2peak}$ was also used to calculate an individualized linear factor for the time trial.

Volunteers performed three to four familiarization trials to reduce training and learning effects, as all volunteers were novice cyclists (13). These sessions mimicked experimental trials in every way, except they took place outside the environmental chamber at room temperature (~22°C). Familiarization trials consisted of 30 min of steady-state cycle ergometry at 50% of $\dot{V}O_{2peak}$, followed by a brief 5-min rest period, after which a 15-min time trial was completed. Pedal cadence and workload were blinded so that only time was known during the time trial, and no external motivation was provided. Elapsed time was given at standardized times of 5, 10, 12, 13, and 14 min, 30 s, and the final 10 s. Once the time trial was completed, volunteers were provided with feedback on their performance as motivation to improve with each subsequent training bout.

During the 2-wk familiarization period, volunteers were provided with 2 L of carbohydrate–electrolyte beverage to consume the evening before each training day. After an overnight fast, volunteers reported for first-morning nude body mass and urine specific gravity (USG) analysis. These values were used to calculate a reliable baseline nude body mass to ensure that volunteers began each trial in a euhydrated state.

Experimental procedures. Volunteers were randomly assigned to complete experimental trials at two temperature conditions (TEMP = 21°C, 50% RH; HOT = 40°C, 25% RH) separated by 5–7 d each to minimize heat acclimatization effects. All experiments were conducted at the same time of day to control for circadian fluctuations in body temperature, other biological variables, and performance (16,29). Volunteers were also asked to refrain from physical activity and alcohol consumption 24 h before testing. Two liters of carbohydrate–electrolyte beverage was provided for consumption, in addition to normal food and fluid intake, the night before each test. On each test day, first-morning nude weight and first-void USG measures were taken, and volunteers were considered euhydrated if body mass was within 1% of baseline and USG was <1.02.

Volunteers were seminude (shorts, socks, sneakers) and instrumented with an HR monitor and skin temperature sensors at the left chest, forearm, thigh, and calf before entering the chamber. Instrumented body mass was assessed immediately upon entry, followed by a 20-min seated stabilization period in the test environment. After stabilization, volunteers completed a 30-min preload of steady-state cycle ergometry at 50% $\dot{V}O_{2peak}$ intensity. The purpose of this preload was to assess physiological responses (HR, core temperature) at a fixed intensity and to induce modest heat storage. The task is similar to other time-trial protocols in the literature (18). Drinking was not permitted during exercise, but volunteers were weighed and rehydrated within 1% of the instrumented body mass during the ~5-min break that followed the 30-min steady state. Volunteers then completed a 15-min performance time trial as previously described.

All body mass measures were made using an electronic precision balance scale (WSI-600; Mettler Toledo, Columbus, OH; accuracy ±50 g). HR (Polar a_3; Polar Electro Inc., Woodbury, NY), core temperature (Jonah™ core body temperature capsule; Mini Mitter Inc., Bend, OR; inserted as a suppository 8–10 cm beyond the anal sphincter) (19), and skin temperature (YSI, Yellow Springs, OH) were recorded at 5-min intervals. RPE were reported immediately upon completion of the time trial.

Pacing and performance. Performance was assessed as the total work (kJ) completed in 15 min. Percentage changes in performance in HOT relative to TEMP were calculated [(HOT − TEMP) / TEMP × 100%] so that positive and negative values reflect more and less work, respectively. The potential for environmental conditions to affect pacing was also examined by normalizing total work to the minute average, evenly blocking into five 3-min segments and calculating the percentage off average pace using the measured work in each 3-min time block ([actual work − average work] / average work × 100%). A negative number indicates a slower-than-average pace for that time block, and a positive number indicates a faster-than-average pace. End spurt has been defined as acceleration during the final 10% of a performance task; (4) thus, the end spurt during the 15-min performance time trial was considered to be the final 2 min. End spurt analysis was conducted by comparing the average work per minute in the initial 13 min to the average work performed over the final 2 min (~13%) of the time trial.

Statistics. The primary outcome variable of interest in this experiment was time-trial performance. The effect of environment (trial) on total work was examined using a paired *t*-test, as was final RPE. A two-way repeated-measures ANOVA was used to evaluate trial × time comparisons for pacing and HR. *F* values were adjusted for sphericity where appropriate, and main or interaction effects were investigated by Student–Newman–Keuls *post hoc* test.

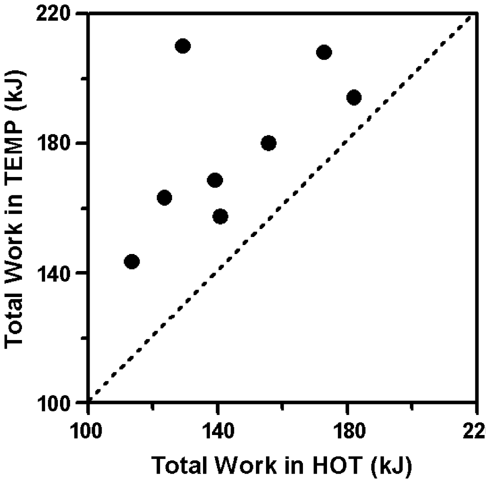

FIGURE 1—Individual time-trial performances (kJ) in HOT and TEMP. Dotted line represents line of identity (equal performances).

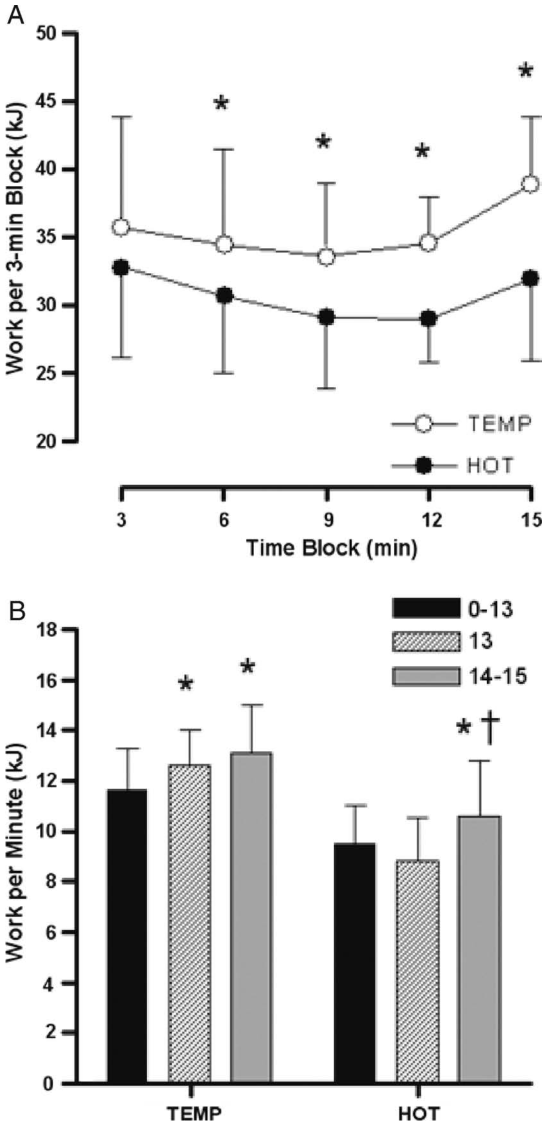

FIGURE 2—A. Total work (kJ) per 3-min block in HOT and TEMP. *Significant difference between HOT and TEMP at selected time point. B. Average work per minute (kJ) performed during minutes 0–13, minute 13, and minutes 14–15 in HOT and TEMP. *Significantly different from minutes 0 to 13. †Significantly different from minute 13.

An analysis selecting conventional α (0.05) and β (0.20) parameters showed that eight subjects would provide sufficient power to detect a >5% difference in time-trial performance between conditions. This estimate was made using the mean total work (170 kJ) and the coefficient of variation (4.2%) calculated from training trials of negligible difference during 2 wk of time-trial practice. The desire to detect a change larger than the % coefficient of variation (ES >1.0) was chosen based on the likelihood of experimental perturbations producing unique performance infidelity (17). A sample size of eight is also adequate to detect ES >1.0 for trial × time interactions in a repeated-measures design (31). Graphical data are presented with unidirectional error bars

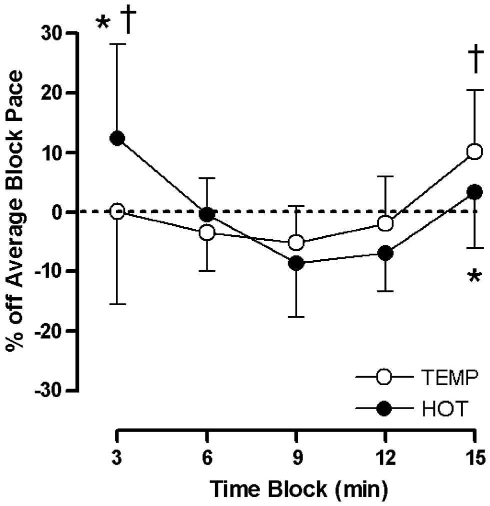

FIGURE 3—Normalized pacing per 3-min time block in HOT and TEMP. Positive values represent a faster-than-average pace, negative values a slower-than-average pace. Dotted line at zero indicates an even pace or the average work performed per 3-min time block. *Significantly different from TEMP. †Significantly different from all other time points within environment.

for clarity of presentation. All data are presented as means ± SD except where indicated. Statistical significance was accepted at $P < 0.05$ (SyStat Software, Inc., Richmond, CA).

RESULTS

Volunteers were euhydrated in each trial as determined by nude body mass within 1% of baseline (TEMP = 0.7% ± 0.7%; HOT = 0.6% ± 1.1%) and first-void USG <1.02 (TEMP = 1.011 ± 0.005; HOT = 1.016 ± 0.006). Mean fluid losses during the 30-min steady state did not differ between conditions (TEMP = 0.38 ± 0.18 L; HOT = 0.56 ± 0.10 L), nor did the average fluid replaced before the time trial (TEMP = 0.22 ± 0.05 L; HOT = 0.22 ± 0.05 L). Volunteers began the time trial within −0.24% ± 0.12% (TEMP) and −0.44% ± 0.16% (HOT) of initial body mass.

All subjects completed both time trials. Mean performance scores were 177.0 ± 25.0 kJ in TEMP and 147.7 ± 23.9 kJ in HOT (Fig. 1). All eight volunteers performed less work in HOT versus TEMP conditions, with a mean decline of 17% ($P < 0.05$). The absolute work performed in the initial 3-min block did not differ between environmental conditions (TEMP = 35.6 ± 8.2 kJ; HOT = 32.5 ± 6.6 kJ; $P > 0.05$); however, work performed in all other time blocks was significantly lower in HOT (Fig. 2A). Both groups produced significant end spurts in the final 2 min of the task, with a 13.9% increase in pace in TEMP (0–13 min = 11.6 ± 1.7 kJ; 14–15 min = 13.1 ± 1.9 kJ) versus an 11.2% increase in HOT (0–13 min = 9.5 ± 1.5 kJ; 14–15 min = 10.6 ± 2.2 kJ; Fig. 2B). The percentage increase in pace was not different between conditions. However, the work performed in the minute preceding the end spurt (minute 13) was different between groups in both absolute and relative terms (Fig. 2). Volunteers in HOT slowed their pace before the end spurt, whereas volunteers in TEMP accelerated (TEMP = 7.4% ± 9.0% vs HOT = −8.6% ± 9.4%, $P < 0.05$).

Pacing strategy, normalized to the average work performed per 3-min time block, was different between HOT and TEMP conditions (Fig. 3). Volunteers in HOT began at a relative pace faster than average ($P < 0.05$) and slowed considerably over the next three time blocks, with a small rebound in the final 3-min time block. In TEMP, a more even pacing strategy was used, with relative pace never deviating by more than 5% of average until the final time block, where there was a marked increase ($P < 0.05$) in work output. The difference between the highest and the lowest amount of work performed per 3-min block in each condition was 13.4% in TEMP (minutes 6–9 = 33.6 ± 5.3 kJ vs minutes 12–15 = 38.8 ± 5.0 kJ) and 18.5% in HOT (minutes 6–9 = 26.5 ± 5.3 kJ vs minutes 0–3 = 32.5 ± 6.6 kJ).

Skin and core temperature data were lost for four volunteers during trial TEMP. For this reason, no comparative analysis of these two physiological variables was performed, although the means and the ranges are provided for descriptive purposes. Core temperature increased over the course of steady-state and time-trial tasks but remained relatively low in both groups. The mean (range) peak core temperatures were 38.20°C (37.97–38.42°C) in HOT and 38.11°C (38.07–38.24°C) in TEMP, which are well below thresholds typically associated with "critical core temperature" (39.5–40.0°C) (21). Skin temperatures, averaged over the course of exercise, were lower in TEMP conditions [mean (range): TEMP = 31.14°C (29.91–32.77°C) vs HOT = 36.19°C (35.65–36.80°C)]. As a result, core to skin gradients were much wider in TEMP [mean (range): TEMP = 6.74°C

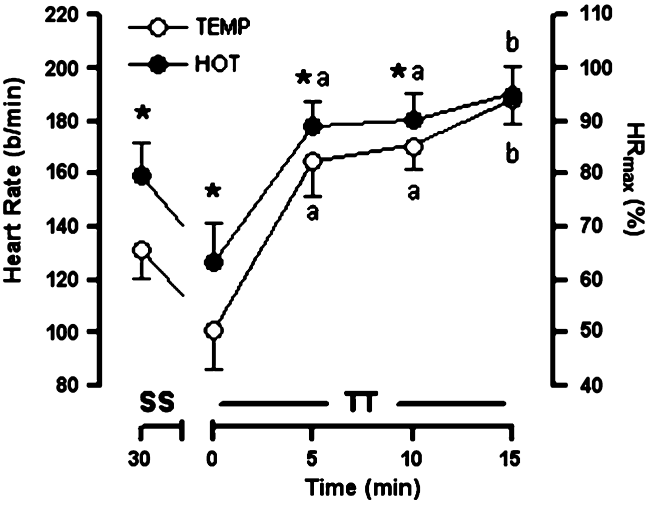

FIGURE 4—HR at completion of steady state (30SS) and during time trial (TT) in HOT and TEMP. *Significantly different from TEMP. [a]Significantly different from zero. [b]Significantly different from minutes 5 and 10.

(4.88–7.86°C) vs HOT = 1.43°C (0.72–2.03°C)]. HR increased over the course of the time trial in both TEMP and HOT ($P < 0.05$; Fig. 4). All HR values during exercise were over 80% of age-predicted maximum, and final HR averaged ~95% of max (TEMP = 94.8% ± 3.6%; HOT = 95.7% ± 3.9%), with every volunteer exceeding 90% of individual age-predicted maximum in both conditions. Final HR were not different between environments; however, HR at 0, 5, and 10 min were significantly higher in HOT. Immediately upon completion of the time trial, RPE were not different between treatments (TEMP = 17.5 ± 1.2; HOT = 18.0 ± 1.2).

DISCUSSION

Aerobic performance decrements in hot environments have been well documented. By examining the impact of environmental heat stress on pacing of short-duration aerobic exercise, we endeavored to elucidate how these overall changes in performance are manifested. Previous research examining performance and pacing in the heat has focused on highly conditioned athletes performing long-duration high-intensity tasks (9,30,32), but little was known about moderately fit individuals and the independent effect of heat when other confounders (critical core temperature, substrate availability, dehydration) were controlled.

Performance declined significantly in the heat despite modest hyperthermia, adequate hydration status, and brief exercise task. The heat-related decrement in aerobic performance noted in this study was not from a modification of pace from the outset but rather from an inability to maintain initial pace and a gradual slowing over time, with a small rebound in the final 2 min due to the production of an end spurt. Various successful pacing strategies have been found during aerobic exercise in temperate conditions (2,15); however, it is commonly believed that an even pace is often optimal (as reviewed in Foster et al. [11]). In this experiment, volunteers in TEMP used an even pacing strategy (±5%) with a significant increase in pace over the final 3 min (Fig. 1). In contrast, by failing to appropriately modify their early pace in HOT, volunteers began at a relative workload more than 12% faster than average for the initial time block and were therefore unable to maintain even pace. This resulted in a marked slowing of pace, with a nadir at minute 10 (−12% off average pace; range = −2% to −30%). Although volunteers in HOT were able to rebound in the final 2 min, work performed remained significantly lower than TEMP for all but the first 3-min time block, where no differences in absolute workload were found between conditions. It is conceivable that, despite a counterbalanced design, subjects learned a pacing strategy in familiarization trials (20–22°C), which was not modified despite increased ambient temperature in HOT. This resulted in an overly aggressive initial pace in HOT and diminished work output in successive time blocks. The greatest relative pacing differences between environments were found in early pace (first 3 min) and late pace (final 3 min), the latter of which related to the end spurt.

Irrespective of task length, end spurts often occur when a task is 90% complete (4,5). In longer-duration events, many potential fatigue factors may affect an ability to produce an end spurt (9). Although end spurts have been observed in warmer conditions (9,30), the work performed in the preceding time interval may be compromised in anticipation of the final effort. An end spurt was present in both temperate and warm conditions; however, a different trend was observed in the preceding minute interval. With 3 min remaining (20% of task), volunteers in TEMP had already increased work output, whereas volunteers in HOT were performing significantly less work than average at the same time point (Fig. 2). Volunteers in TEMP, therefore, had a longer (3 min) end spurt, but volunteers in HOT were able to produce an end spurt in the final 2 min only after slowing in the preceding minute. This accounts for the difference in the final 3-min block between groups.

The intensity and the length of the preload and performance task were designed to eliminate or to minimize potential confounders to performance in the heat. Aerobic performance changes due to “critical core temperature,” and glycogen depletion were highly unlikely considering the brevity of the task, and dehydration was carefully avoided in both conditions. Despite similar final HR and ratings of perceived effort, a 17% reduction in performance ($P < 0.01$) was found in the heat. The performance decrement found was dependent on environmental heat stress, and the magnitude is similar to other recently reported short-duration tasks in hot environments (1,35).

The environmental heat-related performance reduction seen in the time trial may be related to physiological alterations known to reduce $\dot{V}O_{2peak}$ in hot environments despite modest elevations in core body temperature (3,27,36). The only gross physiological difference between trials HOT and TEMP was a higher skin temperature (~5°C) in HOT and, presumably, a reduced central blood volume due to higher skin blood flow demands (23). The observed consequence was a higher HR at the same exercise workload in HOT (+28 beats·min^{-1}) at 30 min of steady-state exercise (30SS; Fig. 4). During the time trial, final HR and RPE were the same, but performance was consistently reduced in HOT (Fig. 1). A plausible explanation is that blood displaced to the skin decreased the maximal cardiac output available for exercise (23), which sufficiently reduced $\dot{V}O_{2peak}$ (3,27,36). Subjects were therefore working at a higher relative $\%\dot{V}O_{2peak}$ (3,36), which they could not maintain for the duration of the time trial. Indeed, this explanation is also plausible when interpreting the findings of others (e.g., [30,32]). More specifically, early down-regulation of pace in the heat may have more to do with cardiorespiratory limitations related to a feedback from high skin temperatures, a greater displacement of peripheral blood volume, a reduction in maximal cardiac output, and a resultant downward adjustment in conscious RPE (33). It is clear that volunteers in this study began the time trial by attempting to perform the same amount of work in HOT as TEMP but abandoned this strategy early on, similar to what others report (30,32). It may be that a more even-paced effort, modified for environmental conditions, would yield more successful results in longer-duration activities (9), albeit with absolute slower performances. Further research may elucidate whether an early modification of pace in the heat may minimize the overall requisite decline in performance (1,8,12,30,35) associated with environmental heat stress.

CONCLUSIONS

This study clearly demonstrated that environmental heat stress can degrade aerobic exercise performance despite modest hyperthermia. Overall performance was significantly reduced in the heat because of a gradual slowing of initial pace and a reduced ability to produce an end spurt. These findings provide insight into the effects of environmental heat stress on reducing aerobic exercise performance in the absence of a "critical core temperature." The data support the complexity of physiological feedback (33) and demonstrate that performance in the heat is about more than core body temperature. Finally, these findings have implications for moderately fit individuals taking part in shorter duration work or competition.

The authors thank the volunteers who donated their time and effort to participate in this study. The opinions or the assertions contained herein are the private views of the authors and are not to be construed as official or as reflecting the views of the Army or the Department of Defense. The results of the present study do not constitute endorsement by the American College of Sports Medicine.

Disclosure of funding: None.

REFERENCES

1. Altareki N, Drust B, Atkinson G, Cable T, Gregson W. Effects of environmental heat stress (35 degrees C) with simulated air movement on the thermoregulatory responses during a 4-km cycling time trial. *Int J Sports Med*. 2009;30(1):9–15.
2. Ansley A, Schabort E, Gibson A, Lambert M, Noakes TD. Regulation of pacing strategies during successive 4-km time trials. *Med Sci Sports Exerc*. 2004;36(10):1819–25.
3. Arngrimsson SA, Stewart DJ, Borrani F, Skinner KA, Cureton KJ. Relation of heart rate to percent $\dot{V}O_{2peak}$ during submaximal exercise in the heat. *J Appl Physiol*. 2003;94:1162–8.
4. Catalano JF. Effect of perceived proximity to end of task upon end-spurt. *Percept Mot Skills*. 1973;36:363–77.
5. Catalano JF. End-spurt following simple repetitive muscular movements. *Percept Mot Skills*. 1974;39:763–6.
6. Cheung SS, Sleivert GG. Multiple triggers for hyperthermic fatigue and exhaustion. *Exerc Sport Sci Rev*. 2004;32(3):100–6.
7. Drust B, Rasmussen P, Mohr M, Nielsen B, Nybo L. Elevations in core and muscle temperature impairs repeated sprint performance. *Acta Physiol Scand*. 2005;183(2):181–90.
8. Ely MR, Cheuvront SN, Roberts WO, Montain SJ. Impact of weather on marathon running performance. *Med Sci Sports Exerc*. 2007;39(3):487–93.
9. Ely MR, Martin DE, Cheuvront SN, Montain SJ. Effect of ambient temperature on marathon pacing is dependent on runner ability. *Med Sci Sports Exerc*. 2008;40(9):1675–80.
10. Foster C, Schrager M, Snyder AC, Thompson NN. Pacing strategy and athletic performance. *Sports Med*. 1994;17(2):77–85.
11. Foster C, Snyder AC, Thompson MN, Green MA, Foley M, Schrager M. Effect of pacing strategy on cycle time trial performance. *Med Sci Sports Exerc*. 1993;25(3):383–8.
12. Galloway SD, Maughan RJ. Effects of ambient temperature on the capacity to perform prolonged cycle exercise in man. *Med Sci Sports Exerc*. 1997;29(9):1240–9.
13. Gleser MA, Vogel JA. Endurance exercise: effect of work-rest schedules and repeated testing. *J Appl Physiol*. 1971;31:735–93.
14. Gonzales-Alonso J, Crandall CG, Johnson JM. The cardiovascular challenge of exercising in the heat. *J Physiol*. 2008;586(1):45–53.
15. Gosztyla AE, Edwards DG, Quinn TJ, Kenefick RW. The impact of different pacing strategies on five-kilometer running time trial performance. *J Strength Cond Res*. 2006;20(4):882–6.
16. Hobson RM, Clapp EL, Watson P, Maughan RJ. Exercise capacity in the heat is greater in the morning than in the evening in man. *Med Sci Sports Exerc*. 2009;41(1):174–80.
17. Hopkins WG, Hawley JA, Burke LM. Design and analysis of research on sport performance enhancement. *Med Sci Sports Exerc*. 1999;31(3):472–85.
18. Jeukendrup A, Saris WHM, Brounds F, Kester ADM. A new validated endurance performance test. *Med Sci Sports Exerc*. 1996;28(2):266–70.
19. Kenefick RW, Ely BR, Cheuvront SN, Palombo LJ, Goodman DA, Sawka MN. Prior heat stress: effect on subsequent 15-min time trial performance in the heat. *Med Sci Sports Exerc*. 2009;41(6):1311–6.
20. Marino FE. Anticipatory regulation and avoidance of catastrophe during exercise-induced hyperthermia. *Comp Biochem Physiol Biochem Mol Biol*. 2004;139:561–9.
21. Nybo L. Exercise and heat stress: cerebral challenges and consequences. *Prog Brain Res*. 2007;162:29–43.
22. Nybo L, Jensen T, Nielsen B, Gonzales-Alonso J. Effects of marked hyperthermia with and without dehydration on $\dot{V}O_2$ kinetics during intense exercise. *J Appl Physiol*. 2001;90:1057–64.
23. Rowell LB, Murray JA, Brengelmann GL, Kraning KK. Human cardiovascular adjustments to rapid changes in skin temperature during exercise. *Cir Res*. 1969;24:711–24.
24. Sawka MN, Latzka WA, Montain SJ, et al. Physiologic tolerance to uncompensable heat: intermittent exercise, field vs laboratory. *Med Sci Sports Exerc*. 2001;33(3):422–30.
25. Sawka MN, Wenger CB, Pandolf KB. Thermoregulatory responses to acute exercise-heat stress and heat acclimation. In: *Handbook of Physiology, Environmental Physiology*. Bethesda: American Physiological Society; 1996. p. 157–85.
26. Sawka MN, Young AJ. Physiological systems and their responses to conditions of heat and cold. In: *ACSM's Advanced Exercise Physiology*. Baltimore, MD: Lippincott Williams & Wilkins; 2006. p. 535–63.
27. Sawka MN, Young AJ, Cadarette BS, Levine L, Pandolf KB. Influence of heat stress and acclimation on maximal aerobic power. *Eur J Appl Physiol Occup Physiol*. 1985;53(4):294–8.
28. St Clair Gibson A, Lambert EV, Rauch LH, et al. The role of information processing between the brain and peripheral physiological systems in pacing and perception of effort. *Sports Med*. 2006;36(8):705–22.

29. Stephenson LA, Wenger CB, O'Donovan BH, Nadel ER. Circadian rhythm in sweating and cutaneous blood flow. *Am J Physiol*. 1984;246:R321–4.
30. Tatterson AJ, Hahn AG, Martin DT, Febbraio MA. Effect of heat stress on physiological responses and exercise performance in elite cyclists. *J Sci Sports Med*. 2000;3(2):186–93.
31. Tran ZV. Estimating sample size in repeated measures analysis of variance. *Meas Phys Educ Exerc Sci*. 1997;1(1):89–102.
32. Tucker R, Marle T, Lambert EV, Noakes TD. The rate of heat storage mediates an anticipatory reduction in exercise intensity during cycling at a fixed rating of perceived exertion. *J Physiol.* 2006;574(3):905–15.
33. Tucker R, Noakes TD. The physiological regulation of pacing strategy during exercise. *Br J Sports Med*. 2009. [Epub ahead of print]
34. 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; 448:422–30.
35. Tyler C, Sunderland C. The effect of ambient temperature on the reliability of a preloaded treadmill time-trial. *Int J Sports Med*. 2008;29:812–16.
36. Wingo JE, Lafrenz AJ, Ganio MS, Edwards GL, Cureton KJ. Cardiovascular drift is related to reduced maximal oxygen uptake during heat stress. *Med Sci Sports Exerc*. 2005;37(2):248–55.