Journal of Thermal Biology 43 (2014) 7–12

Contents lists available at ScienceDirect

Journal of Thermal Biology

journal homepage: www.elsevier.com/locate/jtherbio

A reduced core to skin temperature gradient, not a critical core temperature, affects aerobic capacity in the heat☆

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ARTICLE INFO

Article history:
Received 5 February 2014
Received in revised form
8 April 2014
Accepted 8 April 2014
Available online 18 April 2014

Keywords:
Hyperthermia
Thermotolerance
Volitional fatigue
Environmental physiology
Heat stress

ABSTRACT

The purpose of this study was to determine the impact of the core to skin temperature gradient during incremental running to volitional fatigue across varying environmental conditions. A secondary aim was to determine if a "critical" core temperature would dictate volitional fatigue during running in the heat. 60 participants ($n=49$ male, $n=11$ female; 24 ± 5 yrs, 177 ± 11 cm, 75 ± 13 kg) completed the study. Participants were uniformly stratified into a specific exercise temperature group (18 °C, 26 °C, 34 °C, or 42 °C) based on a 3-mile run performance. Participants were equipped with core and chest skin temperature sensors and a heart rate monitor, entered an environmental chamber (18 °C, 26 °C, 34 °C, or 42 °C), and rested in the seated position for 10 min before performing a walk/run to volitional exhaustion. Initial treadmill speed was 3.2 km h^{-1} with a 0% grade. Every 3 min, starting with speed, speed and grade increased in an alternating pattern (speed increased by 0.805 km h^{-1}, grade increased by 0.5%). Time to volitional fatigue was longer for the 18 °C and 26 °C group compared to the 42 °C group, (58.1 ± 9.3 and 62.6 ± 6.5 min vs. 51.3 ± 8.3 min, respectively, $p < 0.05$). At the half-way point and finish, the core to skin gradient for the 18 °C and 26 °C groups was larger compared to 42 °C group (halfway: 2.6 ± 0.7 and 2.0 ± 0.6 vs. 1.3 ± 0.5 for the 18 °C, 26 °C and 42 °C groups, respectively; finish: 3.3 ± 0.7 and 3.5 ± 1.1 vs. 2.1 ± 0.9 for the 26 °C, 34 °C, and 42 °C groups, respectively, $p < 0.05$). Sweat rate was lower in the 18 °C group compared to the 26 °C, 34 °C, and 42 °C groups, 3.6 ± 1.3 vs. 7.2 ± 3.0, 7.1 ± 2.0, and 7.6 ± 1.7 g m^{-2} min^{-1}, respectively, $p < 0.05$. There were no group differences in core temperature and heart rate response during the exercise trials. The current data demonstrate a 13% and 22% longer run time to exhaustion for the 18 °C and 26 °C group, respectively, compared to the 42 °C group despite no differences in beginning and ending core temperatures or baseline 3-mile run time. This capacity difference appears to result from a magnified core to skin gradient via an environmental temperature advantageous to convective heat loss, and in part from an increased sweat rate.

1. Introduction

Physically active individuals exercising in hot and warm environments are susceptible to exertional heat-related injury (EHI), including exercise-associated muscle cramps, heat syncope, exercise heat exhaustion, and exertional heat stroke (Armstrong et al., 2007; Binkley et al., 2002; Nelson et al., 2011). EHI demonstrates high core body temperatures, primarily driven by the physical exertion during exercise and/or physical activity. In the general population, EHI occurs during sport or exercise participation (75.5% of cases), most often with males (71.9%) and people ≤ 19 yrs old (47.6%) (Nelson et al., 2011). During military recruit training, individuals with excess body fat and poorer physical conditioning are more susceptible to EHI (Bedno et al., 2010; Wallace et al., 2006).

During exercise, metabolic heat production increases disproportionately with respect to the ability to off-load the heat, thereby increasing core body temperature. Exercise capacity is affected by different ambient conditions, with the most favorable conditions occurring at 11 °C (Galloway and Maughan, 1997), though Ely et al. (2007) showed that marathon performance progressively diminishes as temperatures advance from 5 °C to 25 °C. It has been proposed that exercise in the heat is limited by a

Abbreviations: EHI, exertional heat-related injury; BW, body weight; ANOVA, analysis of variance; SD, standard deviation; VO_2, volume of oxygen

☆Funded by Office of Naval Research, Grant Award N000140910850.
The funding source did not contribute to study design, collection, analysis, and interpretation of data, writing of manuscript, and the decision to submit the article for publication.

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http://dx.doi.org/10.1016/j.jtherbio.2014.04.002
0306-4565/

critical internal temperature, occurring in humans at esophageal temperatures of 39.5–40.1 °C (Gonzalez-Alonso et al., 1999; Nielsen et al., 1993), and in rats with rectal temperatures between 41.9 and 42.2 °C (Walters et al., 2000). The dominant theory in the literature suggests that muscle work in the heat diminishes when a "critical" core body temperature threshold is exceeded. However, in recent years this concept has been questioned since even modest hyperthermia (38.2 °C) has been shown to degrade aerobic performance (Ely et al., 2009a). Byrne et al. (2006) showed that runners sustained "critical" temperatures over the course of a half-marathon (mean finish time 118 ± 3 min) in the heat (wet bulb 26.0–29.2 °C) without adverse effect. Further, Ely et al. (2009b) showed that rectal temperatures > 40 °C were not associated with a degradation of performance or imminent fatigue in runners completing an 8-km track trial.

While the increase in core temperature elevation occurs proportionately to exercise intensity, skin temperature is highly dependent upon ambient conditions (Galloway and Maughan, 1997; Sawka et al., 2012). Skin temperature increases accompany increased core temperature during exercise in the heat, as heat loss via evaporation of sweat requires heat transfer to the skin via cutaneous vasodilation (Galloway and Maughan, 1997; Hargreaves, 2008). Increased cutaneous blood flow coincides with increasing skin temperature (Cheuvront et al., 2010) though Gonzalez-Alonso et al. (1999) demonstrated that cutaneous blood flow leveled off when esophageal temperature reached 38 °C. At high cutaneous perfusion, VO_{2max} is reduced since less blood is available for the working muscle (Arngrimsson et al., 2003; Gonzalez-Alonso and Calbet, 2003).

A potential mechanism to explain sustained high core temperatures during continuous exercise is the maintenance of a cool skin temperature, resulting in a large core to skin gradient that allows effective offloading of heat to the environment (Ely et al., 2009b). It has been suggested that the core to skin temperature gradient is a critical variable for exercise tolerance in the heat, as increased blood flow to the skin decreases stroke volume, increases heart rate, and ultimately compromises cardiac output (Ely et al., 2009b; Kenefick et al., 2010; Periard et al., 2012; Sawka et al., 2012). The core to skin temperature gradient provides information on both metabolic heat production and dissipation, indicating the overall thermal strain being incurred by the combination of the environment and work output. Cheung (2010) suggests that it is important to evaluate the central and peripheral thermal afferents concomitantly. The purpose of this study was to determine the impact of the core to skin temperature gradient during incremental running to volitional fatigue across varying environmental conditions. A secondary aim was to determine if a "critical" core temperature would dictate volitional fatigue during running in the heat.

2. Methods

2.1. Participants

60 participants ($n=49$ male, $n=11$ female; 24 ± 5 yrs, 177 ± 11 cm, 75 ± 13 kg) were enrolled in the study. Subjects completed a Physical Activity Readiness Questionnaire (PAR-Q) and were briefed on the experimental protocol and possible risks prior to giving written informed consent. All procedures were approved by the University Institutional Review Board.

2.2. Preliminary testing

Participants completed a 3-mile run on a measured 440 yard outdoor track. Participants were instructed to complete the 3-mile run as quickly as possible, and were provided 1 mile and 2 mile split times. Based upon a participant's run time he/she was stratified into a specific exercise temperature group (18 °C, 26 °C, 34 °C, or 42 °C) to ensure that each group had similar run performance capabilities and anthropometrics.

2.3. Experimental protocol

Preceding the experimental trial, participants were free to exercise as they wished 2 days before the trial, but were instructed to abstain from exercise 24 h before the trial. Participants were free to eat whatever they wished 1 day before the trial, but instructed to refrain from alcohol consumption. Following an overnight 12 h fast, participants arrived at the laboratory and had nude body mass measured (CW-11, Ohaus Corporation, Pine Brook, NJ). Next, body composition was measured using hydrodensitometry. Underwater mass was measured with a digital scale (Exertech, Dreshbach, MN). Body density was corrected for estimated residual lung volume (Boren et al., 1966) and converted to percent body fat using the race appropriate Siri equation (Siri, 1993). Participants then completed one exercise capacity trial in a temperature and humidity controlled environmental chamber (Tescor, Warminster, PA) in one ambient condition: 18 °C, 26 °C, 34 °C, or 42 °C. All trials were conducted with 40% relative humidity. Participants were equipped with core and chest skin temperature sensors and a heart rate monitor, entered the chamber and rested in the seated position for 10 min, and then performed a walk/run to volitional exhaustion. Initial treadmill speed was 3.2 km h^{-1} with a 0% grade. Every 3 min, starting with speed, speed and grade increased in an alternating pattern (speed increased by 0.805 km h^{-1}, grade increased by 0.5%). Participants consumed water ad-libitum. Immediately after the walk/run, participants toweled off and provided another nude body mass measurement.

2.4. Measures

2.4.1. Core and skin temperature

Core and chest skin temperatures were continually monitored during each laboratory trial with a digital data logger (Physitemp Instruments Inc., Clifton, NJ). A rectal thermistor was inserted 12 cm past the anal sphincter and a skin temperature thermistor was placed on the left pectoralis muscle 2.5 cm medial and 2.5 cm superior from the nipple. Data was collected every ½ s and the time point temperature values at each minute were used for analysis.

2.4.2. Heart rate

Heart rate was collected using a Polar RS800CX heart rate monitor (Polar Electro Inc., Lake Success, NY). Data was recorded at 5-s intervals and the time point heart rate values at each minute were used for analysis.

2.4.3. Sweat rate

Sweat rate was calculated using the pre- and post-trial nude body weights and corrected for urine excreted, fluid volume consumed, and expiratory water loss (Mitchell et al., 1972). Sweat loss was converted to a sweat rate relative to body surface area (Mosteller, 1987):

$$\text{sweat rate } (\text{g m}^{-2}\text{ min}^{-1}) = (BW_{pre} + \text{liquid int}) - (BW_{post} + \text{urine weight} + \text{resp water loss})$$

2.5. Statistical analysis

A one-way ANOVA with least significant difference post-hoc was used to compare differences in anthropometric data, 3-mile run time, sweat rate, fluid intake, and trial time to volitional fatigue