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Exercise Core Temperature Response with a Simulated Burn Injury: Effect of Body Size

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Abstract

Although the severity of a burn injury is often associated with the percentage of total body surface area burned (%TBSA), the thermoregulatory consequences of a given %TBSA injury do not account for the interactive effects of body morphology and metabolic heat production (H_{prod}).

Purpose—Using a simulated burn injury model to mimic the detrimental effect of a 40% TBSA injury on whole-body evaporative heat dissipation, core temperature response to exercise in physiologically uncompensable conditions between morphologically-disparate groups were examined at (i) an absolute H_{prod} (watts, W), and (ii) a mass-specific H_{prod} (watts per kilogram of body mass, $W \cdot kg^{-1}$).

Methods—Healthy, young, non-burned individuals of small (SM, n = 11) or large (LG, n = 11) body size cycled for 60 min at 500 W or 5.3 $W \cdot kg^{-1}$ of H_{prod} in 39°C and 20% relative humidity conditions. A 40% burn injury was simulated by affixing a highly absorbent, vapor-impermeable material across the torso (20% TBSA), arms (10% TBSA), and legs (10% TBSA) to impede evaporative heat loss in those regions.

Results—While the elevation in core temperature was greater in SM compared to LG at a H_{prod} of 500 W (SM: 1.69 ± 0.26°C, LG: 1.05 ± 0.26°C, $P < 0.01$), elevations in core temperature were not different at a H_{prod} of 5.3 $W \cdot kg^{-1}$ between groups (SM: 0.99 ± 0.32°C, LG: 1.05 ± 0.26°C, $P = 0.66$).

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AUTHOR CONTRIBUTIONS
M.N.C. and C.G.C. were involved in conception and design of the experimental protocol. M.N.C., G.M., M.H., K.K., and P.Y.S.P. were responsible for data collection. Data analysis and interpretation was performed by M.N.C. M.N.C. and C.G.C. drafted the manuscript. All authors critically revised the manuscript and approved its final version.

CONFLICTS OF INTEREST
The authors have no conflicts of interest to disclose. The results of the present study do not constitute endorsement by ACSM. The results of the study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation.

Conclusion—These data suggest that among individuals with a 40% TBSA burn injury, a smaller body size leads to exacerbated elevations in core temperature during physical activities eliciting the same absolute H_{prod} (non-weight-bearing tasks) but not activities eliciting the same mass-specific H_{prod} (weight-bearing tasks).

Keywords

body surface area; effective surface area; heat production; work intensity; burn survivor

INTRODUCTION

The U.S. Army's Standards of Medical Fitness state that for Army recruits, "Prior burn injury (to include donor sites) involving a total body surface area of 40 percent or more does not meet the standard" (AR 40–501, Section 2–28 q1). This standard may also be applied to active duty personnel with burn injuries (AR 40–501, Section 3–38 y). Although the severity of a burn injury is often characterized by the percentage of total body surface area injured (%TBSA), a criterion for inclusion based on the relative size of a burn injury ignores the effects of metabolic heat production and body morphology on the core temperature response, and thus the risk of heat illness, during prolonged physical activity and heat stress (1–9).

Surgical treatment of deep burn injuries with skin grafts disrupts the structure and innervation of sweat glands (10), resulting in a suppressed or severely attenuated sweat rate within grafted areas (11–16) and thus a reduced capacity for evaporative heat dissipation (E_{max}) (17). Consequently, during physiologically uncompensable exercise-heat stress (i.e., when the required rate of evaporative heat loss exceeds E_{max}), burn survivors exhibit greater elevations in core temperature (15, 18–21), the magnitude of which is inversely associated with the surface area of non-injured skin that can be saturated with sweat and thereby contribute to evaporative heat dissipation (22). It follows that for a given %TBSA injury, burn survivors of larger vs. smaller body size would retain a greater non-injured skin surface area, and would thus be expected to have a greater absolute E_{max}. However, whether a larger body size confers a thermoregulatory advantage, despite the same %TBSA injury, is unlikely to be dependent solely on the absolute value of E_{max}. In a recent study, Ravanelli *et al.* (7) demonstrated that in uncompensable heat stress, exercise-induced elevations in core temperature are determined mainly by the mass-specific rate of metabolic heat production (H_{prod}; in watts per kilogram of total body mass, $W \cdot kg^{-1}$). It follows that during non-weight-bearing activities with absolute energetic requirements, which typically elicit the same absolute H_{prod} (in watts), burn survivors of larger body size, but the same %TBSA injured as burn survivors of smaller body size, may demonstrate lesser increases in core temperature due to a higher body mass and thus a lower corresponding mass-specific H_{prod} (1, 2, 7). In such cases, Army recruits or soldiers of larger body size with a 40% TBSA injury may be at lower risk of a heat-related illness than those of smaller body size, but would be nonetheless excluded from service based on the 40% TBSA inclusion criterion. In contrast, burn survivors of vastly different body size, but the same %TBSA injury, may exhibit similar elevations in core temperature during weight-dependent activities, which elicit the same mass-specific H_{prod} (23). In this scenario, the risk of a heat illness during prolonged weight-bearing activity and heat stress may be similar among morphologically-disparate individuals with the same 40% TBSA injury.

In the current study, a simulated burn injury model was used to replicate the effect of a 40% total BSA burn injury—consistent with the U.S. Army's standard for inclusion of burned personnel—on whole-body evaporative heat dissipation and core temperature responses to exercise-heat stress. The following hypotheses were tested: (i) the elevation in core temperature would be greater in individuals of smaller body size during exercise at the same absolute H_{prod} due to a higher corresponding mass-specific H_{prod}; and (ii) the elevation in core temperature would not be different between groups of vastly different body size during exercise eliciting the same mass-specific H_{prod}.

METHODS

Ethical Approval

The experimental protocol was approved by the Institutional Reviews Boards of the University of Texas Southwestern Medical Center (STU 072015–032), Texas Health Presbyterian Hospital Dallas, and the Human Research Protections Office of the Defense Health Agency. Each participant was fully informed of the study procedures and potential risks of participation before providing informed written consent. All procedures conformed to the standards outlined in the Declaration of Helsinki.

Participants

Using power analysis software (G*power version 3.1.5), a minimum sample size of 20 participants (10 per group) was required based on α (0.05) and β (0.20) values, a mean elevation in core temperature of 0.75°C and standard deviation of 0.35°C following 60 min of exercise at ~500 W in hot conditions (7). Enrolled participants were young, physically-active non-smokers with no known cardiovascular, respiratory, metabolic, or neurological diseases. Participants were categorized as 'large' (LG; n=11) or 'small' (SM; n=16) based on body size. Depending on participant availability, individuals categorized as SM completed either the fixed absolute H_{prod} trial only (five subjects), the fixed mass-specific H_{prod} trial only (five subjects), or both (six subjects). Subsequent comparisons at each H_{prod} were performed between LG and SM groups, each consisting of 11 subjects with nine males and two females, which approximates the relative proportions of males and females in the U.S. Army (24). Female participants were tested during the early-follicular phase.

Instrumentation and Measurements

Body mass was measured with a precision platform balance (Mettler Toledo PBD655-BC120, Toledo, OH), and standing height was measured using a stadiometer (Detecto, Webb City, MO). Using these values, BSA was calculated according to the equation of DuBois and DuBois (25). Urine specific gravity (USG) was assessed using a refractometer (Atago Inc., Bellevue, WA). Gastrointestinal temperature was measured using an ingestible telemetric pill (HQ Inc., Palmetto, FL). In seven participants per group, esophageal temperature was also recorded using a general-purpose pediatric temperature probe inserted to a maximum depth of 40 cm (Mon-a-therm, Mallinckrodt Medical, St. Louis, MO). Core temperature data were sampled throughout the protocol at 25 Hz (Biopac MP150, Santa Barbara, CA). Expired gases were analyzed for the rates of oxygen uptake (VO_2) and carbon dioxide production (VCO_2) for 3 min at rest and from 0–10, 25–35, and 50–60 min of exercise using a metabolic cart calibrated before each trial according to the manufacturer's instructions (Parvo Medics TrueOne 2400, Sandy, UT).

Burn injuries were simulated using highly absorbent material with a vapor-impermeable exterior placed over 40% of the individual's total BSA. By absorbing secreted sweat, evaporative heat loss from the covered area was prevented, mimicking the effect of skin grafting on sweat evaporation following a burn injury (11–13, 16, 17, 26). After calculating a participant's BSA, the absorbent material was cut to dimensions that would cover 20%, 10%, and 10% of total BSA on the torso, arms, and legs, respectively. Within each segment, placement of the material was balanced anteriorly and posteriorly, and between left and right sides. Surgical tape (3M Transpore, London, ON) and tubular net bandages (Owens & Minor MediChoice, Mechanicsville, VA) were used to secure absorbent material to the skin surface.

Experimental Protocol

Participants visited the laboratory on multiple occasions, separated by at least 48 hours. During the initial visit, a 12-lead electrocardiogram and blood pressure measurement were first performed, followed by a two-phase exercise test performed in a climate chamber under 20.5 ± 0.7°C and 34.1 ± 1.5% relative humidity (RH) conditions. The first phase involved three consecutive 4-min stages of increasing intensity to provide a warm-up and to determine the external work rate required to meet target H_{prod} values during subsequent experimental visits. After 10 min of rest, the second phase—a graded exercise test to exhaustion—was performed beginning at an external work rate equivalent to 1 $W \cdot kg^{-1}$ of total body mass and subsequently increasing the work rate by 20 or 25 $W \cdot min^{-1}$ to volitional exhaustion.

Prior to each experimental trial, participants were instructed to avoid alcohol and strenuous exercise, and to consume a light meal and ~500 ml of water 2 h before arriving at the laboratory. Upon arrival, USG was determined to ensure euhydration, which was accepted at values ≤ 1.025 (27). After a nude body mass measurement was taken, participants donned a standard clothing ensemble consisting of cotton athletic shorts, socks, athletic footwear, and a sports bra for female participants. Following instrumentation, including application of the absorbent material to simulate a 40% BSA burn injury, participants entered the climate chamber with ambient conditions of 39.3 ± 0.3°C and 20.6 ± 3.0% RH. After a 30-min baseline equilibration period, participants cycled for 60 min at an external work rate that elicited an absolute H_{prod} (~500 W) or mass-specific H_{prod} (~5.3 $W \cdot kg^{-1}$), which reflect moderate-to-high intensity non-weight-bearing Army activities such as lifting or digging (28) and weight-bearing Army activities such as foot patrol (23), respectively. External work rate was adjusted as necessary to maintain the target H_{prod}. For the LG group, only a single experimental visit was needed since the target body size and H_{prod} for this group ensured that 500 W corresponded to ~5.3 $W \cdot kg^{-1}$. Meeting these target H_{prod} required an additional experimental condition for SM because of the targeted difference in body size between groups. Bottled water was provided *ad libitum*. To ensure that water ingestion did not cause fluctuations in core temperature measurements, bottled water was kept in a water bath maintained at core temperature and drinking was permitted only after obtaining measurements at the time points used in the statistical analysis (see below).

Calculations

Metabolic rate (M) was calculated using indirect calorimetry from VO_2, the respiratory exchange ratio (RER, VCO_2/VO_2), and the caloric equivalents for carbohydrate (e_c, 21.12 $kJ \cdot L^{-1}$ O_2) and fat (e_f, 19.61 $kJ \cdot L^{-1}$ O_2) oxidation (29):

$$M = VO_2 \cdot \frac{\left(\left(\frac{RER - 0.7}{0.3}\right)e_c\right) + \left(\left(\frac{1.0 - RER}{0.3}\right)e_f\right)}{60} \cdot 1000\ [W]$$

H_{prod} was taken as the difference between the metabolic rate and external work rate, which was regulated using a semi-recumbent electronically-braked cycle ergometer (Lode Corival, Groningen, Netherlands).

Statistical Analyses

Single comparisons of mean participant characteristics, heat balance parameters, baseline core temperatures, and 60-min core temperature changes were made using independent-samples t-tests. Core temperature data were analyzed as average values collected over 2-min time periods ending at 0, 15, 30, 45, and 60 min of exercise. For each condition, a two-way mixed model analysis of variance was used with the non-repeated factor of body size (LG and SM) and the repeated factor of time (0, 15, 30, 45, and 60 min). A Bonferonni correction for multiple comparisons was applied at each time point. Statistical analyses were performed using commercially-available software (GraphPad Prism version 7.0, La Jolla, CA). Data are reported as means ± standard deviations. P values < 0.05 were considered statistically significant.

RESULTS

Participant Characteristics

Mean participant characteristics are presented in Table 1. Groups were not different with regard to age ($P = 0.11$), but the SM group tended to exhibit lower absolute VO_{2max} values ($P = 0.06$). By design, the LG group demonstrated greater body mass, height, total BSA, and effective BSA (all $P < 0.01$).

Exercise at a Fixed Absolute Rate of Metabolic Heat Production

Details related to exercise intensity for the fixed absolute H_{prod} trial are presented in Table 2. To achieve a target absolute H_{prod} of ~500 W, similar external work rates were prescribed between groups ($P = 0.28$). However, due to lower body mass and VO_{2max} values in the SM group, exercise at the same absolute H_{prod} led to significantly greater mass-specific H_{prod} values and relative exercise intensities (%VO_{2max}) in the SM group ($P < 0.01$).

Prior to exercise, baseline gastrointestinal (SM: 37.19 ± 0.23°C, LG: 37.31 ± 0.19°C, $P = 0.19$) and esophageal (SM: 36.44 ± 0.25°C, LG: 36.47 ± 0.21°C, $P = 0.82$) temperatures were not different between groups. The 60-min changes in both gastrointestinal (SM: 1.69 ± 0.26°C, LG: 1.05 ± 0.26°C; $P < 0.01$) and esophageal (SM: 1.60 ± 0.29°C, LG: 0.97 ± 0.27°C, $P < 0.01$) temperatures were significantly greater in SM compared to LG, with between-groups differences in both indices of core temperature evident from 15 min onward (Fig. 1).

Exercise at a Fixed Mass-specific Rate of Metabolic Heat Production

Due to differences in body mass between the SM and LG groups, meeting the target mass-specific H_{prod} of 5.3 W·kg^{-1} required a lower external work rate and absolute H_{prod} in the SM group (Table 3). No differences in %VO_{2max} were found between groups at a H_{prod} of 5.3 W·kg^{-1} (Table 3).

Baseline gastrointestinal (SM: 37.15 ± 0.25°C, LG: 37.31 ± 0.19°C, $P = 0.11$) and esophageal (SM: 36.48 ± 0.30°C, LG: 36.47 ± 0.21°C, $P = 0.92$) temperatures were no different between SM and LG groups. During the ensuing exercise bout (Fig. 2), the 60-min change in gastrointestinal (SM: 0.99 ± 0.32°C, LG: 1.05 ± 0.26°C, $P = 0.66$) and esophageal (SM: 0.96 ± 0.30°C, LG: 0.97 ± 0.27°C, $P = 0.93$) temperatures were not different between groups, with no differences in the changes in gastrointestinal and esophageal temperatures found at any time point.

DISCUSSION

Using a simulated burn injury model to replicate the effect of a 40% total BSA burn injury (i.e., the U.S. Army's cut-off for inclusion of burned personnel) on whole-body evaporative heat loss during uncompensable exercise-heat stress, the present study investigated whether (i) elevations in core temperature are greater among individuals of smaller body size during exercise eliciting the same absolute H_{prod} in watts (W); and (ii) elevations in core temperature are similar during exercise eliciting the same mass-specific H_{prod} between groups of vastly different body size. In accordance with our hypotheses, the current data indicate that with a "burn injury" of 40% total BSA, prolonged exercise performed at the same absolute H_{prod} leads to greater elevations in core temperature among individuals of smaller body size due to a higher corresponding mass-specific H_{prod} (W·kg^{-1}) (Fig. 1). However, when exercise is performed by individuals of different body sizes at the same mass-specific H_{prod}, the effect of body mass is normalized and core temperature increases to the same extent regardless of body size (Fig. 2). These findings suggest that among morphologically-disparate Army soldiers or recruits with a burn injury of 40% TBSA, a larger body size is advantageous during non-weight-bearing tasks eliciting fixed rates of metabolic heat production, but is neither advantageous nor deleterious during weight-bearing tasks.

The current study is the first to systematically investigate the effect of body size on core temperature regulation with a fixed %TBSA (albeit simulated) burn injury during exercise-heat stress. Several previous studies examined core temperature responses to exercise between groups of burn survivors with different %TBSA injuries, but matched for morphological features (19–21). Additionally, some prior investigations examined single cases or small groups of burn survivors of different body sizes and %TBSA injuries; however, limited sample sizes in these studies preclude generalization of those findings (15, 30). By including two groups with vastly different morphological features, prescribing exercise intensities that permit comparisons at absolute or mass-specific H_{prod} values, and using a simulated burn injury model to impede evaporative heat dissipation over precisely 40% of TBSA, our experimental approach allowed us to assess the impact of body size on exercise thermoregulation in burn survivors with the same %TBSA during weight-independent and weight-dependent tasks.

Higher elevations in core temperature in the SM group compared to the LG group at the same absolute H_{prod} (Figure 1) are explained by differences in two morphological factors between these groups: i.e., the effective BSA and body mass. In physiologically uncompensable heat stress, the magnitude of the elevation in core temperature over a fixed time period is related to heat storage and inversely related to body mass, where heat storage is determined by the H_{prod}-E_{max} difference, and E_{max} determined in part by the effective BSA for heat exchange (31). At the same absolute H_{prod}, elevations in core temperature should be higher in smaller individuals due to greater absolute heat storage, since a smaller absolute effective BSA for heat dissipation yields a lower absolute E_{max} and thus a greater H_{prod}-E_{max} difference, as well as a lighter body mass (7). Similar findings would be expected among burn survivors of different body sizes with the same %TBSA injury, with the only difference being that for a given absolute H_{prod}, heat storage and thus the rise in core temperature would be greater in burn-injured vs. non-injured individuals due to lower absolute effective BSA and E_{max} values. Therefore, among morphologically-disparate burn survivors with the same 40% TBSA injury, increases in core temperature and the ensuing risk for heat illness/injury are higher in smaller individuals performing mass-independent physical tasks that yield a fixed absolute H_{prod} (e.g., cycling, digging, lifting).

In contrast to the absolute H_{prod} trial, no difference in the core temperature response to exercise eliciting the same mass-specific H_{prod} was observed between LG and SM groups (Figure 2). This trial was included in the present study to replicate weight-bearing tasks, which typically elicit similar mass-specific H_{prod} values (23, 28). With the independent influence of body mass normalized (1, 7), elevations in core temperature during prolonged exercise at the same mass-specific H_{prod} under uncompensable heat stress will be dictated by the mass-specific value of E_{max}. Among individuals of different body sizes, mass-specific E_{max} values are lower in larger individuals due to a lower BSA-to-mass ratio (7). However, mass-specific H_{prod}-E_{max} values that differ between groups of larger and smaller individuals by ≤ 1 $W \cdot kg^{-1}$ are unlikely to produce significantly different elevations in core temperature between such groups (7). Although E_{max} was not directly assessed in the present investigation, based on the study conditions and a reasonable assumption of a 36°C mean skin temperature, mass-specific E_{max} values of ~2.7 and 3.2 $W \cdot kg^{-1}$ were estimated for the LG and SM groups, respectively (32), resulting in calculated mass-specific H_{prod}-E_{max} values of 2.6 and 2.2 $W \cdot kg^{-1}$ in LG and SM groups, respectively. The absence of any appreciable differences in these mass-specific H_{prod}-E_{max} values, as well as any significant difference in the core temperature response, between LG and SM groups reported herein (Figure 2) are in line with the findings of Ravanelli *et al.* in non-injured individuals (7).

Therefore, during weight-bearing tasks eliciting the same mass-specific H_{prod} values (e.g., running, foot patrol), the current findings suggest that for the same 40% TBSA injury, differences in body size do not alter the mass-specific E_{max} to an extent that affects the time-dependent rise in core temperature.

Perspectives

Currently, soldiers and recruits with burn injuries of ≥40% TBSA do not meet the U.S. Army's Standards of Medical Fitness. The current findings suggest that military personnel of a larger body size, despite the same 40% TBSA injury, would be at a thermoregulatory advantage during activities that elicit the same absolute H_{prod}, but not during weight-bearing activities that elicit the same mass-specific H_{prod}. It follows that during non-weight-bearing activities, a larger individual would have to either work at a higher intensity or have a burn injury >40% TBSA to achieve similar elevations in core temperature, and thus be at the same risk of heat illness, as a smaller individual with a 40% TBSA injury. Nonetheless, such a larger soldier would not meet the inclusion criterion. Therefore, the nature of physical tasks, the attendant H_{prod}, and body size, rather than a relative burn injury size of 40% TBSA alone, should be important considerations for inclusion of a soldier or recruit with a burn injury. Such considerations may improve the retention of personnel with burn injuries without impairing physical performance or increasing the risk of heat illness.

The present findings may also be applied in the physical rehabilitation of burn survivors. Post-injury exercise training performed at fixed absolute intensities (e.g., cycling at a target absolute intensity) may exacerbate the level of hyperthermia in burn survivors of smaller body size. Since heat intolerance is a common post-burn sequela, it is important for clinicians to recognize that patients of smaller body size with burn injuries should exercise at lower absolute intensities, under cooler conditions, and/or while using external cooling devices.

Considerations

The use of a simulated burn injury model has some limitations. Firstly, application of any material to the skin surface will create resistance to dry heat exchange. Since air temperature exceeded body surface temperature in this study, the insulation imposed by the absorbent patches would have resisted body heat gain via convection and radiation; however, this effect would have been minimal due to the narrow skin-air temperature gradient (~2°C within areas covered by the absorbent material) and minimal air velocity ($\sim 0.2\ \mathrm{m \cdot s^{-1}}$). Secondly, the simulated injury model is unlikely to produce quantitatively similar whole-body sweat rate responses to exercise-heat stress as in burn survivors with the same reduction in effective BSA, since sudomotor responses are still engaged in skin areas with the simulated burn injury.

Another aspect of the absorbent material worth noting is its absorbent capacity, and whether high sweat rates in covered areas can saturate the material, and thereby potentially impact the results. Preliminary testing revealed that the material used has an absorbent capacity of $\sim 1{,}520\ \mathrm{g \cdot m^{-2}}$. Based on pre- vs. post-exercise changes in body mass (assumed to be largely indicative of sweat losses), the highest sweat loss in any subject from covered areas was estimated to be 425 $g \cdot m^{-2}$, representing only 30% of the absorbent capacity. Therefore, it is unlikely that high sweat losses saturated the absorbent material and impacted the observed results.

Some individuals in the SM group found that maintaining the target intensity was very challenging in the absolute H_{prod} trials, and as a result, the work intensity was lowered in these individuals to ensure trial completion. Consequently, the rate of metabolic heat production was lower in SM vs. LG in the absolute H_{prod} condition by ~47 W, though not significantly (Table 2). It is important to note, however, that had these individuals been able to maintain the target rate of metabolic heat production, this would have only further exacerbated the difference in the core temperature responses between groups in the 500 W trial, which does not change the interpretation of the findings.

The present study was conducted at one intensity per condition (i.e., absolute and mass-specific H_{prod} values), under a single combination of air temperature and relative humidity, and with minimal clothing. Such conditions would make the current findings most applicable during training exercises performed in hot-dry climates, but would limit application in conditions of greater humidity, those requiring vapor-impermeable clothing, etc. Additionally, soldiers are often required to carry heavy loads during training and operational activities. The extent to which body size would influence the core temperature response to prolonged exercise-heat stress during load carriage in individuals with a particular %TBSA injury is unknown. However, it is conceivable that heavy load carriage of a fixed mass would exacerbate the mass-specific H_{prod} during prolonged work to a greater extent in individuals of smaller *versus* larger body size (33), leading to greater elevations in core temperature in smaller individuals. Therefore, future studies should address how different work intensities, environmental conditions, clothing ensembles, and load carriage alter the thermoregulatory responses to exercise among burn survivors with a particular %TBSA injury.

CONCLUSION

Using a simulated burn injury model, the present data suggest that a burn injury spanning 40% of total body surface area leads to heightened elevations in core temperature during prolonged exercise-heat stress at a work intensity eliciting a fixed absolute rate of metabolic heat production (i.e., an intensity with an absolute energetic requirement) among individuals of smaller body size due to a combination of a lower body mass and a reduced effective body surface area for heat exchange. However, when prolonged work is performed at a fixed rate of metabolic heat production per unit of total body mass (e.g., weight-bearing exercise), individuals with a burn injury of 40% total body surface area exhibit similar elevations in core temperature, irrespective of body size.

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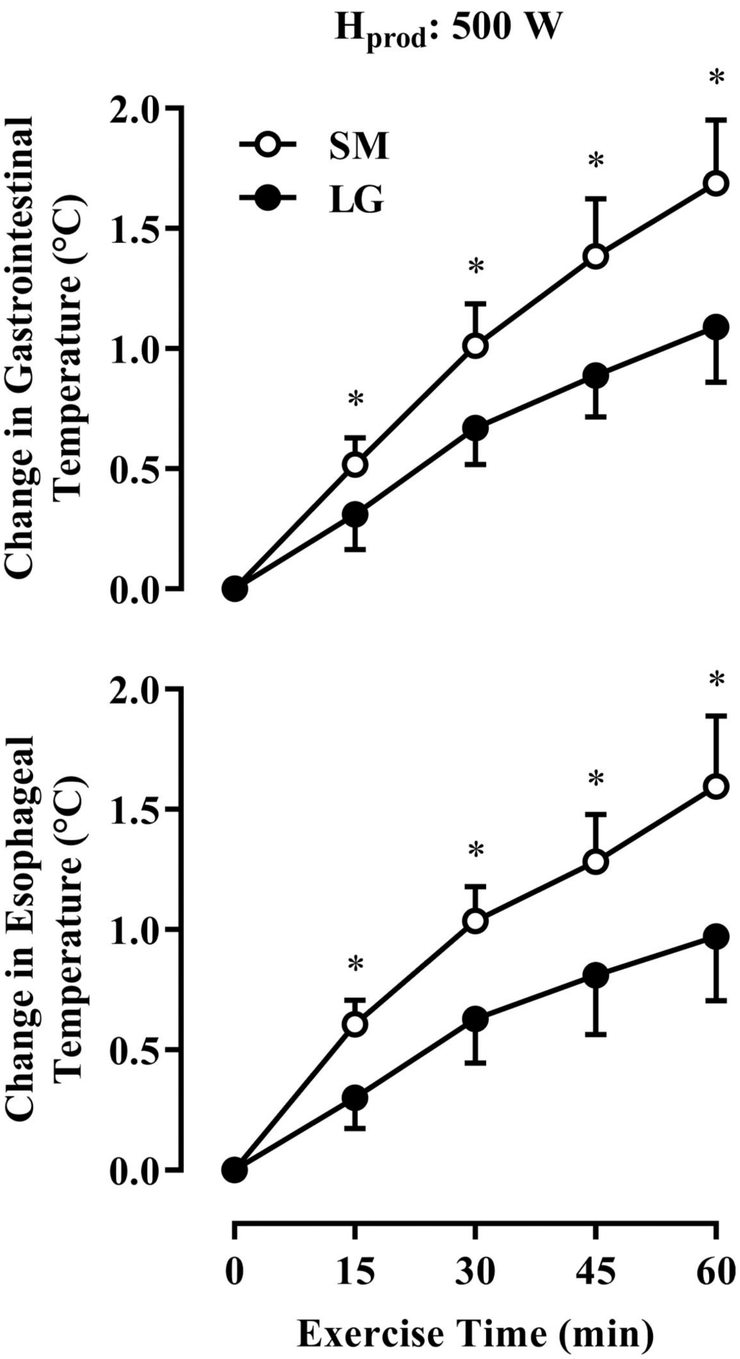

Figure 1—.

Changes in gastrointestinal temperature (*top*; n=11) and esophageal temperature (*bottom*; n=7) in groups of small (SM) or large (LG) body size throughout 60 min of exercise on a cycle ergometer eliciting an absolute rate of metabolic heat production (H_{prod}) of 500 W. Data represent means ± standard deviations. * Significantly greater in SM ($P < 0.05$).

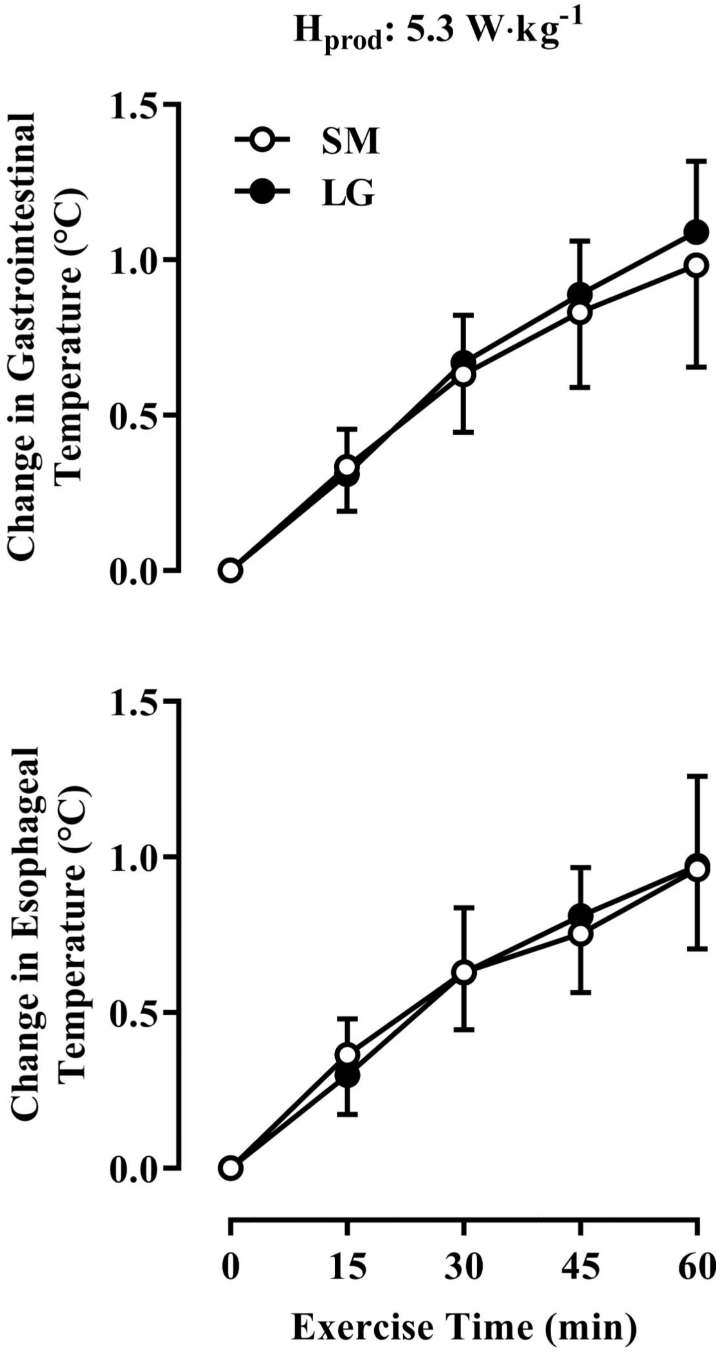

Figure 2—.

Changes in gastrointestinal temperature (*top*; n=11) and esophageal temperature (*bottom*; n=7) in groups of small (SM) or large (LG) body size throughout 60 min of exercise on a cycle ergometer eliciting an absolute rate of metabolic heat production (H_{prod}) of 5.3 W·kg^{-1}. Data represent means ± standard deviations.

Table 1.

Characteristics of participants in the large (LG, n=11) or small (SM, n=11) body size groups.

	LG	SM (500 W)	SM (5.3 W·kg−1)
Age (years)	29 ± 7	26 ± 8	23 ± 5
VO_{2max} ($L \cdot min^{-1}$)	3.99 ± 0.74 *	3.30 ± 0.72	3.13 ± 0.78
VO_{2max} ($mL \cdot kg^{-1} \cdot min^{-1}$)	43.9 ± 8.3	50.3 ± 12.7	51.5 ± 11.6
Body Mass (kg)	96.15 ± 9.79 *	64.51 ± 4.33	61.17 ± 6.61
Height (m)	1.88 ± 0.04 *	1.72 ± 0.07	1.70 ± 0.06
BMI ($kg \cdot m^{-2}$)	27.3 ± 3.1 *	21.7 ± 2.2	21.1 ± 1.5
BSA (m^2)	2.22 ± 0.10 *	1.76 ± 0.07	1.70 ± 0.12
Effective BSA (m^2)	1.33 ± 0.06 *	1.05 ± 0.04	1.02 ± 0.07

Note: Two groups of SM individuals were included, one of which performed exercise at an intensity targeting a rate of heat production of 500 W, and one of which performed exercise at an intensity targeting a rate of heat production of 5.3 $W \cdot kg^{-1}$ of body mass. The LG group performed a single bout of exercise that targeted a rate of heat production of 500 W and 5.3 $W \cdot kg^{-1}$ simultaneously.

Data represent means ± standard deviations.

* Significantly greater in LG vs. both SM groups.

VO_{2max}, maximal rate of oxygen uptake; BSA, body surface area.

Table 2.

Heat balance parameters at a target heat production of 500 W in participants of large (LG) or small (SM) body size.

	LG	SM	***P*-value**
External Work (W)	97 ± 11	104 ± 10	0.28
H_{prod} (W)	510 ± 45	463 ± 43	0.06
H_{prod} ($W \cdot kg^{-1}$)	5.3 ± 0.4	7.1 ± 0.9 *	< 0.01
$\%VO_{2max}$	44.1 ± 5.6	53.9 ± 7.4 *	0.01

Data represent means ± standard deviations for 11 participants per group.

*Significantly greater in SM compared to LG.

H_{prod}, rate of metabolic heat production.

$\%VO_{2max}$, percentage of maximal oxygen uptake.

Table 3.

Heat balance parameters at a target heat production of 5.3 W·kg^{-1} in participants of large (LG) or small (SM) body size.

	LG	**SM**	***P*-value**
External work (W)	97 ± 11 [*]	75 ± 8	< 0.01
H_{prod} (W)	510 ± 45 [*]	331 ± 40	< 0.01
H_{prod} (W·kg^{-1})	5.3 ± 0.4	5.4 ± 0.2	> 0.99
%VO_{2max}	44.1 ± 5.6	39.5 ± 7.6	0.56

Data represent means ± standard deviations for 11 participants per group.

[*] Significantly greater in LG compared to SM.

H_{prod}, rate of metabolic heat production.

%VO_{2max}, percentage of maximal oxygen uptake.