A comparison of thermoregulatory responses to exercise between mass-matched groups with large differences in body fat

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Dervis S, Coombs GB, Chaseling GK, Filingeri D, Smoljanic J, Jay O. A comparison of thermoregulatory responses to exercise between mass-matched groups with large differences in body fat. J Appl Physiol 120: 615–623, 2016. First published December 24, 2015; doi:10.1152/japplphysiol.00906.2015. We sought to determine 1) the influence of adiposity on thermoregulatory responses independently of the confounding biophysical factors of body mass and metabolic heat production (Hprod); and 2) whether differences in adiposity should be accounted for by prescribing an exercise intensity eliciting a fixed Hprod per kilogram of lean body mass (LBM). Nine low (LO-BF) and nine high (HI-BF) body fat males matched in pairs for total body mass (TBM; LO-BF: 88.7 ± 8.4 kg, HI-BF: 90.1 ± 7.9 kg; P = 0.72), but with distinctly different percentage body fat (%BF; LO-BF: 10.8 ± 3.6%; HI-BF: 32.0 ± 5.6%; P < 0.001), cycled for 60 min at 28.1 ± 0.2°C, 26 ± 8% relative humidity (RH), at a target Hprod of 1) 550 W (FHP trial) and 2) 7.5 W/kg LBM (LBM trial). Changes in rectal temperature (∆Tre) and local sweat rate (LSR) were measured continuously while whole body sweat loss (WBLS) and net heat loss (Hloss) were estimated over 60 min. In the FHP trial, ∆Tre (LO-BF: 0.66 ± 0.21°C, HI-BF: 0.87 ± 0.18°C; P = 0.02) was greater in HI-BF, whereas mean LSR (LO-BF 0.52 ± 0.19, HI-BF 0.43 ± 0.15 mg·cm⁻²·min⁻¹; P = 0.19), WBLS (LO-BF 586 ± 82 mL, HI-BF 559 ± 75 mL; P = 0.47) and Hloss (LO-BF 1,867 ± 208 kJ, HI-BF 1,826 ± 224 kJ; P = 0.69) were all similar. In the LBM trial, ∆Tre (LO-BF 0.82 ± 0.18°C, HI-BF 0.54 ± 0.19°C; P < 0.001), mean LSR (LO-BF 0.59 ± 0.20, HI-BF 0.38 ± 0.12 mg·cm⁻²·min⁻¹; P = 0.04), WBLS (LO-BF 580 ± 106 mL, HI-BF 381 ± 68 mL; P < 0.001), and Hloss (LO-BF 1,884 ± 277 kJ, HI-BF 1,341 ± 184 kJ; P < 0.001) were all greater at end-exercise in LO-BF. In conclusion, high %BF individuals demonstrate a greater ∆Tre independently of differences in mass and Hprod, possibly due to a lower mean specific heat capacity or impaired sudomotor control. However, thermoregulatory responses of groups with different adiposity levels should not be compared using a fixed Hprod in watts per kilogram lean body mass.

adiposity; biophysics; heat balance; sweating; temperature regulation

ACCORDING TO THE WORLD HEALTH ORGANIZATION (WHO), a person with excess body fat is more susceptible to greater levels of heat strain during exercise relative to a leaner individual by virtue of the insulative properties of fat tissue reducing heat dissipation from the skin (27). As such, it is proposed that less heat can be produced per unit body mass before core temperature increases by a given magnitude (27). While this notion has important public health implications since some physical activity guidelines potentially discourage exercise in overweight/obese individuals during bouts of warm weather, it is also an essential consideration for physiologists wishing to assess the independent influence of factors such as age (13, 36), injury (31), and disease (10, 22, 39) on changes in core temperature and sweating during exercise. As these study types almost always adopt a between-group experimental design, it must be ensured that the selected exercise intensity does not lead to systematic differences in thermoregulatory responses between groups secondary to disparities in metabolic heat production (Hprod) and/or the evaporative requirement for heat balance (Ereq) (7).

A recent series of studies from our laboratory has demonstrated that changes in core temperature should be compared between groups of dissimilar body size using an exercise intensity that elicits a fixed Hprod per unit total body mass (in W/kg TBM) (8), whereas whole body sweat losses (in g/min) and local sweat rates (in mg·cm⁻²·min⁻¹) should be compared using a fixed Hprod (in W and W/m², respectively) (8, 15, 38), due to its predominant contribution to Ereq (23). The observation of any subsequent differences in core temperature and/or sweating between groups can then be confidently attributed to an independent influence of the factor under investigation as opposed to an underlying bias arising from the experimental design. However, whether Hprod should be further adjusted to account for any differences in body fat that often occur between experimental groups, particularly those with different diseases, has not yet been determined.

While the lower specific heat of fat (2.97 kJ·kg⁻¹·°C⁻¹) relative to lean mass (3.66 kJ·kg⁻¹·°C⁻¹) should theoretically lead to a greater temperature change for a given amount of heat energy stored inside the body, a 20% difference in fat mass only leads to a minor difference (~3-5%) in mean specific heat of the total body (17). However, it is also possible that due to its low thermal conductivity, fat mass may not fully contribute to the total body mass “heat sink” (16). The insulative properties of subcutaneous fat could also impair skin surface heat loss (3), but probably only in cooler environments (19). And while “core-to-shell” heat transfer primarily occurs convectively via the bloodstream, there appears little reason to suspect body fat interferes with sweat production and/or evaporation.

All previous studies examining the role of body fatness on thermoregulatory responses during exercise in a compensable environment are apparently confounded by differences in total body mass, Hprod, and/or Ereq between lean and obese groups. For example, Limbaugh et al. (29) recently reported similar changes in core temperature between groups with a low (11%) and moderate (23%) percentage body fat (%BF) cycling at a fixed external workload (66 W) and therefore presumably very similar absolute rates of Hprod. However, since total body mass

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was vastly different (78.5 ± 9.4 vs. 91.9 ± 14.9 kg) between groups (29), \( H_{\text{prod}} \) in watts per kilogram would have been lower in the higher body fat group, which potentially masked any thermoregulatory impairments in the higher fat group. A classic study by Bar-Or et al. (4) reported a “higher heat strain” in obese (31% BF) compared with lean (15% BF) women during treadmill walking at 4.8 km/h with a 5% grade, after observing a greater whole body sweat rate despite similar changes in rectal temperature. However, the additional energetic cost of carrying the much greater body mass of the obese group (90.5 vs. 51.6 kg) would have elicited a greater \( E_{\text{req}} \) and therefore a greater biophysical requirement for whole body sweating unrelated to fat per se.

It has been proposed that the supposed confounding influence of \%BF on thermoregulatory responses can be eliminated by selecting an exercise intensity that elicits the same \( H_{\text{prod}} \) per unit lean body mass (W/kg LBM) (16). However, if \%BF does not substantially influence the maintenance of core body temperature during exercise, such an approach would inadvertently lead to systematically greater sweat rates in lean individuals due to a greater \( E_{\text{req}} \) (8, 15, 24), and greater changes in core temperature due to a greater \( H_{\text{prod}} \) per kilogram total body mass (8).

The first aim of the present study was to assess for the first known time whether large differences in \%BF truly alter changes in core temperature and thermoregulatory sweating during exercise in a compensable environment by recruiting two independent groups matched for total body mass and body surface area but vastly different in \%BF, and prescribing an exercise intensity to elicit the same absolute \( H_{\text{prod}} \) and therefore simultaneously the same \( H_{\text{prod}} \) in watts per kilogram, and \( E_{\text{req}} \) in watts and watts per square meter. The second aim was to assess the utility of a fixed \( H_{\text{prod}} \) per unit lean body mass (in W/kg LBM) for the comparison of thermoregulatory responses between groups differing greatly in \%BF. It was hypothesized that after matching low (~10%) and high (>30%) body fat participants for total body mass, BSA, age, and sex, changes in core temperature and sweating during exercise would be 1) similar, at an absolute fixed \( H_{\text{prod}} \) (550 W) despite large differences in \( H_{\text{prod}} \) per unit lean body mass, and 2) significantly greater in the low body fat group at the same \( H_{\text{prod}} \) per lean body mass (7.5 W/kg LBM) due to a greater total \( H_{\text{prod}} \) per unit total mass and greater corresponding \( E_{\text{req}} \).

**METHODS**

**Participants**

Using G*Power 3 software [Heinrich-Heine-Universität Düsseldorf, Germany (14)], a power calculation was performed with an \( \alpha \) of 0.05, a \( \beta \) of 0.20, and an effect size of 1.10, determined from the smallest significant difference in the primary outcome variable (\( \Delta T_{\text{tre}} \)) from previous studies employing a similar protocol (8, 24, 38). A minimum sample size of 9 individuals per group was determined; therefore, 18 [9 low BF, 10.7 ± 4.1% (LO-BF group); and 9 high BF, 32.2 ± 6.5% (HI-BF group)] healthy, nonsmoking, and normotensive Caucasian males volunteered for the study. Participants from the LO-BF and HI-BF group were specifically matched in pairs for total body mass (group means: LO-BF 87.8 ± 8.5 kg; HI-BF 89.4 ± 7.8 kg). All participants were similar in age (LO-BF 24 ± 2 yr; HI-BF 25 ± 6 yr) and refrained from the consumption of caffeine or alcohol and any form of strenuous exercise 24 h prior to the experimental trials. Prior to testing, the Research Ethics Board at the University of Ottawa and the University of Sydney approved the experimental protocol. The eligible participants completed a Physical Activity Readiness Questionnaire (PAR-Q), American Heart Association questionnaire (AHA), and informed consent form before experimentation and were excluded if they had cardiovascular or metabolic health disorders. The first seven LO-BF/HI-BF pairs of participants (pairs 1–7; Table 1) were tested at the University of Ottawa, and an additional two LO-BF/HI-BF pairs of participants (pairs 8–9; Table 1) were tested in the Thermal Ergonomics Laboratory at the University of Sydney, Sydney, Australia, using the identical experimental protocol and instrumentation as described below.

**Instrumentation**

Rectal temperature (\( T_{\text{re}} \)) was measured with a pediatriic thermistor probe (Mon-a-therm General Purpose Temperature Probe; Mallinckrodt Medical) inserted to a minimum of 12 cm past the anal sphincter. Skin temperatures (\( T_{\text{sk}} \)) were measured at eight separate sites: forehead (\( T_{\text{f}} \)), triceps (\( T_{\text{t}} \)), shoulder (\( T_{\text{s}} \)), scapula (\( T_{\text{sc}} \)), chest (\( T_{\text{ch}} \)), back of the hand (\( T_{\text{hand}} \)), thigh (\( T_{\text{quad}} \)), and calf (\( T_{\text{c}} \)), using T-type (copper/constantan) thermocouples. Mean \( T_{\text{sk}} \) was calculated using a weighted average of each site (35):

**Table 1. Mean physical characteristics for low (LO-BF) and high (HI-BF) body fat participants matched in pairs for body mass**

<table>
<thead>
<tr>
<th>Pair No.</th>
<th>Body Mass, kg</th>
<th>Body Fat, %</th>
<th>LBM, kg</th>
<th>BSA, m²</th>
<th>( C_{\theta} ), kJ·kg⁻¹·C⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>J</td>
<td>94.8</td>
<td>94.7</td>
<td>66.2</td>
<td>68.9</td>
<td>2.19</td>
</tr>
<tr>
<td>2</td>
<td>100.0</td>
<td>99.5</td>
<td>91.3</td>
<td>84.7</td>
<td>67.9</td>
</tr>
<tr>
<td>3</td>
<td>83.6</td>
<td>85.2</td>
<td>85.7</td>
<td>76.5</td>
<td>62.2</td>
</tr>
<tr>
<td>4</td>
<td>80.6</td>
<td>84.2</td>
<td>94.9</td>
<td>77.0</td>
<td>63.6</td>
</tr>
<tr>
<td>5</td>
<td>83.9</td>
<td>85.1</td>
<td>14.8</td>
<td>71.5</td>
<td>48.7</td>
</tr>
<tr>
<td>6</td>
<td>94.5</td>
<td>97.5</td>
<td>14.2</td>
<td>81.1</td>
<td>71.0</td>
</tr>
<tr>
<td>7</td>
<td>77.3</td>
<td>79.3</td>
<td>7.8</td>
<td>71.3</td>
<td>53.1</td>
</tr>
<tr>
<td>8</td>
<td>98.8</td>
<td>100.4</td>
<td>12.0</td>
<td>86.9</td>
<td>68.4</td>
</tr>
<tr>
<td>9</td>
<td>84.6</td>
<td>84.8</td>
<td>10.2</td>
<td>76.0</td>
<td>58.2</td>
</tr>
<tr>
<td>Mean</td>
<td>88.7</td>
<td>90.1</td>
<td>10.8</td>
<td>79.0*</td>
<td>61.4</td>
</tr>
<tr>
<td>SD</td>
<td>8.4</td>
<td>7.9</td>
<td>3.6</td>
<td>6.0</td>
<td>7.4</td>
</tr>
</tbody>
</table>

Body surface area (BSA) estimated using the equation of DuBois and DuBois (11a). Body fat % and lean body mass (LBM) were measured using dual-energy X-ray absorptiometry (DXA). Mean specific heat of the body (\( C_{\theta} \)) was subsequently estimated by assigning different specific heat capacity values to the various components of lean mass (i.e., muscle, skin, blood, white matter, gray matter, eye, nerve, lens, and cartilage), fat mass, and bone mass (17). *Significantly greater value (\( P < 0.05 \)). See Protocol for specific description of FHP trial and LBM trial.
Whole body sweat rate. Whole body sweat rate (WBSSR) was estimated by calculating the average rate of sweat evaporation from the body surface during exercise. The theoretical sweating rate (in g/min) was estimated using:

\[ W_{BSR} = \frac{W_{BSL}}{t} \]

where \( W_{BSL} \) is the cumulative whole body sweat loss over the exercise bout (in g) and \( t \) is the duration of the exercise bout in minutes.

Local sweat rate. Local sweat rate (LSR) was estimated by placing a ventilated sweat capsule on the forearm and upper back. The LSR, expressed as milligrams per centimeters squared per minute, was calculated using:

\[ LSR = \frac{\text{mass change}}{\text{area} \times \text{time}} \]

where the mass change is the difference between the initial and final mass of the sweat capsule, the area is the surface area of the sweat capsule, and the time is the duration of the measurement.

Heat transfer coefficient. The heat transfer coefficient \( h \) was calculated using the equation:

\[ h = 8.3 \cdot v^{0.4}(W \cdot m^{-2} \cdot K^{-1}) \]

where \( v \) is the velocity of the air flow over the body surface.

The evaporative requirement for heat balance \( E_{res} \) was calculated using:

\[ E_{res} = H_{prod} - (C + R) - (C_{res} + E_{res}) \]

where \( H_{prod} \) is the metabolic heat production, \( C + R \) is the sensible heat loss, \( C_{res} \) is the respiratory heat loss, and \( E_{res} \) is the evaporative heat loss.

Experimental Design

All participants completed one preliminary trial and two experimental trials. All participants completed the experimental trials at the same time of day to prevent any influence of circadian rhythm variation. It is assumed that all participants were not heat acclimatized. For the first 7 LO-BF/HI-BF pairs of participants tested in Ottawa, no seasonal acclimatization is evident for individuals of this age residing in this geographical region. For the additional 2 LO-BF/HI-BF pairs of participants tested in Sydney, these data were collected in the southern hemisphere winter (July/August) during which time the average daily maximum ambient temperature was \( \sim 17^\circ C \). To confirm participants were euhydrated prior to each experimental trial, they were instructed to drink plenty of fluids the night before. On the day of testing, participants ingested an additional 500 ml of water and prior to exercise participants provided a urine sample, which was analyzed for urine specific gravity (USG) using a refractometer (Reichert TS 400, Depew, NY). All participants were required to have a USG below 1.020 to ensure euhydration before exercise (2, 34).

Environmental conditions during each experimental trial were an air temperature \( T_a \) of 28.1 ± 0.2°C, relative humidity (RH) of 26 ± 8% and an air velocity of 0.8 m/s. The ambient conditions and the target rates of heat production were selected to ensure that the level of heat stress was physiologically compensable and the full evaporation of sweat was permitted in all participants. All participants exercised...
semimude in standardized shorts (dry insulation and evaporative resistance of clothing were considered negligible).

Protocol
In the preliminary trial, total body mass and height were measured with a platform scale and stadiometer, respectively. Body fat percentage (BF%) and lean body mass (LBM) were also measured using a Dual-Energy X-Ray Absorptiometry (DXA). Mean specific heat of the body (Cp) was estimated by assigning different specific heat capacity values to the various components of lean mass (i.e., muscle, skin, blood, white matter, gray matter, eye, nerve, lens, and cartilage), fat mass, and bone mass (17). Body surface area (BSA) was estimated using the equation of DuBois and DuBois (5). Subsequently, peak oxygen consumption (VO2peak) was measured using a semirecumbent cycle ergometer involving a graded 16 min warm-up to determine the individualized workload required for each target heat production (8), which was followed by a short break, and then a maximal test where the external workload increased by 20 W every minute until physical exhaustion. The VO2 peak protocol followed the Canadian Society of Exercise Physiology guidelines (9).

In the experimental trials, after instrumentation, participants entered the climate-controlled room and were first seated for a 30-min baseline period. Afterwards, participants cycled for 60 min at an external workload that elicited a fixed absolute heat production of 500 W (FHP trial), or a fixed metabolic heat production of 7.5 W per kilogram of lean body mass (LBM trial). The initial workload was determined based on the target Hprod using the procedure described previously (8), with external workload adjusted slightly throughout if necessary. At 15-min intervals, the participant briefly (60 s) stopped to be weighed. Participants were not towed down prior to each body mass measurement to avoid an overestimation of evaporative heat loss. Participants did not drink any fluid throughout exercise.

Statistical Analysis
All data were expressed as means ± SD and analyzed within exercise trials (i.e., FHP trial and LBM trial). A two-way mixed ANOVA was used to analyze the data, with the repeated factor of “time” (at five levels: 0, 15, 30, 45, and 60 min of exercise for ΔTrec, Trec, LSR (mean of upper-back and forearm); and at four levels: 0–15, 15–30, 30–45, 45–60 min of exercise for WBSR]; and the nonrepeated factor of “body fat group” (2 levels: high body fat and low body fat). Any significant interaction or main effect was subjected to post hoc comparisons using a Bonferroni correction. All statistical analyses were performed using GraphPad Prism (v6.0, GraphPad Software, La Jolla, CA).

RESULTS

Physical Characteristics
Mean participant characteristics for each mass-matched LO/ HI-BF pair are presented in Table 1. By design, no differences in total body mass (P = 0.72) or body surface area (P = 0.36) were observed between LO-BF and HI-BF groups, but a significantly greater %BF was observed in the HI-BF group (P < 0.001). Consequently, lean body mass (P < 0.001) and specific heat capacity (P < 0.001) were greater in the LO-BF group. VO2peak was also greater (P = 0.003) in the LO-BF (47.7 ± 7.2 ml·kg⁻¹·min⁻¹) compared with the HI-BF (37.8 ± 5.8 ml·kg⁻¹·min⁻¹) group.

External Workload, Heat Production, and Evaporative Requirements for Heat Balance (Ereq)
Average Hprod, Ereq, and external workload values for both trials are presented in Table 2. In the FHP trial, Hprod was, as intended, similar between groups in watts (P = 0.73), and therefore similar in watts per kilogram TBM (P = 0.89). However, Hprod in watts per kilogram LBM was significantly (P < 0.001) greater in the HI-BF group. Ereq was similar between LO-BF and HI-BF in watts (P = 0.92), and watts per square meter (P = 0.57). In parallel, external workload was the same between groups (P = 0.13).

In the LBM trial, Hprod in watts per kilogram LBM was successfully maintained the same for both groups (P = 0.88). In parallel, external workload was significantly greater in the LO-BF group (P = 0.002), as were Ereq in watts and watts per kilogram TBM, and Ereq in watts and watts per square meter (all P < 0.001).

Core Temperature
In the FHP trial, after 60 min of exercise the change in Trec in the HI-BF (0.88 ± 0.18°C) group was greater (P = 0.022) compared with the LO-BF (0.66 ± 0.21°C) group (Fig. 1A). On the other hand, in the LBM trial, the change in Trec from rest to the end of exercise was greater (P < 0.001) in the LO-BF group (0.82 ± 0.18°C) compared with the HI-BF group (0.54 ± 0.19°C). A difference was observed between LO-BF and HI-BF after 30 min of exercise, which was subsequently sustained for the remainder of exercise (Fig. 1B).

Table 2. Average external workload, metabolic heat production, evaporative heat balance requirements (Ereq) and relative exercise intensities for low (LO-BF) and high (HI-BF) body fat participant groups for exercise in the FHP trial and LBM trial

<table>
<thead>
<tr>
<th>Trial</th>
<th>External Work, W</th>
<th>Metabolic Heat Production</th>
<th>Ereq</th>
<th>Ereq/m²</th>
<th>Relative Intensity, %VO2peak</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>W/kg TBM</td>
<td>W/kg LBM</td>
<td>W</td>
<td>W/m²</td>
<td></td>
</tr>
<tr>
<td>FHP trial</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LO-BF</td>
<td>99 ± 16</td>
<td>6.1 ± 0.7</td>
<td>6.9 ± 0.7</td>
<td>420 ± 61</td>
<td>199 ± 24</td>
</tr>
<tr>
<td>HI-BF</td>
<td>113 ± 22</td>
<td>6.1 ± 0.7</td>
<td>9.1 ± 1.3*</td>
<td>423 ± 45</td>
<td>206 ± 25</td>
</tr>
<tr>
<td>P value</td>
<td>0.13</td>
<td>0.89</td>
<td>&lt;0.001</td>
<td>0.92</td>
<td>0.57</td>
</tr>
<tr>
<td>LBM trial</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LO-BF</td>
<td>111 ± 17*</td>
<td>6.7 ± 0.7*</td>
<td>7.5 ± 0.7</td>
<td>464 ± 42*</td>
<td>220 ± 17*</td>
</tr>
<tr>
<td>HI-BF</td>
<td>80 ± 17</td>
<td>5.1 ± 0.6</td>
<td>7.6 ± 0.9</td>
<td>350 ± 62</td>
<td>169 ± 26</td>
</tr>
<tr>
<td>P value</td>
<td>0.002</td>
<td>&lt;0.001</td>
<td>0.88</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

Values given are means (± SD) in watts (W), watts per unit total body mass (W/kg TBM), watts per unit lean body mass (W/kg LBM), and watts per unit surface area (W/m²). VO2peak, peak oxygen consumption. *Significantly greater value (P ≤ 0.05).
Local Sweat Rate (LSR)

In the FHP trial, LSR of the forearm (P = 0.25) and upper back (P = 0.22) were similar between HI-BF and LO-BF groups throughout exercise (Fig. 3, A and B). At end-exercise, a similar upper back LSR of 0.55 ± 0.31 mg·cm⁻²·min⁻¹ was observed in the LO-BF group compared with 0.41 ± 0.17 mg·cm⁻²·min⁻¹ in the HI-BF group (P = 0.85). Similarly, end-exercise forearm LSR was not different between the LO-BF (0.52 ± 0.14 mg·cm⁻²·min⁻¹) and HI-BF (0.46 ± 0.15 mg·cm⁻²·min⁻¹) group (P = 0.99). In the LBM trial, LSR of the forearm and upper back were significantly greater in the LO-BF group after 15 min and 60 min of exercise, respectively (P < 0.05) (Fig. 3, C and D). At end-exercise, upper back LSR in the LO-BF group was 0.60 ± 0.34 mg·cm⁻²·min⁻¹, compared with 0.33 ± 0.11 mg·cm⁻²·min⁻¹ in the HI-BF group (P = 0.05). Likewise, end-exercise LSR of the forearm was 0.66 ± 0.18 mg·cm⁻²·min⁻¹ in the LO-BF group compared with 0.42 ± 0.15 mg·cm⁻²·min⁻¹ in the HI-BF group (P = 0.01)

Whole Body Sweating

In the FHP trial, whole body sweat loss (WBSL) after 60 min of exercise in the LO-BF group (586 ± 82 ml) was very similar (P = 0.47) to the HI-BF group (559 ± 75 ml). Likewise, whole body sweat rate (WBSR) was similar (P = 0.93) between LO-BF and HI-BF groups throughout exercise (Fig. 2A). In the LBM trial, WBSL after 60 min of exercise in the LO-BF group (580 ± 106 ml) was much greater (P < 0.001) than the HI-BF group (381 ± 68 ml). Correspondingly, WBSR was greater in the LO-BF group throughout exercise (P < 0.001) relative to the HI-BF group (Fig. 2B).

Mean Skin Temperature

In the FHP trial, mean skin temperature throughout the 60-min exercise bout was similar (P = 0.64) between the HI-BF group (33.03 ± 0.92°C) and the LO-BF group (32.79 ± 1.17°C). Likewise, in the LBM trial mean skin temperature in the HI-BF group (32.59 ± 0.85°C) was not different (P = 0.53) from the LO-BF group (32.37 ± 0.57°C).

Whole Body Calorimetry

Partitional calorimetry were given in Table 3. In the FHP trial, after 60 min of exercise, both cumulative Hₚ (P = 0.73) and the cumulative sum (Hloss) of dry, evaporative and respiratory heat losses (i.e., C + R, Eₕ, and Cₚ + Eₚ) (P = 0.69) were similar between the LO-BF and HI-BF group (Table 3). In the LBM trial, after 60 min of exercise, cumulative Hₚ (P < 0.001) and Hloss (P < 0.001) were greater in the LO-BF group compared with the HI-BF group. These differences in Hloss primarily arose due to differences in the potential evaporative heat loss from the skin (Eₕ); however, respiratory heat loss (Cₚ + Eₚ) was also greater in the LO-BF group due to the higher minute ventilation associated with the greater absolute VO₂ required to sustain a fixed Hₚ of 7.5 W/kg LBM in the leaner group.

DISCUSSION

The present study assessed for the first known time the truly independent influence of large (3-fold) differences in body fat on thermoregulatory responses during exercise by eliminating

![Fig. 1. Changes of rectal temperature (Tre)(A) for low (gray symbols) and high (white symbols) body fat groups matched for total body mass and body surface area (BSA) during 60 min of exercise in the FHP trial (A) and the LBM trial (B). Error bars indicate SD. *P < 0.05 after Bonferroni correction. See Protocol for specific description of FHP trial and LBM trial.

![Fig. 2. Whole body sweat loss (WBSL) for low (gray bars) and high (white bars) body fat groups matched for total body mass and BSA during 60 min of exercise in the FHP trial (A) and the LBM trial (B). Error bars indicate SD. Alpha (α) indicates a main effect of %BF (P < 0.05).
any potential confounding effects of body mass, body surface area (BSA), and metabolic heat production (H\text{prod}). The first primary finding was that at a fixed H\text{prod} (FHP trial) of 550 W (6 W/kg TBM), high body fat levels (>30%BF) lead to significantly greater increases in core temperature relative to lower body fat levels (<12%BF), whereas no independent influence of adiposity was observed on time-dependent changes in whole body or local sweating responses. The second primary finding was that a fixed H\text{prod} per unit lean body mass (LBM trial) of 7.5 W/kg LBM led to systematically greater changes in core temperature and whole body and local sweating in the LO-BF participant group due to large differences in H\text{prod} per unit total body mass and concurrent evaporative heat balance requirements. This observation clearly demonstrates that the previously held concept that differences in body fat between independent groups should be accounted for by prescribing an exercise intensity that elicits a fixed H\text{prod} per unit lean body mass, is flawed.

Despite the greater core temperature change in the HI-BF group in the FHP trial, similar whole body and local sweating responses (Figs. 2 and 3) were observed between groups. In parallel, the potential for net heat dissipation from the skin (H\text{res}) was also similar between HI-BF and LO-BF groups (Table 3). Since heat storage is the cumulative difference between heat production and heat dissipation, and heat production was fixed in the FHP trial (Table 2), the amount of heat energy stored inside the body during exercise would also have been similar. It therefore appears that from a biophysical perspective, the lower mean specific heat capacity in the HI-BF group (Table 1) may have been at least partially responsible for their greater change in core temperature. The fact that similar sweat rates were observed alongside dissimilar changes in core temperature also implies that large differences in %BF potentially disrupt the physiological control of sudomotor control. However, as we were unable to collect a full set of esophageal temperature data, we are unable to determine whether this arose due to a prolonged onset threshold and/or a blunted thermosensitivity. It has also been recently proposed that due to its low conductivity, fat mass may not contribute fully to an individual’s “heat sink” (16). It follows that such a mechanism may also explain the greater rise in core temperature in the HI-BF group in the FHP trial. However, in view of the

**Table 3. Cumulative heat balance parameters estimated using partitional calorimetry for low (LO-BF) and high body fat (HI-BF) participant groups for 60-min exercise in the FHP trial and LBM trial**

<table>
<thead>
<tr>
<th>Trial</th>
<th>H\text{metab}, kJ</th>
<th>C + R, kJ</th>
<th>C\text{res} + E\text{res}, kJ</th>
<th>E\text{sk}, kJ</th>
<th>H\text{res}, kJ</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FHP trial</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LO-BF</td>
<td>1,959 ± 224</td>
<td>262 ± 29</td>
<td>163 ± 19</td>
<td>1,421 ± 200</td>
<td>1,867 ± 208</td>
</tr>
<tr>
<td>HI-BF</td>
<td>1,994 ± 188</td>
<td>300 ± 46</td>
<td>171 ± 20</td>
<td>1,355 ± 183</td>
<td>1,826 ± 224</td>
</tr>
<tr>
<td>P value</td>
<td>0.73</td>
<td>0.34</td>
<td>0.42</td>
<td>0.47</td>
<td>0.69</td>
</tr>
<tr>
<td><strong>LBM trial</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LO-BF</td>
<td>2,145 ± 213*</td>
<td>296 ± 56</td>
<td>179 ± 27*</td>
<td>1,408 ± 258*</td>
<td>1,884 ± 277*</td>
</tr>
<tr>
<td>HI-BF</td>
<td>1,676 ± 261</td>
<td>273 ± 48</td>
<td>143 ± 13</td>
<td>925 ± 166</td>
<td>1,341 ± 187</td>
</tr>
<tr>
<td>P value</td>
<td>&lt;0.001</td>
<td>0.33</td>
<td>0.02</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

Values given are means (± SD) in kilojoules (kJ). H\text{metab}, metabolic heat production; C + R, sum of convective and radiative heat loss from the skin; C\text{res} + E\text{res}, combined heat loss via convection and evaporation from the respiratory tract; E\text{sk}, evaporative heat loss from the skin; H\text{res}, is the cumulative sum of all heat loss avenues [i.e., (C + R) + C\text{res} + E\text{res} + E\text{sk}]. *Significantly greater value (P ≤ 0.05).
relatively small differences in core temperature despite large differences in fat mass (~9 vs. ~29 kg), this does not seem likely. Furthermore, if fat mass did not contribute to a person’s heat sink, similar changes in core temperature would have been expected in the LBM trial, whereas lower values were observed in the HI-BF group. Nevertheless, future research should measure changes in fat tissue temperature to examine the extent of heat storage in this intermediate compartment.

Arguably the most important finding of the present study was that the relatively small influence of %BF on core temperature changes during exercise should clearly not be countered by prescribing a fixed Hprod in watts per kilogram LBM. This traditionally held notion (16, 28) is based on the rationale that during non-weight-bearing exercise (e.g., cycling), fat tissue functions primarily as surplus mass because it is not actively producing heat, so it is assumed that a rate of heat production based on lean body mass (i.e., metabolically active tissue) would remove any confounding influence of body fat differences. However, the LBM trial shows that large systematic differences in core temperature changes, and sweating responses, are generated by the much greater Hprod in watts per kilogram TBM (8) and Eeq (15, 24, 38) in the LO-BF group. While differences in specific heat capacity (Cp) secondary to differences in body composition may be responsible for the greater change in core temperature during exercise in the HI-BF group at fixed Hprod in watts per kilogram TBM (Fig. 1A), using a watts per kilogram LBM approach seems to overcorrect Hprod to a far greater extent (~28%; Table 3) relative to differences in Cp (~4–5%; Table 1). It follows that any studies fixing Hprod in watts per kilogram LBM may incorrectly conclude that individuals with a high %BF have a blunted sweating response relative to their leaner counterparts, whereas a lower sweat rate would simply be due to a systematic bias arising from the experimental design.

Several previous studies have concluded that adiposity influences thermoregulatory responses during exercise; however, all previous investigations have been apparently confounded by large differences in total body mass and/or Hprod between lean and nonlean (or obese) groups (1, 4, 12, 21). For example, Eijsvogels et al. (12) reported a greater core temperature in an obese (100.4 kg) compared with lean (69.6 kg) group, but any influence of differences in average specific heat between groups was likely masked by concomitant differences in Hprod in watts per kilogram TBM (which was not measured). On the other hand, the seminal study by Bar-Or et al. (4) reported a “higher heat strain” in their obese group by virtue of a greater sweat rate (obese 238 ± 33 ml·m⁻²·h⁻¹, lean 207 ± 22 ml·m⁻²·h⁻¹) during a weight-bearing exercise (walking), but Hprod and parallel evaporative heat balance requirements would have been much greater in the obese group as they had to carry a much greater mass (90 vs. 52 kg). Historically, some authors have contended that heat dissipation from the skin (Hlos) in obese individuals is impaired due to insulative properties (17) of adipose tissue (3, 5, 27, 30); however, the FHP trial in the present study demonstrates that this is not the case (Table 3). Indeed, peripheral vasodilation during exercise in the heat increases skin blood flow, and with internal core-to-skin heat transfer occurring mainly via the bloodstream, the subcutaneous layer of adipose tissue is likely bypassed, rendering its insulation properties in this case inconsequential.

In the present study, aerobic capacity (V̇O₂peak) was the only characteristic, in addition to %BF, that was different between LO-BF (47.7 ± 7.2 ml·kg⁻¹·min⁻¹) and HI-BF (37.8 ± 5.8 ml·kg⁻¹·min⁻¹) groups. However, we recently demonstrated similar changes in core temperature and sweating between aerobically fit (>60 ml·kg⁻¹·min⁻¹) and unfit (40–45 ml·kg⁻¹·min⁻¹) participants matched for total body mass and body surface area exercising at a fixed heat production in a physiologically compensable environment during both cycling (24) and treadmill running (38), despite large differences in relative exercise intensity (%V̇O₂peak). As such, the difference in core temperature between the HI-BF and LO-BF groups in the present study can only be ascribed to differences in adiposity, and not fitness or relative intensity.

**Perspectives**

The most immediate application of the present study is to the design of experiments assessing the influence of a between-group factor (e.g., age, disease, injury, etc.) on differences in thermoregulatory responses during exercise. In addition to our previous contributions to this topic (8, 24, 25, 38), we now demonstrate that a difference in body fat percentage of 20% between experimental groups may lead to systematically greater changes in core temperature in the group with a higher %BF unrelated to any other independent factor. For groups of unequal body mass and BSA, we have previously shown that the biophysical influence of these characteristics on changes in core temperature and local sweat rate can be eliminated by adjusting Hprod in watts per kilogram TBM and watts per square meter, respectively (7, 8). However, the present study clearly demonstrates that fixing Hprod in watts per kilogram LBM to account for any differences in %BF is not advisable since it will generate systematic differences in core temperature and both whole body and local sweating responses. Future studies should ensure that differences in %BF between groups are within ~10%, as a disparity of this magnitude has been previously demonstrated to not alter thermoregulatory responses (24).

One implication of the higher adiposity in HI-BF group is a parallel difference in body volume and therefore estimated BSA values using the DuBois and DuBois formula of height and weight (5) secondary to the lower density of fat (0.9 kg/l) relative to muscle (1.1 kg/l). A ~20% greater body fat would yield a BSA that is greater by ~3% (18); therefore BSA in the HI-BF group is probably underestimated. However, since mean estimated BSA using the DuBois formula was slightly smaller in the HI-BF group (Table 1), a tissue density-related adjustment of BSA of ~3% would actually bring mean group BSA values closer together.

**Limitations and Future Studies**

Cutaneous vascular conductance was not measured in the present study; as such potential differences in vascular control could not be assessed. Nevertheless, our partitional calorimetry estimations suggest that if any differences in skin blood flow control did arise as a function of %body fat, they were insufficient to alter skin surface heat transfer (Table 3). The present study assessed males between 4.9% to 42.8% body fat and 18 to 36 yr of age. Therefore, all findings are only relevant to males within that range, and may not apply to females, a
more obese population (i.e., >40% body fat), or younger and older individuals. Future studies should consider examining potential interactions between sex, age, and adiposity on thermoregulatory responses to exercise. Another limitation is that the present study was conducted under physiologically compensable conditions, with the parameters selected to ensure the full evaporation of all sweat secreted onto the skin surface (thus permitting heat storage estimations via partitional calorimetry) and steady-state core temperatures toward the end of exercise. The completely independent influence of fat on thermoregulatory responses during uncompensable heat stress has not yet been determined. Under such conditions, Selkirk and McLellan (37) reported a greater heat tolerance in fitter and leaner individuals; however, differences in body mass and heat production existed between their groups in addition to the differences in fat mass and aerobic fitness. Furthermore, Deren et al. (11) reported that maximum skin wettedness may be altered due to a lower sweating efficiency arising from a lower sweat gland density in very high BSA individuals (~2.7 m²) with a high fat percentage (~28%). However, the exclusive roles of BSA and fat mass are unknown. Skin surface heat loss was not directly measured, but estimated via partitional calorimetry. While the environmental conditions were precisely measured and specifically selected to limit inaccuracies (i.e., high air flow and low ambient humidity to maximize the likelihood of complete evaporation of sweat from the skin surface), these calculations remain limited by inherent assumptions. However, it is known that evaporative efficiency is determined by the $\frac{E_{\text{req}}}{E_{\text{max}}}$ ratio (6), which was similar between groups (HI-BF 0.61 ± 0.29; LO-BF 0.57 ± 0.27; $P = 0.79$). Due to the exercise mode employed (i.e., semirecumbent cycling), a small proportion of BSA (~0.15 m²) was covered by the ergometer seat, and while maximum evaporative heat loss would have consequently been reduced by ~5–7%, this reduction would have been similar between the HI-BF and LO-BF groups as they were matched for body size and the conditions therefore remained similarly compensable. Finally, we cannot be certain there were no differences in heat acclimatization status between groups. However, this seems unlikely given our previous observation of no physiological heat adaptation in individuals within this age cohort (i.e., healthy college-aged males) attributed to the prevalent use of air conditioning in homes as well as work and exercise spaces (3).

Conclusions

At a fixed metabolic heat production, a greater change in core temperature was observed in nonlean participants (>30%BF) relative to a group of mass-matched lean individuals (<12%BF). However, whole body and local sweating responses as well as skin surface heat dissipation to the surrounding environment, estimated using partitional calorimetry, were not independently altered by large differences in adiposity. Furthermore, when prescribing an exercise intensity that generated a fixed heat production per unit lean body mass, as previously suggested in the literature to eliminate the supposed influence of fat mass on thermoregulatory responses, systematically greater changes in core temperature and sweating were observed in the lean group. Collectively, our findings further inform between-group experimental design demonstrating that when comparing thermoregulatory responses between independent groups, differences in %BF of more than 10%, which have been previously demonstrated to not alter thermoregulatory responses (24), should be avoided. Moreover, comparing thermoregulatory responses using a fixed heat production per unit lean mass, as opposed to per unit total body mass, is not advised as such an approach will potentially generate systematic differences in core temperature and sweating.

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DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the author(s).

AUTHOR CONTRIBUTIONS


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