The Independent Influence of Large Differences in Adiposity on Thermoregulatory Responses during Exercise

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THESIS ABSTRACT

Currently no previous study has isolated the independent influence of body fat (BF) on thermoregulatory responses from the confounding biophysical factors of body mass and metabolic heat production (H_{prod}). Therefore, seven lean (L, BF:10.7 ± 4.1%) and seven non-lean (NL, BF:32.2 ± 6.4%) males matched for total body mass (TBM, L: 87.8 ± 8.5 kg, NL: 89.4 ± 7.8 kg; P= 0.73), cycled for 60 min in a 28.2 ±0.2˚C and 27 ± 10% RH room at i) a H_{prod} of 546 W; and ii) a H_{prod} of 7.5 W·kg lean body mass (LBM). Rectal (T_{re}) and esophageal (T_{es}) temperatures, and local sweat rate (LSR) were measured continuously; while whole body sweat loss (WBSL) was measured from 0-60 mins. At 546 W, changes in T_{re} (L: 0.74 ± 0.16ºC, NL: 0.83 ± 0.14ºC), mean local sweat rate (MLSR) based on an average of upper-back and forearm local sweat rates (L: 0.65 ± 0.25, NL: 0.59±0.12 $mg \cdot cm^{-2} \cdot min^{-1}$) and WBSL (L: 568 ± 28 mL, NL: 567 ± 29 mL) were similar (P>0.58). At 7.5 W·kg LBM, the L group had greater changes in T_{re} (L: 0.87 ± 0.16ºC, NL: 0.55 ± 0.11ºC), MLSR (L: 0.83 ±0 .38, NL: 0.41 ± 0.13 $mg \cdot cm^{-2} \cdot min^{-1}$) and WBSL (L: 638 ± 19 mL, NL: 399 ± 17 mL) (P<0.05). In conclusion, i) body fat does not independently alter thermoregulatory responses during exercise; ii) core temperature comparisons between groups differing in BF should be performed using a H_{prod} normalized for TBM, not LBM.

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Chapter I
Introduction

Background

The World Health Organization (WHO)[1] has anticipated an increase in the average hot temperatures during the summer months and consequently a greater risk of heat waves. In 2003 a heat wave hit several countries in Europe and thousands of heat related deaths were reported [1]. Heat related injuries also occur during physical activity in hot/humid environments, such as playing sports (e.g. football) or carrying out physically demanding jobs (e.g. firefighters and miners). For example, the latest annual survey of football injuries from 1960 to 2011 reported 132 cases of heat stroke related deaths across various levels of competition[2]. Furthermore, according to the United States Department of Labour, thousands of employees suffer occupational heat related injuries annually[3]. It is therefore a top priority to understand how different populations (e.g. individuals with obesity) respond to the heat during physical activity in pursuance of appropriate intervention measures.

The isolation of the effect of any physiological variable (e.g. body composition) on human thermoregulatory responses requires an experimental design that controls all other pertinent factors; these include environmental conditions (e.g. air temperature and humidity), activity level (e.g. fixed heat production) and biophysical (e.g. body mass) factors (Fig.1)[4]. As such, this research proposal will compare thermoregulatory responses to exercise at a fixed heat production per unit mass between males of similar total body mass and very different body compositions (e.g. lean and non-lean groups) in a temperature/humidity controlled room.

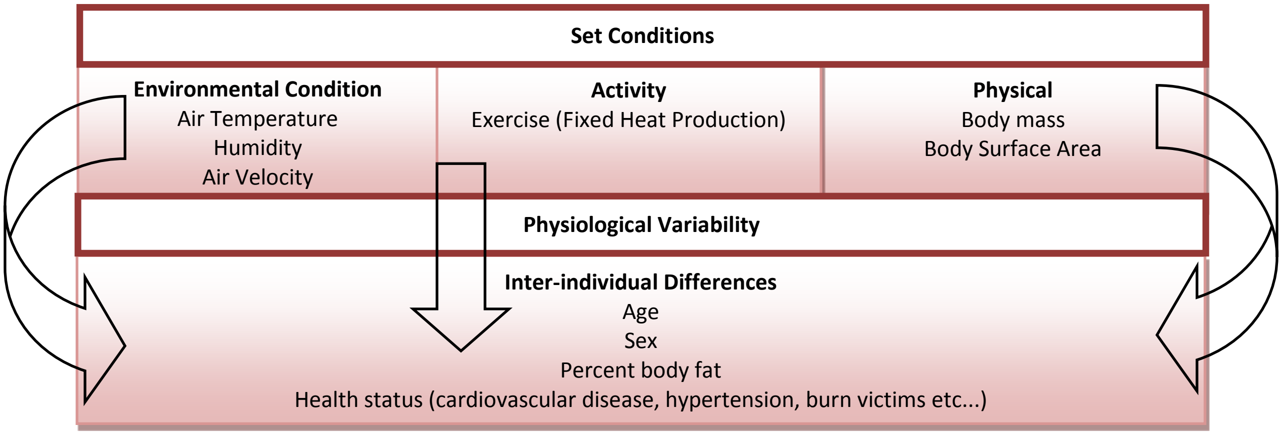


Figure 1. Key Factors that Influence Changes in Core Temperature[4]
This concept map demonstrates the importance of creating set conditions to independently measure inter-individual differences in thermoregulatory responses.

Public health guidance issued by the WHO[1], supported by several other research papers[5,6,7,8] states that obese compared to lean individuals are more susceptible to heat related injuries. The prevailing logic is that lower fitness levels and greater percent body fat typically found in individuals with obesity lead to greater heat storage and therefore greater changes in core temperatures during exercise, compared to their lean counterparts[5–8]. Conforming to the prevalent understanding of thermoregulatory responses to heat in obese populations, Eijsvogels et al[5], reported a greater peak core temperature and sweat rates in obese compared to lean groups when exercising at similar relative intensities (72±9% of maximum heart rate). The authors attributed obesity as an influence on core temperature during exercise; however the reported baseline (lean: 37.5±0.4°C, obese: 37.5±0.3°C) and peak (lean: 38.3±0.3°C, obese: 38.5±0.3°C) core temperatures between groups were similar. Accordingly, if aerobic capacity (VO_{2peak}) was measured in this study it is reasonable to assume that the obese group would have had a lower VO_{2peak} than the lean group. Additionally, the total body mass of the lean and obese groups were not matched (lean: 69.6±11.0 kg, obese: 100.4±10.9 kg), so exercise at a relative intensity of 72±9% of maximum heart rate would have likely resulted in a lower heat production per kilogram of total body mass in the obese compared to lean group. Furthermore, due to the large differences in total body mass, the obese group would have had a higher absolute heat production compared to the lean group, leading to a greater evaporative requirement for heat balance and subsequently sweat rate. Thus, due to the differences in heat production, any differences in core temperature or sweating between groups cannot be attributed solely to obesity. So, eliminating differences in total body mass, body surface area (BSA) and heat production between groups is crucial for identifying the independent influence of adiposity on changes in core temperature.

A recent study by Jay et al[11] reported that participants with large differences in VO_{2peak} (fit: 60.1±4.5 $mL \cdot kg^{-1} \cdot min^{-1}$, unfit:40.3±2.9 $mL \cdot kg^{-1} \cdot min^{-1}$) matched for body mass and BSA, and exercising at a fixed heat production (fit: 542±38 W (7.0±0.6 W/kg): unfit: 535±39 W (6.9±0.9 W/kg)) had identical changes in core temperature (fit: 0.87±0.15°C, unfit: 0.87±0.18°C) and whole body sweat rates (fit: 434±80 mL, unfit: 440±41 mL). On the contrary, it was reported that exercising at the same relative intensity (fit: 61.7±7.1%VO_{2peak}, unfit: 63.9±7.9% VO_{2peak}) yielded much greater changes in core temperature (fit: 1.43±0.28°C, unfit: 0.89±0.19°C) and sweat rates (fit: 807±155 mL, unfit: 486±59 mL) in the fit compared to unfit group, since they were exercising at a greater metabolic heat production per unit mass (fit: 834±77 W (10.7±1.3 W/kg), unfit: 600±90 W (7.7±1.4 W/kg)). This study supports the notion that VO_{2peak} does not influence changes in either core temperature or whole body sweat rate independently of heat production and mass [11]. As such, any potential differences in VO_{2peak} and therefore relative exercise intensity between obese and lean groups will not directly lead to any differences in core temperature or sweat rate during exercise.

Another notable finding by Jay et al was that the differences in body fat percentage between the fit (11.9±5.9%) and unfit (22.2±7.0%) VO_{2peak} groups did not influence thermoregulatory responses within this particular range [11]. The unfit group theoretically had an overall lower tissue specific heat capacity, due to the lower specific heat capacity of fat (2.973 $kJ•kg^{-1}•^{o}C^{-1}$) compared to lean muscle (3.64 $kJ•kg^{-1}•^{o}C^{-1}$) [12]. Thus, similar heat storage would presumably lead to a greater increase of core temperature in the unfit (higher adiposity) group relative to the fit (lower adiposity) group. Considering no differences in core temperature were observed it can be concluded that a small difference in body fat (~10%) does not result in observable differences in core temperature or sweating during exercise at a fixed heat production[11]. The question that remains is whether greater differences in body fat (>20%) result in measurable differences in thermoregulatory responses during exercise at a fixed heat production? In accordance with the conclusions of several research papers[4,11,13,14], the primary source of thermogenesis during exercise is lean muscle tissue. It follows that during non-weight bearing exercise (e.g. cycling) as opposed to weight bearing exercise (e.g. running), fat tissue functions principally as surplus mass (i.e. a heat sink) albeit with a low blood perfusion and does not actively contribute to heat production because the extra mass does not have to be carried. Fat tissue may also impair heat dissipation due to its high insulative properties, but following cutaneous vasodilation after the onset of exercise the insulative effect of fat tissue may be minimized.

In conclusion, heat stress has been shown to increase the risk of serious health problems. Understanding how different populations interact in warm environments will allow the implementation of preventative measures and advisories, while still advocating physical activity in hot weather by populations who are potentially at an elevated health risk due to their sedentary behaviour. Obesity is a growing pandemic and according to the WHO 2012 Factsheet[15] has doubled globally since 1980. Currently from a biophysical perspective it is unknown if large differences in percent body fat independently alters how the body regulates its temperature during exercise in a compensable environment.

Chapter II

Literature Review & Rationale

Literature Review

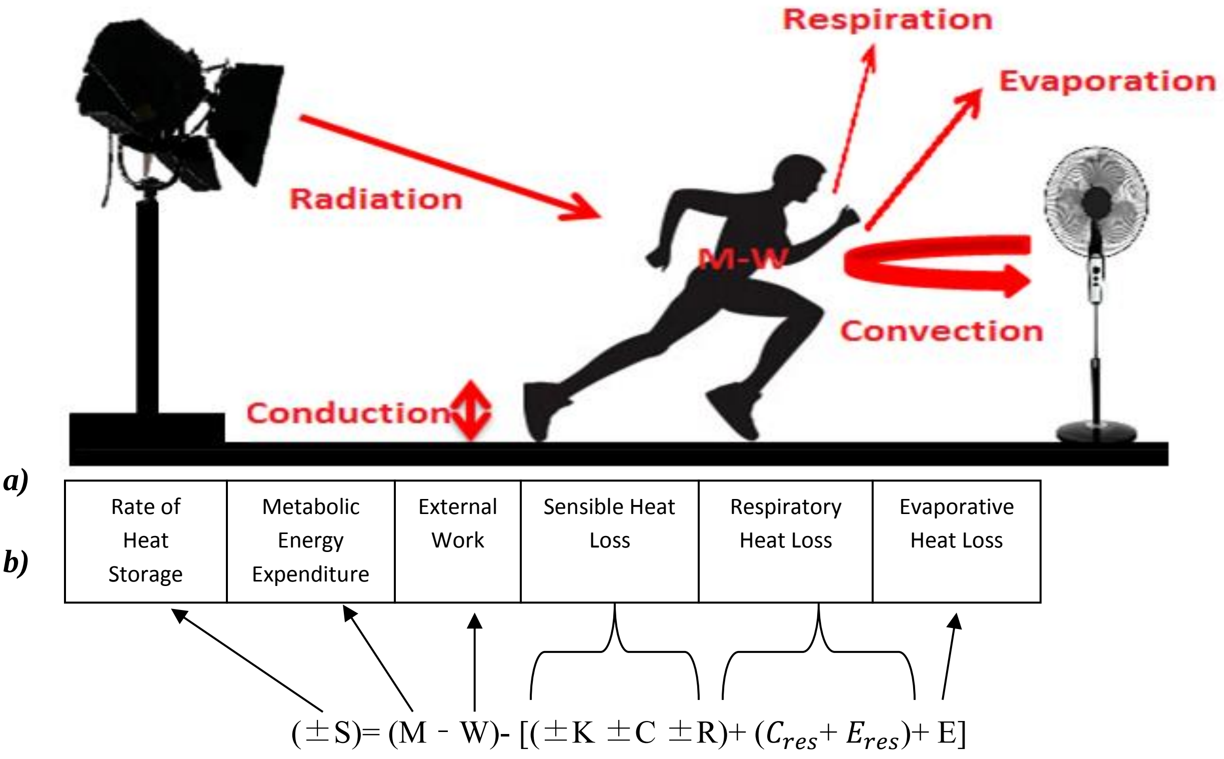
Fundamental Parameters of Human Thermal Environments

At rest, human body temperature is regulated at about 37^{o}C. This temperature permits optimal physiological and enzymatic functioning and is considered a normothermic/euthermic state.

There are six fundamental parameters that define the dynamic human thermal interaction with an environment (e.g. both cold and hot environments). The parameters are air and radiant temperatures, humidity, air velocity and metabolic heat production and clothing insulation[16]. For the purpose of the present study an air temperature (T_{air}), measured in ºC can be defined as the temperature of the air surrounding the human body and is in part a determinant of dry heat transfer. Radiant temperature (T_r) is the temperature from radiant sources such as the sun (or a radiant lamp source) and is also measured in ºC[16]. Humidity can be expressed in either absolute and/or relative terms. Absolute humidity is the total water (or moisture) content in the air in mass per volume; and relative humidity (%) is the percentage of saturated water vapour pressure of the environment[16]. Air velocity is the movement of air across the human body in a given environment and is measured in meters per second ($m \cdot s^{-1}$). Metabolic heat production is the by-product of heat from cellular activity and is measured in Watts. Lastly, clothing insulation is a property of the clothing material and indicates resistance to heat transfer (dry and evaporative) from skin to the clothing surface. Interactions between the six fundamental parameters define the human thermoregulatory requirements for heat balance.

Heat Balance

In order to attain a steady state in core temperature, the rate of heat production from physical activity must be balanced by the rate of net heat loss to the environment. The conceptual heat balance equation is depicted in Figures 2a and 2b. This equation states that a rate of body heat storage (S) occurs if metabolic heat production (M-W), which is the difference between metabolic energy expenditure (M) and external work (W), is not balanced by the combined heat dissipation to the surrounding environment via conduction (K), convection (C), radiation (R) and evaporation (E). By definition, heat balance is a rate of heat storage (S) equal to zero. Positive heat storage will lead to an increase in core temperature and vice versa.



$$(\pm S) = (M - W) - [(\pm K \pm C \pm R) + (C_{res} + E_{res}) + E]$$

Figure 2: Schematic of the basic heat balance equation
a) This heat balance schematic defines the sources of each part of the heat balance equation.
b) S = rate of heat storage, M = metabolic energy expenditure, W= external work, K = conduction, C = convection, R= radiation, C_{res}*= respiratory convection,* E_{res}*= respiratory evaporation, E = evaporation*[16]

Metabolic Heat Production (M-W)

Humans are colloquially referred to as warm-blooded, meaning their thermoregulatory system follows that of endotherms[17]. Endotherms produce heat internally via metabolism, and increasing it enables various physiological processes including mechanical work and shivering. Metabolic energy (M) is generated from the use of oxygen and substrates including carbohydrates, lipids and proteins. The ingested substrates are converted into glucose, fatty and amino acids respectively[17]. Glucose and fatty acids are metabolized mostly aerobically and a small percent anaerobically to produce energy in the form of adenosine-triphosphate (ATP), however this process of providing energy is very inefficient. For example, when cycling only ~20% of metabolic energy produced is for external work, and the remainder is transferred as internal metabolic heat via the bloodstream[17]. A calorific value of the ingested substrates and oxygen used provides a value of metabolic energy available. A ratio of the volume of carbon dioxide produced relative to volume of oxygen consumed (respiratory quotient: RQ) provides the proportion of carbohydrates (RQ = 1.0), fat (RQ =0.71), protein (RQ =0.835) and mixed diet (RQ =0.85) being oxidized during a given task[17].

The volume of oxygen (VO_2) required to metabolize carbohydrates, fats and protein is constant with the energy yield per litre of oxygen consumed being 21.13 kJ for carbohydrates, 19.62 kJ for fats and 19.48 kJ for protein[17]. Indirect calorimetry is commonly used to calculate metabolic rate (M) by estimating how much oxygen has been used to convert substrates for ATP production[18]:

$$M = \mathrm{VO_2} \frac{\left(\frac{\mathrm{RER}-0.7}{0.3}\mathrm{e_c}\right) + \left(\frac{1-\mathrm{RER}}{0.3}\mathrm{e_f}\right)}{60} \times 1000 \quad \ldots\ldots\ldots\ldots\ldots\ldots \mathrm{W} \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where VO_2 is the rate of oxygen consumed in L/min; RER is the respiratory exchange ratio of carbon dioxide and oxygen; e_c is the caloric energy equivalent per liter of oxygen for the oxidation of carbohydrates (21.13 kJ); e_f is the caloric energy equivalent per liter of oxygen for the oxidation of fat (19.62 kJ)[18].

Mechanical/external work is a product of a constant magnitude of force (measured in Newton) to displace a body along the direction of force (meters). The unit of newton meter is also expressed as joules (J):

$$W = F \times d \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \mathrm{J} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Where: W is the mechanical or external work done and is expressed in Joules (J); F is the magnitude of force placed on a body and measured in Newton (N); d is the distance and direction of the applied force measured in meters (m). For the purposes of our research we will express mechanical/external work as a rate, Joules per second or Watts. Therefore metabolic heat production (M-W) is determined by calculating the difference between M and W.

Sensible Heat Loss (±K±C±R) abides by the second law of thermodynamics, which states that heat flows from a higher to lower temperature until thermal equilibrium is attained[19]. Sensible heat transfer has three components; conduction *(K)*, convection *(C)* and radiation *(R).* Each component is a potential source of heat gain (-) or loss (+).

Conduction (±K): is the rate of heat transfer between two solid objects in contact and can be estimated using the following equation[16]:

$$K = -kA\frac{T_2 - T_1}{d} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \mathrm{W} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Where: K is the rate of conductive heat transfer (W); k is thermal conductivity ($W \bullet m^{-1} \bullet K^{-1}$); A is the cross-sectional area normal to the conductive direction (m^2); $T_2 - T_1$ is the temperature between the two surfaces (^oK) and d is the distance between points at temperatures T_2 and T_1 (m). The present study will be in a thermoneutral environment and heat transfer across a small conductive cross-sectional area from the semi-recumbent bicycle to skin surface will not be sufficient to meaningfully influence whole-body heat loss, thus whole-body heat exchange via conduction is considered negligible.

Convection (±C): is the transfer of heat between the body (surface of the skin) and surrounding air, and is promoted by movement of a medium (e.g. air). C is related to the temperature difference between the skin surface and surrounding air, as well as air velocity[16]. Therefore, the rate of convective heat exchange can be expressed using the following equations[20]:

$$C = BSA \cdot h_c(t_{sk} - t_a) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{W} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

$$h_c = 8.3v^{0.6} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{W} \bullet m^{-2} \bullet K^{-1} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

In *Equation 4,* h_c is the convective heat transfer coefficient in W•m^{-2}K^{-1} and in *Equation 5* v is the velocity of air in m•s^{-1}. However, this convective heat transfer equation only accounts for air velocities between 0.2 and 4.0 m•s^{-1}, for air velocities between 0 and 0.2 m•s^{-1} h_c is fixed at 3.1 W·m^{-2}·K^{-1} [20]. In *Equation 5,* BSA is the surface area of the nude body in m^2, t_{sk} is the weighted mean temperature of the skin surface in °C and t_a is the mean air temperature in °C and will be equal to surrounding air temperature[16].

Radiation (±R): Heat exchange through radiation depends on BSA, the difference between mean skin temperature (t_{sk}) and mean radiant temperature (equal to $t_{a,}$ when sources of radiant heat are negligible) and the radiative heat transfer coefficient (h_r) measured in W•m-^{2}•K^{-1} [20]. The radiative heat transfer coefficient considers emissivity (Ɛ) of the clothed body, however since the participants will be semi-nude the value used will reflect that of the surface of the skin which is ~1.0. The radiative area (A_r) referring to a proportion of total BSA exposed to a radiant heat source, also influences ±*R*. In the present study semi-recumbent cycling is the modality of exercise and A_r will be assumed to be ~0.7 [51].

$$R = BSA\ h_r(t_{sk} - t_r) \ldots\ldots\ldots\ldots \mathrm{W} \ldots\ldots\ldots\ldots (7)$$

$$h_r = 4\varepsilon\sigma \frac{A_r}{BSA} + \left[273.2 + \frac{(t_{sk}-t_r)}{2}\right]^3 \ldots\ldots\ldots \mathrm{W} \bullet m^{-2} \bullet K^{-1} \ldots\ldots\ldots (8)$$

Where: σ is the *Stefan-Boltzmann constant* (5.67×10^{-8} $\mathrm{W{\bullet}m^{-2}{\bullet}K^{-4}}$) and $\frac{A_r}{BSA}$, is the effective radiative area of the body[16,1].

Respiratory Heat Loss ($+C_{res}+E_{res}$) occurs via ‘dry’ convective heat transfer (C_{res}), meaning inhaled air at a lower temperature than core temperature is heated along the respiratory tract and in the lungs and exhaled at a higher temperature than ambient temperature. When air of certain absolute humidity (P_a) is inhaled, it also passes through the turbinates found in the nasal conchae where it is saturated with water vapour before reaching the respiratory tract and lungs. This process also leads to evaporative heat loss via respiration (E_{res}). The combined heat losses via respiration are calculated using *Equation 9* [22]:

$$C_{res} + E_{res} = [0.0014(M - W)(34 - t_a) + 0.0173(M - W)(5.87 - P_a)] \ldots\ldots \mathrm{W} \ldots\ldots (9)$$

$$P_a = \frac{\left[exp\left[18.956 - \frac{4030.18}{t_a+235}\right]\right]}{10} \times Relative\ Humidity\ (\%) \ldots\ldots\ldots \mathrm{kPa} \ldots\ldots\ldots (10)$$

Where *M-W* is the metabolic heat production in W; t_a is the ambient air temperature in ºC; and in *Equation 10*, P_a is the partial pressure of water vapour in the ambient air measured in kPa.

Evaporative Heat Loss (+E)

During physical activity and/or when exposed to hot environments, an essential avenue of heat loss is the evaporation of sweat[16, 17]. Moisture present on the skin in the form of sweat creates a vapour pressure difference between the surface of the skin and surrounding air enabling evaporation. Every gram of vaporized sweat at a constant temperature results in 2.426 kJ of energy dissipated to the environment[23]. The evaporative requirement (E_{req}) for heat balance can be calculated when all of the other heat balance components are known (*Equation 11*):

$$E_{req} = (M - W) - (C_{res} + E_{res}) - (C + R) \ldots\ldots\ldots\ldots\ldots\ldots \text{W} \ldots\ldots\ldots\ldots\ldots\ldots (11)$$

The ratio of this E_{req} value relative to the maximum evaporative capacity (E_{max}) of the ambient environment (E_{max}) is the required skin wettedness for heat balance (ω_{req}). If ω_{req} is greater than ~0.5 not all secreted sweat is evaporated from the skin with the remainder dripping off the skin and not contributing to heat loss[16]. There are several parameters that alter heat loss via evaporation including vapour pressure difference between the skin and ambient air, ω and BSA. Thus E_{max} can be calculated using *Equations 12, 13* and *14*:

$$E_{max} = \omega(P_{skin} - P_{air})(A_D h_e) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{W} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (12)$$

$$P_{skin} = \frac{\left[exp\left[18.956 - \frac{4030.18}{t_{skin}+235}\right]\right]}{10} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{kPa} \ldots\ldots\ldots\ldots\ldots\ldots\ldots (13)$$

$$h_e = 16.5(h_c) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{W} \bullet m^{-2} \bullet kPa^{-1} \ldots\ldots\ldots\ldots\ldots\ldots\ldots (14)$$

Where: ω is assumed to be 1.0 and $P_{skin} - P_{air}$ is the partial pressure difference in kPa between the saturated water vapour pressure on the skin surface and surrounding air. The evaporative heat transfer coefficient (h_e) expressed in $\text{W}\bullet\text{m}^{-2}\bullet\text{kPa}^{-1}$ is 16.5 times the convective heat transfer coefficient.

Collectively metabolic heat production and sensible, respiratory and evaporative heat losses are all elements contributing to a net gain or loss in heat storage. The components of the heat balance equation are delegated by thermal physiological processes/pathways which will be discussed in detail in the following section.

Thermal Physiology

The primary region of the brain responsible for processing and integrating afferent signals to conduct appropriate output efferent signals for core temperature regulation is the preoptic anterior hypothalamus (POAH)[24]. There are temperature sensitive receptors throughout the body and these are classified as either central or peripheral thermosensory neurons[24]. Collectively, the POAH receives information from central and peripheral receptors and depending on the thermal status of the body, output will vary from vasoconstriction/shivering in response to excessive heat loss or vasodilation/sweating in response to excessive heat gain[24].

Thermosensors

Central thermosensors are located in the brain/brainstem and along the spinal cord. They are considered to be warm-sensitive neurons, that is, they increase their activity with an increase in brain temperature. Peripheral thermosensors are situated in the epidermal layer of the skin and are primarily cold-sensitive neurons, but warm-sensitive thermorecepters also reside deeper in the epidermis. They are very active with changing environmental temperature and quickly adapt to stable temperatures. The autonomic effector provides both metabolic and vascular responses to afferent signals in order for core temperature to reach a steady state [24].

Sweating

Active heat storage occurs when metabolic heat production exceeds net heat loss due to an increase in energy requirements of active muscle. Passive heat gain occurs when environmental temperatures approach or even exceed skin temperature ($T_a>T_{sk}$) and heat loss is suppressed due to a high ambient humidity. Physiological responses to passive or active heat storage begin with cutaneous vascular dilation which is an increased blood circulation to the skin facilitating a greater temperature gradient between skin surface and ambient environment to enhance convective heat loss and promote a more effective heat loss mechanism for the evaporation of sweat[16,25].There are two types of sweat glands: apocrine glands are predominantly located in the armpits and pubic areas; eccrine glands are dispersed throughout the entire body and are primarily responsible for thermoregulatory control[25]. At high ambient temperatures/humidity or during exercise the evaporation of sweat is the principal mean of heat loss[26]. The quantity of heat energy liberated by sweat as it evaporates is called latent heat of vaporization and the body loses 2.426 kJ of heat for each evaporated gram of water[23].

Heat activated sweat glands are stimulated by the sympathetic nervous system (SNS) via cholinergic sudomotor nerves that primarily release the neurotransmitter acetylcholine (ACh) [25, 28, 29]. ACh binds to muscarinic receptors found on eccrine sweat glands stimulating sweat secretion on to the surface of the skin [25, 28, 29].

The rate of evaporation is dependent on the rate of the secretion of sweat on to skin surface[27,28]. Sweat rate is determined by the density of heat activated sweat glands and the overall rate/volume of sweat output per gland which is controlled by a central integration of core and skin temperatures[9, 29–31]. Sweat losses are generally reported as whole-body or local sweat rates.

Body Composition & Heat Stress

The variability in body surface area, mass and composition between individuals affects the biophysical process of heat exchange and results in differences in thermoregulatory responses during exercise[4]. Body surface area gives an indication of the surface available for heat transfer by means of convection, radiation and evaporation[9, 34]. Total body mass influences changes in core temperature for a given absolute metabolic rate, that is, a larger compared to a smaller mass requires greater heat storage for a given change in core temperature[11]. People with obesity generally have a lower BSA to mass ratio; this is an important biophysical characteristic because it indicates that for a given mass and therefore given heat production the skin surface area available for heat loss through evaporation is lower. In addition, differences in body composition are believed to affect the change in core temperature for a given heat storage because the proportions of fat and lean muscle tissue between obese and lean populations are different (lean muscle is 3.64 $kJ•kg^{-1}•^{o}C^{-1}$ and fat is 2.97 $kJ•kg^{-1}•^{o}C^{-1}$) and should theoretically modify average overall specific heat capacity of the body[12]. It follows that lean compared to obese individuals matched for mass would theoretically require a greater heat storage to increase a given core temperature.

Dougherty et al[8] reported end-exercise core temperature between young lean and obese boys during exercise at 30% of their VO_{2peak} (lean: ~49 $mL·kg^{-1}·min^{-1}$, obese: ~37 $mL·kg^{-1}·min^{-1}$) pre and post heat acclimation. In support of previous studies assessing the role of body fat on the increase of core temperature during exercise at relative intensities[36–40] , the authors interpreted lower end-exercise core temperature in lean compared to obese groups (lean:37.72 ±0.06°C, obese: 37.89 ±0.05°C) as evidence of a lower metabolic heat production in the lean group[8]. However, the lean group was fitter than the obese group, therefore exercise prescribed at 30% of VO_{2peak} would have actually yielded (assuming a respiratory quotient of 0.85) a heat production per unit mass of ~5.1 $W·kg^{-1}$ in the lean group compared to only ~3.8 $W·kg^{-1}$ in the obese group. In parallel, the change of core temperature from rest to end-exercise, which is more indicative of heat storage, was actually slightly greater in the lean (0.54 ±0.02°C) relative to the obese (0.48 ±0.08°C) group. Also, absolute heat production in the obese and lean group would have been 204 W and 214 W, respectively. The similar evaporative requirement's in both groups explains the comparable whole-body sweat rates reported (obese: 310.5±33 $ml·h^{-1}$, lean: 316.5±44 $ml·h^{-1}$) suggesting that the potential for heat dissipation was not altered by adiposity. It is clear that Dougherty et al[8] did not isolate the influence of adiposity on the changes in core temperature during exercise due to the confounding effects of differences in mass and heat production. Similarly, a recent study by Leites et al[42], reported greater changes in core temperature in lean (total body mass: 25.4±4.6 kg) compared to obese (total body mass: 40.6 ±8.8 kg) groups when exercising at a relative intensity of ~55% VO_{2peak}. Their observed differences in core temperature can be explained by the greater heat production per unit total body mass in the lean (8.4 W/kg) relative to the obese group (6.7 W/kg), however the influence of adiposity on core temperature change may have been masked in their study. Selkirk et al[7], reported heat tolerance between trained, untrained, obese and lean participants at a fixed heat production of lean body mass, with significantly greater changes in core temperature in lean trained compared to obese untrained participants. The participants were not matched for either total or lean body mass which indicates that changes in core temperature were different between the groups due to greater heat production per unit total/lean body mass[7]. In addition, this experiment was conducted in an uncompensable environment (e.g., exercise in a hot and humid environment) where even maximum heat loss is insufficient to attain heat balance, and core temperature will therefore not reach a steady-state (i.e. core temperature will continue to rise). Since the environment limited heat dissipation, because the maximal evaporative capacity of the environment is reduced and for a given evaporative requirement, heat dissipation is impaired due to E_{req}:E_{max} ratio being closer to 1 (where sweating becomes inefficient), adiposity cannot be measured independently as a variable of core temperature change.

Two studies in the literature report similar changes in core temperature in obese and lean groups exercising at similar heat productions per unit total body mass in compensable conditions[13, 14]. When walking at a fixed heat production per unit total body mass in a thermo-neutral and hot environment (48-50°C & 20-30% relative humidity), Miller et al[13] reported similar mean changes in core temperature in obese and lean participants (obese: +0.81°C, lean: +0.83°C) [13]. Similarly, Bar-Or et al[14] found equal changes core temperature in lean and non-lean participants with a difference in body fat of 5.9 to 21.2% walking at a fixed speed/incline in a range of effective temperatures (21.1 to 26.7°C). While these two studies oppose the prevailing belief within the literature that adiposity does alter changes in core temperature independently of heat production and mass, no study has fully isolated the influence of body fat% on thermoregulatory responses during exercise by matching lean and obese individuals for total body and assessing their core temperature and sweating responses during exercise prescribed at a fixed metabolic heat production.

Proposed Research Project

Rationale

Assessing whether individuals with a high adiposity are at greater risk of physiological heat strain during physical activity or work in warm environments is necessary given the recent global increase of obesity[15]. There have been many studies comparing thermoregulatory responses between obese and lean participants during exercise[7,8,13,14,39,40]. However, the independent influence of adiposity on changes in core temperature during exercise is unclear[5, 13]. In order to truly isolate the influence of adiposity from other biophysical factors, two groups with large differences in body fat, must be matched for a) total body mass (TBM), in order to permit the comparison of core temperature changes and b) BSA, in order to avoid biophysically mediated differences in sweating efficiency, and permit the comparison of whole-body sweat rates. Table 1 demonstrates hypothetical lean and non-lean participants of similar TBM exercising at a fixed heat production of 6 W/TBM. Since heat production and TBM are the same, both groups should also have comparable evaporative requirements for heat balance. Using this experimental paradigm, if adiposity does not independently influence thermoregulatory responses, changes in core temperature and whole body sweating should be the same between the lean and non-lean groups. Assuming that adiposity will indeed alter thermoregulatory responses, a previously suggested method [7] to perform an unbaised comparison of two groups with different fat masses is to prescribe exercise that elicits the same rate of heat production per unit lean body mass. As such, Table 2 shows hypothetical lean and non-lean participants of similar TBM and different lean body mass (LBM), exercising at a fixed heat production of 7.5 W/LBM. However, lean and non-lean participants should have different evaporative requirements for heat balance and a greater heat production per unit total body mass. Therefore if adiposity does not independently alter thermoregulatory responses, changes in core temperature and whole-body sweating should be greater in the lean group in this particular condition.

Table 1. An estimate of heat production and heat loss parameters during 60 minutes of cycling at fixed heat productions of TBM . The TBM fixed heat production is compared between lean and non-lean groups.

Fixed Heat Production: 6 Watts/TBM (kg)								
				Heat Production		Heat Loss		
Group	TBM	Height	BSA	Metabolic Heat Production		E_{req}	E_{max}	E_{req}/E_{max} (ω_{req})
	kg	m	m^2	Watts	Watts/m^2	Watts/m^2	Watts/m^2	
Lean	98	1.83	2.197	588	267.7	177.2	393.7	0.45
Non-lean	98	1.83	2.197	588	267.7	177.2	393.7	0.45

Table 2. **An estimate of heat production and heat loss parameters during 60 minutes of cycling at fixed heat productions of LBM. The LBM fixed heat production is compared between lean and non-lean groups of the same TBM.**

Fixed Heat Production: 7.5 Watts/LBM(kg)								
				Heat Production		Heat Loss		
Group	LBM	Height	BSA	Metabolic Heat Production		E_{req}	E_{max}	E_{req}/E_{max} (ω_{req})
	kg	m	m^2	Watts	Watts/m^2	Watts/m^2	Watts/m^2	
Lean	80	1.83	2.197	600	273.1	182.2	393.7	0.46
Non-lean	65	1.83	2.197	487.5	221.9	135.7	393.7	0.34

The heat production and heat loss calculations are based on individuals with similar total body mass, height, and varying body fat percentage (non-lean: ~30% body fat, lean: ~10% body fat). It is assumed that the participants in the lean group have a greater lbm than the non-lean group. Both tables 1 & 2 measure heat production (Metabolic Rate-Work) in absolute (watts, W) and relative (watts per kg of TBM or LBM ,$W \cdot kg^{-1}$) conditions. The evaporative requirements for heat balance in ($W \cdot m^{-2}$) and the maximum capacity for evaporative heat loss in ($W \cdot m^{-2}$) are expressed in a ratio known as skin wettedness. The value for skin wettedness is the minimum in order to achieve heat balance. The evaporative requirement is calculated as the difference between metabolic heat production and total sensible (convective & radiative heat loss) and respiratory heat losses (convective and evaporative). The heat balance equation is calculated based on the following: 33°C mean skin temperature, 28°C air temperature, 30% relative humidity, and 1.1 $m \cdot s^{-1}$ air velocity.

Research Question

The following research questions will be addressed:

I. Are there significant differences in changes in core temperature and sweating during exercise at a fixed heat production of TBM and LBM between lean and non-lean groups?

II. Is there a difference in body heat storage between lean and non-lean groups during exercise at a fixed heat production of TBM and LBM.

Hypothesis

The hypotheses for this experiment are as follows:

I. Participants of lean and non-lean groups will not show different changes in core temperature and sweating during exercise at fixed heat production of TBM. However, the lean compared to non-lean group will have a greater change in core temperature and sweating during exercise at a fixed heat production of LBM due to a greater total lean mass and therefore a greater heat production (absolute and per unit total body mass).

II. Heat storage will be similar between lean and non-lean groups during exercise at a fixed heat production of TBM. However, during exercise at a fixed heat production of LBM, heat storage will be greater in lean compared to non-lean participants due to the greater total lean mass and therefore absolute heat production.

Methods

Participants

Eligible participants will be separated into two groups based on their body fat percentages: 1) <10% body fat or 2) >30% body fat. Both groups will consist of eight healthy males aged between 18 to 40 years, each with no contraindications to perform peak oxygen uptake testing (VO_{2peak})[44]. The exclusion criteria include cardiovascular/respiratory disease, diabetes, high blood pressure or metabolic disorders, smokers and individuals taking medications related to the management of the above mentioned conditions. As shown in Figure 3, the participants will have similar TBM but with significantly different LBM.

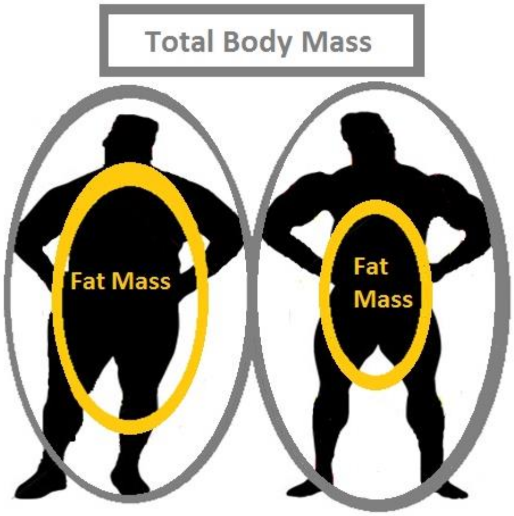


Figure 3: Body composition differences between lean (~10% body fat) and obese (~30% body fat) participants of similar TBM

The lean participant (on the right) will have a greater lean mass and smaller fat mass compared to the obese (on the left) participant. Both groups will have similar total body masses.

Instrumentation

Temperature: Esophageal temperature (T_{eso}) will be measured with a pediatric thermocouple probe (Mon-a-therm Nasopharyngeal Temperature Probe; Mallinckrodt Medical) inserted through the participant's nostril and into the esophagus. The approximate placement of the probe will correspond to the level of the 8th/9th thoracic vertebrae, close to the region between the lower left atrium and upper left ventricle[45]. Rectal temperature (T_{re}) was measured with a pediatric thermocouple probe (Mon-a-therm Nasopharyngeal Temperature Probe; Mallinckrodt Medical) self-inserted to a minimum of 12 cm past the anal sphincter. Skin temperatures (T_{sk}) was measured at eight separate sites: forehead (T_{fh}), triceps (T_{tri}), shoulder (T_{sh}), scapula (T_{scap}), chest (T_{chst}), back of the hand (T_{hand}), thigh (T_{quad}) and calf (T_{clf}), using T-type (copper/constantan) thermocouples. Mean skin temperature (T_{sk}) was subsequently calculated using a weighted proportion for each site in the following equation[16]:

$$T_{sk} = 0.07T_{fh} + 0.07T_{tri} + 0.07T_{sh} + 0.175T_{scap} + 0.175T_{chest} + 0.05T_{hand} + 0.19T_{quad} + 0.20T_{clf}$$

Whole body sweat rate (WBSR) was estimated by measuring the participant's body mass with a platform scale (Combics 2, Sartorius, Mississauga, Ontario, Canada) immediately before the start of exercise, and then after 15, 30, 45 and 60 minutes of exercise. The changes in body mass between each weigh-in was divided by 15 and by BSA (m^2) and calculated using the equation by DuBois and DuBois (1916), resulting in values of WBSR ($g \cdot m^{-2} \cdot min^{-1}$).

Local Sweat Rate (LSR) was estimated by placing a ventilated sweat capsule on the forearm and upper back. Anhydrous air at a flow rate of 1.80 L/min passed through the ventilated sweat capsules and over the skin surface. The large difference in partial pressure from the moisture on the surface of the skin to the influent anhydrous air is optimal for the evaporation of moisture, increasing vapour content in the air. A precision dew point mirror (RH Systems, Albuquerque, NM) measured the effluent air expressed as relative humidity (%). The LSR, expressed as milligrams per centimeters squared per minute, was calculated using flow rate (L/min), ambient air temperature (°C) and relative humidity (%) of the effluent air, and sweat capsule surface area (4.0 cm^2).

Mean Arterial Pressure (MAP) was calculated using measured systolic and diastolic pressures in mmHg (i.e. MAP=$\frac{2}{3}diastolic\ pressure + \frac{1}{3}systolic\ pressure$). Blood pressure was measured on the arm that did not have a sweat capsule and was taken before exercise and two minutes prior to the end of each 15 minute block during exercise, using a sphygmomanometer (Welch Allyn, Ontario Medical Supplies, Ottawa, Ontario) and a stethoscope (Littmann, Ontario Medical Supplies, Ottawa, Ontario).

Skin Blood Flow (SkBF) was estimated using laser-Doppler flowmetry (PeriFlux System 5000, main control unit; PF5010 LDPM, function unit; Perimed, Stockholm, Sweden) and expressed in arbitrary perfusion units (PU). The laser-Doppler probe (PR 401 angled probe, Perimed) was taped to cleaned skin, in an area on the upper-back that did not appear to be overly vascularised. Cutaneous vascular conductance (CVC) was calculated using *Equation 15* and expressed as a percentage of the maximum CVC (%CVC_{max}) which was measured using a local heating manoeuvre at the end of the trial (see Experimental Protocol):

$$CVC = \frac{SkBF}{MAP} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots .. PU \cdot mmHg^{-1} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (15)$$

Metabolic rate and whole body heat balance: Whole body heat balance was estimated using indirect and partitional calorimetry. Metabolic heat production was difference between metabolic energy expenditure and external workload. Metabolic energy expenditure *Equation 1* was estimated by indirect calorimetry with a Vmax Encore Metabolic Cart (Carefusion, San Diego, CA) that sampled oxygen and carbon dioxide concentrations. The external workload was regulated using a semi-recumbent cycle ergometer (Corival Recumbent, Lode B.V., Groningen, Netherlands). Rates of radiative (*Equation 7*) and convective (*Equation 4*) heat exchange was estimated using skin to air temperature gradients and measurements of air velocity using a multi-directional Hot Wire Anemometer (Model HHF2005HW, Omega Canada, Laval, QC). Respiratory heat loss was estimated using *Equation 9* and the required rate of evaporation ($\dot{E}_{\text{req}}$) for heat balance was calculated as the difference between metabolic heat production, and the sum of sensible and respiratory heat losses (*Equation 11*). The maximum rate of evaporation was estimated using *Equation 12*. Calculations for E_{req}, E_{max} and ω_{req} under the selected environmental conditions for the proposed study are provided in Figure 3. The data from indirect and partitional calorimetry was used in the conceptual heat balance equation presented in figure 2b.

Given constants:

Caloric equivalent per liter of oxygen for the oxidation of carbohydrates :

e_c=21.13kJ

Caloric equivalent per liter of oxygen for the oxidation of fat:

e_f = 19.62kJ

Stefan-Boltzmann constant, used for the radiative heat transfer coefficient (h_r):

$\sigma = 5.67 \times 10^{-8}$ ($W \cdot m^{-2} \cdot K^{-4}$)

Measured values:

VO_2: (L/min), RQ: 0.71 = fat, 1.0 = carbohydrates

Mechanical Efficiency of cycling: 16.6%

Core Temperature (^oC): T_{eso}, T_{rec}

Air Temperature (^oC), Relative Humidity (%)

Whole body mass (kg), lean body mass (kg), Height (m), Body Composition: DXA(g), Skinfold (mm)

Air velocity (m/s)

External Work (Watts): Measured directly using a semi-recumbent cycle ergometer (Watts).

Calculated values:

Body Surface Area (m^2):

Dubois Surface Area (A_D)= $0.202 \times W(kg)^{0.425} \times H(m)^{0.725}$

Mean Skin Temperature (^oC):

$T_{sk} = 0.07T_{fh} + 0.07T_{tri} + 0.07T_{sh} + 0.175T_{scap} + 0.175T_{chest} + 0.05T_{hand} + 0.19T_{thigh} + 0.20T_{calf}$

Metabolic Energy Expenditure (M):

$$M(Watts) = VO_2 \frac{\left(\frac{RER-0.7}{0.3}e_c\right) + \left(\frac{1-RER}{0.3}e_f\right)}{60} \times 1000$$

$$M\ (W \cdot m^2) = VO_2 \frac{\left(\frac{RER-0.7}{0.3}e_c\right) + \left(\frac{1-RER}{0.3}e_f\right)}{60 \times BSA\ (m^2)} \times 1000$$

Metabolic Heat Production (M-W):

Metabolic Heat Production = Metabolic Energy Expenditure (Watts) – External Work (Watts)

Sensible Heat Loss (convective + radiative heat exchange at the skin):

Convection (W) = $A_D h_c(t_{cl} - t_r)$

Radiation (W) = $A_D h_r (t_{cl} - t_r)$

$h_c = 8.3v^{0.6}$ *only when air velocity(v) is between 0.2 m/s$<v<$ 4.0 m/s

$$h_r = 4\varepsilon\sigma \frac{A_r}{A_D} + \left[273.2 + \frac{(t_{cl}-t_r)}{2}\right]^3$$

t_{cl} = Mean temperature of clothed body, assumed to be equal to mean skin temperature.

t_r = Mean radiant temperature is assumed to be equal to air temperature.

Respiratory Heat Loss (respiratory heat loss by convection + evaporation):

$$P_{air}(kPa) = \frac{\left[exp\left[18.956 - \frac{4030.18}{t_{air}+235}\right]\right]}{10} \times Relative\ Humidity\ (\%)$$

$C_{res} + E_{res}\ (W \cdot m^{-2}) = [\ 0.0014M\ (34 - t_{db}) + 0.0173M(5.87 - P_{air})\ ]$

Evaporative Heat Loss (Evaporative maximum& requirement):

$$P_{skin}(kPa) = \frac{\left[exp\left[18.956 - \frac{4030.18}{t_{skin}+235}\right]\right]}{10}$$

$E_{req}\ (W) = (M\text{-}W) - (C + R) - (C_{res} + E_{res})$

$E_{max}(W) = \omega(P_{skin} - P_{air})A_D h_e$

ω = skin wettedness; fraction of wet skin from sweat

Figure 4: Metabolic Heat Production and Heat Loss Calculations

Using given constants and measured data, a theoretical evaporative requirement can be calculated.

Body Composition (%): A dual-energy x-ray absorptiometry (DXA) scan will measure each participant's body composition, including lean and fat mass in grams. During the DXA scan the participant will lie down on an examination table, clothed in a hospital gown, while a low-intensity x-ray scans the entire body. The radiation associated with the measurement is equivalent to one day of sun exposure (< 0.02-0.05 millirem).

Experimental Protocol

Preliminary session

Both preliminary and experimental sessions took place at the Thermal Ergonomics Laboratory at the Lees Ave campus at the University of Ottawa. Participants were asked to abstain from consuming any form of caffeine or alcohol, or exercise one full day prior to data collection. During the preliminary session, all procedures/protocols and risks associated with participation were reviewed with each participant. In addition, each subject was asked to sign the informed consent below and complete a *Physical Activity Readiness Questionnaire (Par-Q)* and an *American Heart Association/American College of Sports Medicine Health/Fitness Facility Pre-participation Screening Questionnaire*. Thereafter, basic measurements were taken including height, mass and body composition using dual-energy x-ray absorptiometry (DXA). Then, an aerobic fitness test measuring peak oxygen consumption (VO_{2peak}) using a semi-recumbent cycle ergometer protocol was administered. The aerobic fitness test was divided into a 16-min submaximal test where participants cycle for 4-min at each stage of 60 W, 100 W, 140 W and 180 W, then after a 10-min break, the participants performed a VO_{2peak} test where they cycled with a 20 W incremental increase every minute at a minimum of 80 rpm cadence until physical exhaustion (or failure to maintain the fixed cadence). The VO_{2peak} protocol is in accordance to the Canadian Society of Exercise Physiology.

Experimental sessions

The study consisted of two experimental sessions, all conducted at the Thermal Ergonomics Laboratory. Each session lasted approximately 3 hours. As demonstrated in figure 5, the experimental sessions began with an instrumentation period. After instrumentation was completed and all the equipment and probes were in place and functioning, participants were weighed and then asked to rest for 30 minutes during which time baseline measurements were taken.

Depending on the order of experimental trials, participants wers asked to begin cycling on a semi-recumbent cycle ergometer at a fixed external workload, eliciting rates of metabolic heat production of 6 W per kilogram of total body mass (6 W/TBM) or 7.5 W per kilogram of lean body mass (7.5 W/LBM), in a climate-controlled room maintained at ~28ºC, 40%RH. Participants cycled for 60 minutes, unless rectal temperature exceeded 39.5ºC, or there was volitional termination. Exercise was divided by four 15-min blocks. Two minutes prior to the end of each 15-min block, estimations of blood pressure were taken from participants while cycling. Then at the end of the 15-min block participants stopped cycling to be weighed which took two minutes. At the end of exercise there was 45 minutes of local heating at 42°C while resting until a maximum plateau of SkBF was reached followed by de-instrumentation.

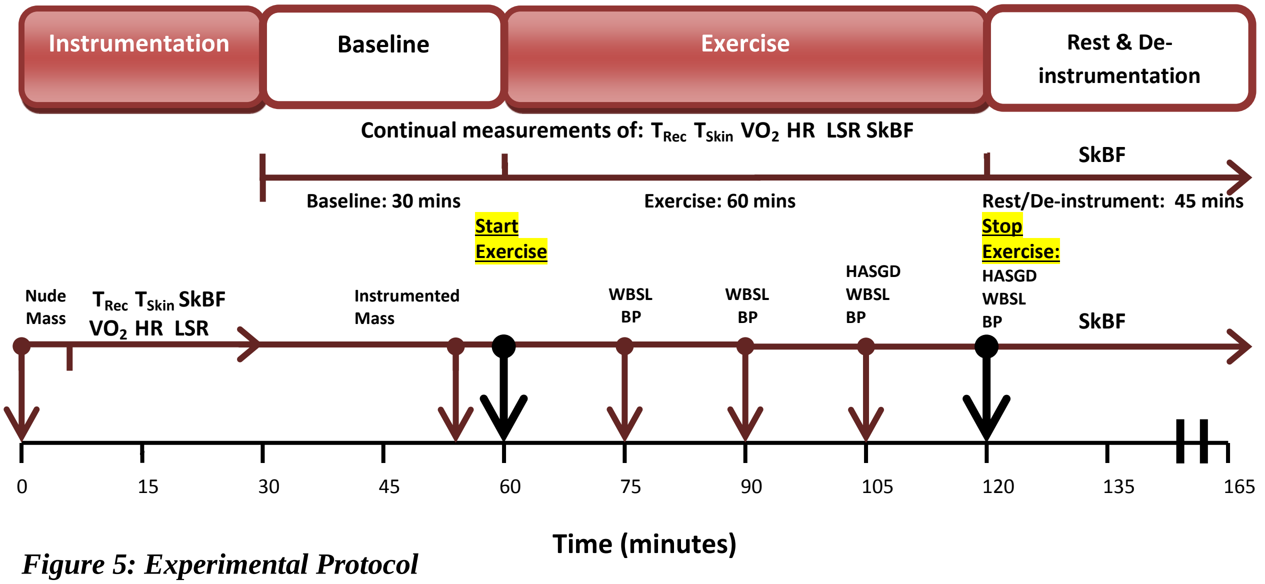


Figure 5: Experimental Protocol

The whole experimental session includes instrumentation, baseline measurements of HR, VO_2 , LSR , skin and core temperature at rest. Then continuous measurements as seen during baseline, with intermittent (every 15 minutes) weigh-in for whole body sweat rates. Also, every 10 minutes throughout the exercise period there will be subjective measures of perceived exertion and thermal sensation.

Statistical Analysis

All data was expressed as means ± standard deviations, and analyzed within exercise trials (i.e., Exercise at fixed heat production of 6 W/TBM and 7.5 W/LBM). A two-way mixed analysis of variance (ANOVA) was used to analyze the data, with a repeated factor of "time" (at five levels: 0, 15, 30, 45 and 60 minutes of exercise; four blocks of weigh-in times: 0-15, 15-30, 30-45, 45-60 minutes of exercise) and a non-repeated factor of " Body Fat Group" (two levels: non-lean group~30% and a lean group ~ 10%) was used to analyze the dependent variables of T_{rec}, T_{skin}, LSR (upper back and forearm), cutaneous vascular conductance (CVC) and WBSR. An independent sample t-test was performed with significant interactions to identify the individual differences between groups. In order to decrease the probability of a Type 1 error, the significance was at an alpha level of 0.05 for all comparisons using a Holm-Bonferroni correction. The data was analysed using SPSS statistical software 19.0 for Windows (SPSS, IL, USA).

Chapter III

Results

Thesis Article

Body fat does not independently alter changes in core temperature and thermoregulatory sweating during exercise

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Abstract

Currently no previous study has isolated the independent influence of body fat (BF) on thermoregulatory responses from the confounding biophysical factors of body mass and metabolic heat production (H_{prod}). Therefore, seven lean (L, BF:10.7 ± 4.1%) and seven non-lean (NL, BF:32.2 ± 6.4%) males matched for total body mass (TBM, L: 87.8 ± 8.5 kg, NL: 89.4 ± 7.8 kg; P= 0.73), cycled for 60 min in a 28.2 ±0.2˚C and 27 ± 10% RH room at i) a H_{prod} of 546 W; and ii) a H_{prod} of 7.5 W·kg lean body mass (LBM). Rectal (T_{re}) and esophageal (T_{es}) temperatures, and local sweat rate (LSR) were measured continuously; while whole body sweat loss (WBSL) was measured from 0-60 mins. At 546 W, changes in T_{re} (L: 0.74 ± 0.16ºC, NL: 0.83 ± 0.14ºC), mean local sweat rate (MLSR) based on an average of upper-back and forearm local sweat rates (L: 0.65 ± 0.25, NL: 0.59±0.12 $mg \cdot cm^{-2} \cdot min^{-1}$) and WBSL (L: 568 ± 28 mL, NL: 567 ± 29 mL) were similar (P>0.58). At 7.5 W·kg LBM, the L group had greater changes in T_{re} (L: 0.87 ± 0.16ºC, NL: 0.55 ± 0.11ºC), MLSR (L: 0.83 ±0 .38, NL: 0.41 ± 0.13 $mg \cdot cm^{-2} \cdot min^{-1}$) and WBSL (L: 638 ± 19 mL, NL: 399 ± 17 mL) (P<0.05). In conclusion, i) body fat does not independently alter thermoregulatory responses during exercise; ii) core temperature comparisons between groups differing in BF should be performed using a H_{prod} normalized for TBM, not LBM.

Introduction

Obesity is a condition in which body fat is elevated to the extent that health and well-being are impaired[11]. World Health Organization (WHO) guidelines suggests that those with obesity have a greater vulnerability to heat strain during exercise due to lower fitness levels, greater percent body fat (%BF) and therefore greater heat storage and changes in core temperature[15]. The established relationship between obesity, exercise and a greater risk of heat strain is supported by the prevailing notion that large differences in %BF alter thermoregulatory responses and therefore heat dissipation during exercise[7,8,13,15,23]. However, none of these previous studies have isolated the influence of body fat from the biophysical factors of total body mass and metabolic heat production (H_{prod}).

Due to lower fitness levels typically existing alongside a higher %BF, and the prevailing logic that aerobic fitness profoundly alters thermoregulatory responses[8,17,22,25], changes in core temperature and sweating of obese and lean groups are usually compared using a fixed relative intensity (%VO_{2max}) [8,17,22,25]. However it is now known that in a compensable environment, changes in core temperature and whole-body sweating are almost identical between groups with large differences in aerobic fitness but matched for total body mass and exercising at the same absolute H_{prod}[4,10,13,14]. Furthermore, the comparison of groups with different fitness levels using exercise prescribed to elicit a fixed %VO_{2max} leads to systematically different changes in core temperature due to different rates of H_{prod} per unit body mass[4,14], and systematically different rates of whole-body sweating due to differences in absolute H_{prod} and therefore the evaporative requirement for heat balance (E_{req}) [10,14].

It follows that, while the lower specific heat of fat tissue should theoretically lead to a greater body temperature change for a given amount of heat energy stored inside the body, and skin surface heat loss could be impaired due to the insulative properties of subcutaneous fat, all previous studies examining the role of body fatness on thermoregulatory responses during exercise in a compensable environment are confounded by differences in total body mass and/or H_{prod} between lean and obese groups. Limbaugh et al[16] recently reported similar changes in core temperature between groups with a low (11%) and moderate (23%) body fat percentage exercising at a fixed external workload (66 W) and presumably very similar absolute rates of H_{prod}. However the total body masses of the two groups (78.5 ± 9.4 kg and 91.9 ± 14.9 kg) were vastly different, leading to a much greater heat sink in the higher body fat group, which potentially masked any thermoregulatory impairments in the higher fat group. A classic study by Vroman et al[25] compared lean and obese groups using relative exercise intensities of 30%, 50% and 70% VO_{2max}. However, the large difference in VO_{2max} (lean: 48.1 ± 2.1 mL·kg^{-1}·min^{-1}; obese: 36.0 ± 4.8 mL·kg^{-1}·min^{-1}) between the two groups, would have probably resulted in a higher H_{prod} and E_{req} which would have led to a systematically greater sweat rates in the lean group[10,14], not due to an influence of the adiposity per se but due to the experimental approach adopted. Moreover, two other studies[2,13] followed a similar protocol (fixed walking speeds at 4.8 km·h^{-1} and 5% grade), with the obese group in each study ~17 kg heavier than the lean group. It is likely that the additional energetic cost of carrying extra weight in the obese group would have elicited a greater H_{prod} and E_{req}, which would not have permitted an experimental isolation of the influence of adiposity on changes in core temperature or thermoregulatory sweating during exercise.

A method proposed in the literature for evaluating the thermoregulatory responses of two independent groups with different %BF, assumes that the supposed confounding influence of fat can be eliminated by prescribing an exercise intensity that elicits the same rate of H_{prod} per unit lean body mass ($W \cdot LBM^{-1}$)[15]. However, if %BF does not actually influence the maintenance of core body temperature during exercise, such an approach would lead to systematically greater sweat rates in lean individuals due to a greater E_{req}[10,14], and possibly greater changes in core temperature due to a greater H_{prod} per unit total body mass.

The aim of the present study was to assess whether large differences in %BF independently alter changes in core temperature and thermoregulatory sweating during exercise in a compensable environment by recruiting two independent groups matched for total body mass but vastly different in body fat percentage and prescribing exercise intensity to elicit the same absolute H_{prod}. A second aim of this study was to assess the utility of the $W \cdot LBM^{-1}$ method for unbiased comparison of changes in thermoregulatory responses between groups differing greatly in %BF. It was hypothesized that after matching lean and non-lean participants for total body mass, BSA, age and sex, changes in core temperature and sweating during exercise would be i) similar, despite large differences in %BF, at an absolute fixed H_{prod} (490 W) and ii) significantly greater in the lean group at the same H_{prod} per lean body mass (7.5 $W \cdot kg^{-1}$) due to a greater total H_{prod} per unit total mass and greater corresponding E_{req}. The results would demonstrate that contrary to conventional wisdom, large differences in %BF do not independently alter changes in thermoregulatory responses during exercise in a compensable environment[2,18] .

Methods

Participants

Prior to testing, the Research Ethics Board at the University of Ottawa approved the experimental protocol. The eligible participants completed a Physical Activity Readiness Questionnaire (PAR-Q), American Heart Association questionnaire (AHA) and consent form before experimentation and were excluded if they had cardiovascular or metabolic health disorders.

Seven lean (L, BF: 10.7±4.1%) and seven non-lean (NL, BF: 32.2±6.5%) males matched for total body mass (TBM, L: 87.8 ±8.5 kg, NL: 89.4.0±7.8 kg) were recruited (Table 1). All participants refrained from the consumption of caffeine or alcohol and any form of strenuous exercise 24 hours prior to the experimental trials.

Instrumentation

Thermometry. Rectal temperature (T_{re}) was measured with a pediatric thermocouple probe (Mon-a-therm Nasopharyngeal Temperature Probe; Mallinckrodt Medical) inserted to a minimum of 12 cm past the anal sphincter. Skin temperatures (T_{sk}) were measured at eight separate sites: forehead (T_{fh}), triceps (T_{tri}), shoulder (T_{sh}), scapula (T_{scap}), chest (T_{chst}), back of the hand (T_{hand}), thigh (T_{quad}) and calf (T_{clf}), using T-type (copper/constantan) thermocouples. Mean T_{sk} was calculated using a weighted average of each site[21]*:*

$$T_{sk} = 0.07T_{fh} + 0.07T_{tri} + 0.07T_{sh} + 0.175T_{scap} + 0.175T_{chst} + 0.05T_{hand} + 0.19T_{quad} + 0.20T_{clf} \quad [1]$$

Whole body sweat rate (WBSR) was estimated by measuring the participant's body mass with a platform scale (Combics 2, Sartorius, Mississauga, Ontario, Canada) immediately before the start of exercise, then after 15th, 30th, 45th and 60th minute of exercise. The changes in body mass between each weigh-in were divided by 15 minutes, resulting in values of WBSR ($g{\cdot}min^{-1}$).

Final WBSR values were determined after subtracting saliva, respiratory and metabolic mass losses.

Local Sweat Rate (LSR) was estimated by placing a ventilated sweat capsule on the forearm and upper-back. Anhydrous air at a flow rate of 1.80 L/min passed through the ventilated sweat capsules and over the skin surface. A precision dew point mirror (RH Systems, Albuquerque, NM) was used to measure the effluent air expressed as relative humidity (%). The LSR, expressed as milligrams per centimeters squared per minute, was calculated using flow rate (L/min), ambient air temperature (°C) and relative humidity (%) of the effluent air, and sweat capsule surface area (4.0 cm^2).

Mean Arterial Pressure (MAP) was calculated using measured systolic and diastolic pressures in mmHg (i.e. MAP=$\frac{2}{3}diastolic\ pressure + \frac{1}{3}systolic\ pressure$). Blood pressure was measured using a sphygmomanometer (Welch Allyn, Ontario Medical Supplies, Ottawa, Ontario) and a stethoscope (Littmann, Ontario Medical Supplies, Ottawa, Ontario) before exercise and two minutes prior to the end of each 15 minute block during exercise. MAP was used in the calculation for cutaneous vascular conductance, mentioned below.

Skin Blood Flow (SkBF) was estimated using laser-Doppler flowmetry (PeriFlux System 5000, main control unit; PF5010 LDPM, function unit; Perimed, Stockholm, Sweden) and expressed in arbitrary perfusion units (PU). The laser-Doppler probe (PR 401 angled probe, Perimed) was taped onto an area on the upper-back that was not overly vascularized. Cutaneous vascular conductance (CVC) was then calculated using *Equation 2* and expressed as a percentage of the maximum CVC (%CVC_{max}) which was measured using a local heating manoeuvre at the end of the trial (see protocol):

$$CVC = \frac{SkBF}{MAP}\ (PU \cdot mmHg^{-1}) \qquad [2]$$

Metabolic Energy Expenditure: Metabolic energy expenditure was estimated by indirect calorimetry with a Vmax Encore Metabolic Cart (Carefusion, San Diego, CA) that samples breath-by-breath oxygen and carbon dioxide concentrations.

Calculations

Metabolic Heat Production. Metabolic heat production (M-W) was obtained from the difference in metabolic energy expenditure (M) and external work (W) regulated directly using a semi-recumbent cycle ergometer (Corival Recumbent, Lode B.V., Groningen, Netherlands). The metabolic energy expenditure was obtained using minute-average values for oxygen consumption (VO_2) measured in liters per minute and respiratory exchange ratio (RER) as shown in *Equation 3*[19]:

$$M = \mathrm{VO_2}\,\frac{\left(\frac{\mathrm{RER}-0.7}{0.3}\mathrm{e_c}\right) + \left(\frac{1-\mathrm{RER}}{0.3}\mathrm{e_f}\right)}{60} \bullet 1000 \quad (\mathrm{W}) \qquad [3]$$

Where e_c is the caloric energy equivalent per liter of oxygen for the oxidation of carbohydrates (21.13 kJ) and e_f is the caloric energy equivalent per liter of oxygen for the oxidation of fat (19.62 kJ).

Sensible Heat Loss. The sum of convective (C) and radiative (R) heat exchange at the surface of the skin was calculated using *Equations 4 & 5* for convection, then *6 & 7* for radiation:

$$C = BSA \cdot h_c(t_{sk} - t_a)\ (\mathrm{W}) \qquad [4]$$

$$h_c = 8.3 v^{0.6}\ (\mathrm{W} \bullet m^{-2} \bullet K^{-1}) \qquad [5]$$

In *Equation 4*, h_c is the convective heat transfer coefficient in $W \bullet m^{-2}K^{-1}$ and in *Equation 5* v is the velocity of air in $m \bullet s^{-1}$. In *Equation 3*, BSA is the surface area of the nude body in m^2; t_{sk} is the weighted mean temperature of the skin surface in ^{o}C and t_a is the mean air temperature in ^{o}C equal to surrounding air temperature.

$$R = BSA\, h_r \; - t_r)\ \ (\mathrm{W}) \qquad [6]$$

$$h_r \; = 4\varepsilon\sigma \frac{A_r}{BSA} + \left[273.2 + \tfrac{(t_{sk} - t_r)}{2}\right]^3 \ \ (\mathrm{W} \bullet m^{-2} \bullet K^{-1}) \qquad [7]$$

In *Equation 6, h_r* is the radiative heat transfer coefficient in W•m-^{2}•K^{-1}. In *Equation 7, h_r* considers emissivity (ε) of the clothed body, reflecting the surface of the skin which is ~1.0. The radiative area (A_r) referring to a proportion of total BSA exposed to a radiant heat source was assumed to be ~0.7.

Respiratory Heat Loss by Convection and Radiation. Convective respiratory heat loss (C_{res}) and evaporative respiratory heat loss (E_{res}) were calculated using *Equation 8*:

$$C_{res} + E_{res} = [0.0014(M - W)(34 - t_a) + 0.0173(M - W)(5.87 - P_a)]\ \ (\mathrm{W}) \qquad [8]$$

Where (M-W) is the metabolic heat production in watts, P_a is the partial pressure of water vapor in the ambient air in kilopascal and t_a is the air temperature in (°C).

Evaporation. The actual rate of evaporation was calculated using *Equation 9*, and rate of evaporation for heat balance using *Equation 10*:

$$E_{actual} \; = \frac{2426 \bullet (WBSL)}{3600} \ \ (W) \qquad [9]$$

$$E_{req} = \ (M - W) - (C_{res} + E_{res}) - (C + R)\ (\mathrm{W}) \qquad [10]$$

Where the quantity of heat energy liberated by sweat as it evaporates is called latent heat of vaporization and the body loses 2426 Joules of heat for each evaporated gram of water. Whole body sweat loss (WBSL) measured in grams, is the sum of sweat loss for the 60 minutes of exercise.

Heat Storage: was calculated using *Equation 11*:

$$\Delta H_b = (M - W) - [C + R + (C_{res} + E_{res}) + E_{actual}]\ (kJ) \tag{11}$$

All units of the components of *Equation 11* were converted to kJ in order to calculate the sum of heat storage at the end of each experimental trial. To convert the sum of Watts to kJ *Equation 12* was used:

$$Heat\ Storage = \frac{[(Average\ Watts) * 60 * 60]}{1000}\ (kJ) \tag{12}$$

Experimental Design

Participants were instructed to arrive at the Thermal Ergonomics Laboratory in Ottawa, Ontario, Canada, after eating more or less the same meal prior to each experimentation session. All paired participants completed the experimental trials at the same time of day to prevent the influence of circadian rhythm variation. To confirm participants were euhydrated, they were instructed to drink plenty of fluids the night before each experimental trial. 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 spectrometer (Reichert TS 400, Depew, NY). All participants required to have a USG below 1.020 to assure euhydration before exercise[1,20].

Environmental conditions during each experimental trial included an air temperature (T_a) of 28.2 ± 0.2˚C, relative humidity (RH) of 27 ± 9% and an air velocity (v) of 0.83 $m \cdot s^{-1}$. The ambient conditions and the rates of the target heat production selected per unit total body mass (550 W) and lean body mass (~7.5 $W \cdot kg^{-1}$ of lean body mass) were selected to ensure conditions were compensable and permitted the full evaporation of sweat in all the participants. In order to ensure the same body surface area was available for the evaporation of sweat, all participants exercised semi-nude in standardized shorts. The typical evaporative resistance of a semi-nude (wearing shorts) individual is 0.016 $m^2 \cdot kPa \cdot W^{-1}$, was considered negligible[4]

Protocol

In the *preliminary trial,* total body mass and height were measured, as well as body composition using a Dual-Energy X-Ray Absorptiometry (DXA). Subsequently, peak oxygen consumption (VO_{2peak}) was measured using a semi-recumbent cycle ergometer involving a graded 16 minute warm-up, then after a short break a maximal test where the external workload increased by 20 W every minute until physical exhaustion. The VO_{2peak} protocol followed the Canadian Society of Exercise Physiology guidelines[5].

In the *experimental trials*, during baseline, participants remained seated for 30 minutes. Afterwards, participants cycled for 60 minutes at an external workload that elicited an absolute heat production of 550 W (FHP trial), or a metabolic heat production of 7.5 W per kilogram of lean body mass (W/LBM trial). At the end of every 10 minutes of exercise participants were asked their rate of perceived exertion[3] (RPE) on a Borg scale from 6 (no exertion) to 20 (maximal exertion) and thermal sensation[9] (TS) on a scale from -3 (cold) to +3 (hot). Then, at the end of every 15 minutes of exercise, participants were weighed after blood pressure measurements were taken. After 60 minutes of exercise, there was 45 minutes of post-exercise recovery, during which time participants remained resting while measurements of maximal skin blood flow were assessed by locally heating the skin to 42ºC until SkBF reached a maximal plateau (to calculate maximum values of SkBF and CVC), then post exercise blood pressure measurements was taken. Prior to leaving, another measurement of hydration was taken from each participant to ensure they did not become dehydrated during exercise[1,20] (i.e. USG <1.020).

Statistical Analysis

All data was expressed as a mean ± standard deviation, and analyzed within exercise trials (i.e., FHP trial and W/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 minutes of exercise for ΔT_{rec}, T_{skin}, LSR (upper-back and forearm), SkBF and CVC; four levels: 0-15, 15-30, 30-45, 45-60 minutes of exercise for WBSR) and the non-repeated factor of “ Body Fat Group” (two levels: non-lean and lean). Any significant interaction or main effect was subjected to an independent sample t-test to identify the individual differences between groups. In order to decrease the probability of a Type 1 error, the significance was set at an alpha level of 0.05 for all comparisons using a Holm-Bonferroni correction.

Results

Physical Characteristics

Participants were carefully selected and paired to ensure no differences in total body mass ($P=0.730$) and body surface area ($P=0.560$) between lean (L) and non-lean groups (NL). However, the L group had a significantly greater VO_{2peak} ($P=0.025$), lean body mass ($P<0.001$) and specific heat capacity ($P<0.001$), and the NL participants had greater percent body fat (%BF), $P<0.001$). As presented in Table 1, mean participant characteristics are separated according to %BF and paired according to total body mass.

Heat Production & External Workload

Average values for metabolic heat production and external work load for both trials are presented in Table 2. In the fixed heat production (FHP) trial L and NL participants had the same heat production in W ($P=0.585$), W per unit mass (kg) of total body ($P=0.201$), W per unit BSA (m^2) ($P=0.392$) and the external workload to maintain the fixed heat production was also the same between groups ($P=0.281$). However, the W per unit lean body mass was significantly ($P<0.05$) greater in the NL group compared to the L group.

In the $W \cdot LBM^{-1}$ trial, the same fixed W per unit kg of lean body mass was successfully maintained for both groups ($P=0.258$). In parallel, the external workload was significantly greater in the lean group ($P<0.005$) and consequently absolute metabolic heat production in W, W per unit BSA (m^2) and W per unit kg of total body mass were all greater ($P<0.001$) in the L group ($P<0.001$).

Core Temperatures

In the FHP trial, change in rectal (T_{re}) was similar from rest to the end of 60 minutes of exercise (Fig.1). The end-exercise, change in T_{re} was similar in L (0.74 ± 0.16ºC) and NL (0.83 ± 0.14ºC) groups (P=0.25).

In the W·LBM^{-1} trial, the change in T_{re} from rest to the end of exercise was significantly greater ($P<0.01$) in the L group (0.87 ± 0.16ºC) compared to the NL group (0.55 ± 0.11ºC) (Fig. 2).

Skin Temperature

In the FHP trial, resting skin temperature (T_{sk}) was similar (P=0.79) between L (32.0 ± 0.4ºC) and NL (32.0 ± 0.4ºC) participants. End-exercise T_{sk} was lower in L (32.7 ± 0.3ºC) compared to NL (33.2 ± 0.35ºC) group, ($P<0.05$).

In the W·LBM^{-1} trial, resting skin temperature was similar (P=0.471) between L (32.0 ± 0.4ºC) and NL (31.7 ± 0.8ºC) participants. End-exercise T_{sk} was similar between L (32.8 ± 0.3ºC) and NL (32.4 ± 0.8ºC) groups, (P=0.242).

Whole-body sweat loss

In the FHP trial, whole body sweat loss (WBSL) after 60 minutes of exercise was 568 ± 43 mL in the L group, which was almost identical (P=0.989) to the NL group (567 ± 60 mL). Likewise, at the last 15 minutes of exercise whole body sweat rate (WBSR) was similar (P=0.891) between L (10.31 ± 1.72 g·min^{-1}) and NL (10.43 ± 1.40 g·min^{-1}) participants (Fig. 3).

In the W·LBM^{-1} trial, the WBSL after 60 minutes of exercise of 638 ± 19 mL in the L group was significantly greater that the WBSL of 340 ± 17 mL in the NL group ($P<0.01$).

Correspondingly, WBSR at the last 15 minutes of exercise was significantly ($P<0.01$) greater in the L participants at 11.82 ± 1.60 $g \cdot min^{-1}$ relative to the NL group at 7.44 ± 1.80 $g \cdot min^{-1}$ (Fig. 3).

Local sweat rates

Mean forearm and upper-back local sweat rate (mean local sweat rate - MLSR) was calculated throughout. In the FHP trial, end-exercise MLSR was similar ($p=0.58$) between L (0.65 ± 0.25 $mg \cdot (cm^{-2} \cdot min^{-1})$) and NL (0.59 ± 0.12 $mg \cdot (cm^{-2} \cdot min^{-1})$) participants (Fig. 4).

On the other hand, in the $W \cdot LBM^{-1}$ trial, MLSR was significantly greater ($P<0.02$) in the L (0.83 ± 0.38 $mg \cdot (cm^{-2} \cdot min^{-1})$) group compared to the NL (0.41 ± 0.13 $mg \cdot (cm^{-2} \cdot min^{-1})$) group at the end of exercise ($P<0.02$) (Fig. 4).

Cutaneous Vascular Conductance

In the FHP trial, end-exercise cutaneous vascular conductance (CVC) was quite similar ($P=0.36$) between L (58.0 ± 8.9% of maximum) and NL (52.9 ± 11.0% of maximum) (Fig. 5).

Contrarily in the $W \cdot LBM^{-1}$ trial CVC was significantly greater ($P<0.01$) in the L (65.9 ± 9.9% of maximum) group compared to the NL (33.9 ± 6.8% of maximum) group at the end of exercise (Fig. 5).

Indirect Calorimetry

In the FHP trial, after 60 minutes of exercise, cumulative heat production was similar in L (1936 ± 228 kJ) and NL (2068 ± 182 kJ) groups (P=0.251). Correspondingly, the sum of all dry, evaporative and respiratory heat losses (C+R, E_{actual} and $C_{res}+E_{res}$) was also similar (P=0.41) in L (1667 ± 220 kJ) and NL (1769 ± 192 kJ) participants. Consequently, the change in body heat content (ΔH_b) from beginning to end of exercise was similar (P=0.38) between L (268 ± 68 kJ) and NL (299 ± 57 kJ) participants (Table. 3).

In the $W \cdot LBM^{-1}$ trial, after 60 minutes of exercise, cumulative heat production was greater in L (2195± 219 kJ) compared to NL (1540 ± 238 kJ) groups (P<0.001). Likewise, the sum of all heat losses (C+R, E_{actual} and $C_{res}+E_{res}$) was significantly greater (P<0.01) in L (1885 ± 252 kJ) compared to NL (1359 ± 237 kJ) participants, and the ΔH_b from start to the end of exercise was greater in the L (310 ± 64 kJ) compared to NL (181 ± 56 kJ) group (P<0.01).

Discussion

The main findings of the present study demonstrate conclusively for the first time that large differences in body fat do not independently alter thermoregulatory responses during exercise after eliminating any potential confounding effects of body mass and body surface area (BSA). We successfully isolated body fat as an independent variable by matching lean and non-lean participants for total body mass (Table 1 & 2) and then administered exercise eliciting a fixed rate of metabolic heat production. We subsequently observed almost identical changes in core temperature (Fig 1 & 2), whole-body sweat losses (Fig 3), mean local sweat rate (Fig 4) and cutaneous vascular conductance (Fig 5) indicating no independent influence of body fat. Our findings almost demonstrate that contrary to conventional wisdom, heat production and body mass are the primary determinants of changes in core temperature during exercise, irrespective of fat mass, and therefore lean mass. In a second trial, we administered exercise to the same participants eliciting a fixed heat production per kg of lean body mass - a methodological approach previously suggested to eliminate the supposed insulating effects of adipose tissue [16,23]. It was subsequently observed that, somewhat counter-intuitively, a significantly greater change in core temperature was observed in the lean participants relative to the non-lean participants (Fig. 2). It follows that metabolic heat production per unit total body mass was far greater in the lean group, by virtue of the greater absolute heat production in this condition, leading to greater elevations in rectal and esophageal temperature[8,17,22].

Several previous studies have indicated that percent body fat influences thermoregulatory responses during exercise, however their results were apparently confounded by large differences in total body mass and heat production between lean and non-lean (or obese) groups [7,8,13,17]. For example, Eijsvogels et al[8] reported a greater core temperature in obese (100.4 ± 10.9 kg) compared to lean (69.6 ± 11.0 kg) groups with large differences in total body mass. While the average specific capacity may be lower in the obese due to a difference in heat capacity between fat tissue (2.97 $kJ \cdot kg^{-1} \cdot {}^{\circ}C^{-1}$) and muscle tissue (3.64 $kJ \cdot kg^{-1} \cdot {}^{\circ}C^{-1}$) and this could have potentially affected changes in core temperature[11] this effect was likely masked by differences in heat production since the participants engaged in a weight-bearing exercise (walking), and the variance of heat sink by virtue of differences in total body mass. Previous studies have also assumed a reduced rate of heat dissipation in obese groups due to insulative properties of adipose tissue[15]; however during exercise, peripheral vasodilation increases skin blood flow and mostly bypasses the subcutaneous layer of adipose tissue rendering its insulation inconsequential[11,12]. Inconsistent with the assumption of a reduced heat dissipation due to body fat, one study demonstrated a greater sweat rate during exercise in a obese compared to lean group (obese: 238±33 $mL \cdot m^{-2} \cdot h^{-1}$, lean: 207±22 $mL \cdot m^{-2} \cdot h^{-1}$)[7]. However, this observation cannot be attributed solely to differences in fat mass since total body mass and BSA were also different (lean: 42±2 kg, obese: 54±4 kg) and exercise was prescribed using a relative intensity which would have elicited different rates of heat production secondary to differences in VO_{2max} (lean: 49±1 mL·kg-1·min-1, obese: 37±2 mL·kg-1·min-1)[7]. It follows that discrepancies in heat production, total body mass and/or BSA between lean and non-lean (or obese) groups in all previous studies have to-date concealed any possible independent influence of body fat (including differences in average specific capacities) on thermoregulatory responses.

In the present study, average specific heat capacity and aerobic capacity (VO_{2peak}) were the only physical characteristics that were different between lean and non-lean participants (Table 1). The average specific heat capacity was significantly ($P<0.001$) greater in lean (3.65 ± 0.03 $kJ \cdot kg^{-1} \cdot {}^{o}C^{-1}$) compared to non-lean participants (3.49 ± 0.1 $kJ \cdot kg^{-1} \cdot {}^{o}C^{-1}$).

Nonetheless, when the mass-matched participants exercised at the same heat production (FHP trial) the change in rectal/esophageal temperature, whole body sweat losses and total body heat storage (kJ) was the same between both groups. Therefore the difference in specific heat capacity between lean and non-lean participants was physiologically negligible in terms of its influence on observable differences in the changes in core temperature. That is, heat storage was the same, and if the difference in specific heat between groups was influential, a greater change in core temperature would have been observed in the non-lean group. Likewise, aerobic capacity (VO_{2peak}) was significantly ($P<0.05$) greater in the lean (48.0 ± 7.2 $mL \cdot kg^{-1} \cdot min^{-1}$) compared to non-lean (39.0 ± 5.8 $mL \cdot kg^{-1} \cdot min^{-1}$) group. However, a recent study by Jay et al[14] demonstrated similar changes in core temperature and sweating between aerobically fit (60.1 ± 4.5 $mL \cdot kg^{-1} \cdot min^{-1}$) and unfit (40.3 ± 2.9 $mL \cdot kg^{-1} \cdot min^{-1}$) participants matched for total body mass, body surface area and heat production, thus demonstrating that fitness levels do not independently alter thermoregulatory responses during exercise[14]. As such, if any differences in thermoregulatory responses were observed between lean and non-lean groups in the present study, they could have been ascribed to differences in adiposity and not fitness. Additionally, pre-exercise metabolic rate was similar ($P= 0.46$) between lean (6.0 ± 0.7 $mL \cdot kg^{-1} \cdot min^{-1}$) and non-lean (6.2 ± 0.9 $mL \cdot kg^{-1} \cdot min^{-1}$) participants.

Another method suggested in the literature[22,23] to evaluate thermoregulatory responses during exercise in groups with differences in percent body fat is to prescribe an exercise intensity that elicits the same rate of heat production per unit lean body mass. The rationale is 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 the confounding influence of body fat differences. In spite of this logic, we demonstrate (in the FHP trial) that percent body fat does not actually influence the maintenance of core body temperature during exercise. It follows that when prescribing a heat production per unit lean mass (W/LBM trial) an experimental bias is introduced that actually leads to systematically greater values in the lean group for, a) sweat rate (Fig 4) because of greater evaporative heat balance requirements secondary to a greater absolute heat production; and b), changes in rectal and esophageal temperatures (Fig 2) due to a greater H_{prod} per unit total body mass (Table 2). In parallel, local responses including mean local sweat rate (Fig 4) and cutaneous vascular conductance (Fig 5) are similarly greater in the lean group at a fixed heat production per unit lean body mass. Therefore, if a researcher wishes isolate the influence of a particular disorder (e.g. diabetes) on thermoregulatory responses during exercise by matching independent groups for body mass, changes in core temperature and sweating should be compared using fixed heat production and not a fixed heat production per unit lean body mass even if large differences in body fat percentage exist between groups.

Perspectives

The absence of any influence of percent body fat on thermoregulatory responses was evidenced by mass-matched lean and non-lean participants exhibiting similar changes in core temperature and sweat losses during exercise at a fixed heat production. Prior to the current study, the methods employed in previous studies led to conflicting conclusions about the independent influence of fat on thermoregulatory control[2,7,8,13,23,25]. The findings of the current study therefore have important implications by informing experimental design for future studies wishing to compare thermoregulatory responses during exercise between independent groups that may differ in fat mass. The present study clearly demonstrates that rates of heat production do not need to be adjusted between groups with differences in fat mass between ~6 and ~35% in order to attain an unbiased comparison of core temperature changes and sweat losses. Recognizing that mass and heat production are some of the primary determinants of thermoregulatory responses during exercise could lead to improvements in public health guidelines, particularly for physical activity guidelines in obese populations. Physical activity warnings[15,24] exist for the obese because of the alleged increased risk of heat-related injuries associated with greater percent body fat and generally lower fitness levels[7,11,13,15,23]. However, we demonstrate that fat does not independently impair the potential for heat loss, and any elevated risk of heat injury/illness in the obese is probably not due to fat *per se* but due to a greater heat production since everyday physical activity is typically weight bearing and it can be assumed that the majority of individuals with obesity are heavier than their lean counterparts.

Limitations & Future studies

The present study assessed participants between 4.9% to 42.8% body fat and 18 to 36 years old, and all findings are only relevant to populations within that range, and may not apply to a more obese population (i.e. >40% body fat) or the elderly. Future studies are therefore needed to populate this range of adiposity and age. Additionally, the sample size was validated with a 90% power to detect the same difference in means between the L and NL groups in the 7.5 W per kg of LBM trial at a significance level (alpha) of 0.05 (two-tailed).

The present study was also 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 towards the end of exercise. As such, the completely independent influence of fat on thermoregulatory responses during uncompensable heat stress has not yet been determined. Under such conditions, Selkirk and McLellan[23] 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[2] reported that maximum skin wettedness may be altered due to a lower sweating efficiency arising from a lower sweat gland density in very BSA individuals (~2.7 m^2) with a high fat percentage (~28%). However the exclusive roles of BSA and fat mass on their observations have not been assessed.

Conclusion

At fixed metabolic heat production trial mass-matched lean and non-lean participants demonstrated almost identical changes in core temperature, sweating and skin blood flow. Furthermore, when prescribing exercise intensity to elicit a fixed heat production per unit lean body mass, as previously suggested eliminating the supposed influence of fat mass on thermoregulatory response, systematically greater changes in core temperature, sweating and skin blood flow were observed in the lean group. Collectively, our findings provide direct evidence that large differences in percent body fat do not independently alter thermoregulatory responses during exercise in compensable conditions when eliminating any differences in the biophysical factors of total body mass, body surface area and heat production.

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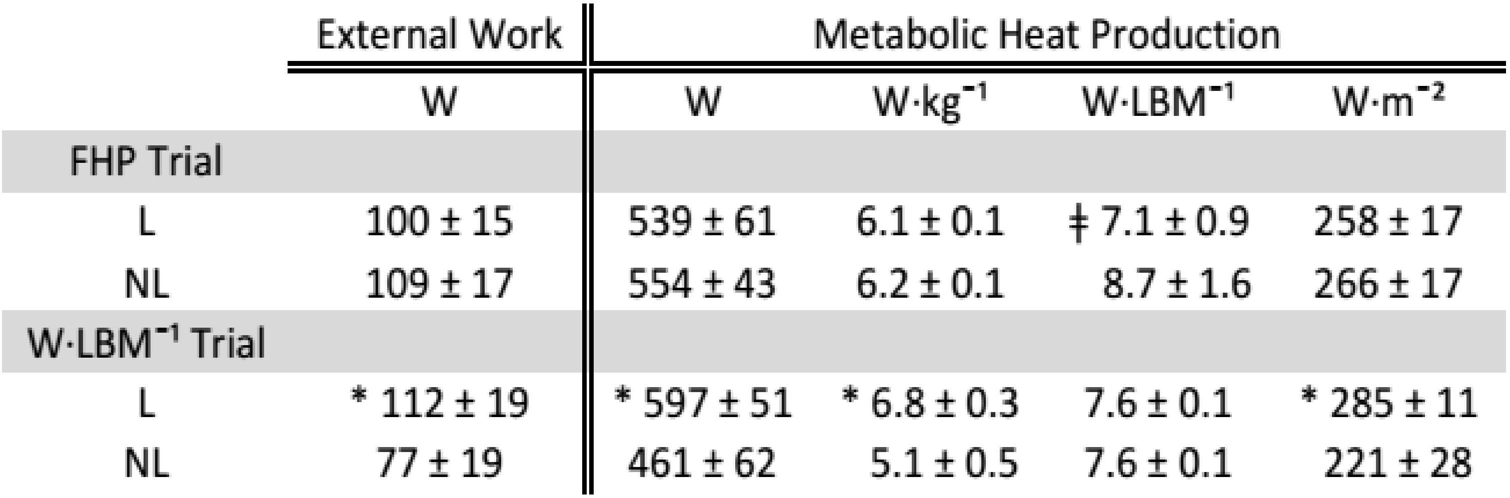
Table 1. *Descriptive characteristics for paired lean (L) and non-lean (NL) participants*

	Lean						Non-lean					
Group Pairs	Age years	C_{sp} kJ·kg^{-1}·°C^{-1}	LBM kg	BSA m^2	Body fat %	TBM kg	TBM kg	Body fat %	BSA m^2	LBM kg	C_{sp} kJ·kg^{-1}·°C^{-1}	Age years
P1	24	3.66	86.2	2.19	9.1	94.8	94.7	37.8	2.18	58.9	3.43	21
P2	23	3.67	84.7	2.25	15.3	100.0	99.5	32.6	2.09	67.9	3.50	26
P3	22	3.62	76.5	2.06	8.5	83.6	85.2	27.0	1.97	62.2	3.52	36
P4	27	3.69	77.0	2.07	4.9	80.6	84.2	24.4	2.02	63.6	3.54	24
P5	24	3.63	71.5	2.02	14.8	83.9	85.1	42.8	2.00	48.7	3.41	18
P6	25	3.62	81.1	2.18	14.2	94.5	97.5	28.0	2.19	71.0	3.51	27
P7	24	3.63	71.3	1.90	7.8	77.3	79.3	33.0	1.98	53.1	3.48	22
Mean	24	*3.65	*78.3	2.1	*10.7	87.8	89.4	32.2	2.06	60.8	3.48	25
SD	2	0.03	5.9	0.12	4.1	8.5	7.8	6.5	0.09	7.9	0.05	6

Values given are means and SD. Body surface area (BSA) estimated using the equation of Dubois and Dubois; volume of peak oxygen consumption (VO_{2peak}) is expressed in milliliters of oxygen of total body mass per minute. Body fat was measured using dual energy X-ray absorptiometry and lean body mass was measured in kg. *Significant difference between lean and non-lean groups ($P<0.01$), ǂ Significant difference between lean and non-lean groups ($P<0.05$).

Table 2. *Average Metabolic Heat Production in Fixed Heat Production (FHP) and W per LBM (W·LBM^{-1}) trials for L and NL participants*.



	External Work	Metabolic Heat Production			
	W	W	W·kg^{-1}	W·LBM^{-1}	W·m^{-2}
FHP Trial					
L	100 ± 15	539 ± 61	6.1 ± 0.1	ǂ 7.1 ± 0.9	258 ± 17
NL	109 ± 17	554 ± 43	6.2 ± 0.1	8.7 ± 1.6	266 ± 17
W·LBM^{-1} Trial					
L	* 112 ± 19	* 597 ± 51	* 6.8 ± 0.3	7.6 ± 0.1	* 285 ± 11
NL	77 ± 19	461 ± 62	5.1 ± 0.5	7.6 ± 0.1	221 ± 28

Values given are means and SD in Watts (W), Watts per unit total body mass (W·kg^{-1}) and Watts per unit body surface area (W·m^{-2}) in the fixed heat production (FHP) trial. In the Watts per unit lean body mass (W·LBM^{-1}) values given are means and SD in Watts (W), Watts per unit lean body mass (W·kg^{-1}) and Watts per unit body surface area (W·m^{-2}).*Significant difference between L and NL groups ($P<0.01$), ǂ significant difference between L and NL groups ($P<0.05$).

Table 3. *Indirect Calorimetry parameters in L and NL participants during Fixed Heat Production (FHP) and W per LBM ($W \cdot LBM^{-1}$) trials*

	Fixed Heat Production									
	Metabolic Heat Production (kJ)		Heat Loss (kJ)						Heat Storage	
Group	(M-W)		(C+R)		(Cres+Eres)		(Eactual)		(kJ)	
Pair	Lean	Non-lean	Lean	Non-lean	Lean	Non-lean	Lean	Non-lean	Lean	Non-lean
P1	2159	2283	180	270	97	98	1606	1616	276	299
P2	2183	2199	274	313	87	99	1446	1430	376	357
P3	1851	1865	283	265	78	78	1223	1195	267	327
P4	1776	1898	267	261	68	93	1134	1180	307	364
P5	1816	1908	276	304	75	88	1248	1260	217	256
P6	2153	2266	294	306	70	94	1631	1661	158	205
P7	1611	2059	168	207	71	85	1092	1480	280	287
Mean	1936 ± 228	2068 ± 182	249 ± 52	275 ± 37	78 ± 11	91 ± 8	1340 ± 221	1403 ± 196	268 ± 68	299 ± 57
			$W \cdot LBM^{-1}$							
Pair	Lean	Non-lean	Lean	Non-lean	Lean	Non-lean	Lean	Non-lean	Lean	Non-lean
P1	2397	1496	270	314	107	70	1702	903	318	209
P2	2391	1792	313	322	78	79	1651	1193	349	198
P3	2150	1585	265	129	83	68	1549	1254	253	134
P4	2251	1477	261	299	96	74	1555	895	339	209
P5	1863	1100	304	300	79	48	1130	636	350	116
P6	2368	1814	306	517	80	92	1789	1077	193	128
P7	1945	1515	200	360	82	65	1295	820	368	270
Mean	*2195 ± 219	1540 ± 238	274 ± 39	320 ± 114	86 ± 11	71 ± 13	*437 ± 53	325 ± 59	*310 ± 64	181 ± 56

Values given are means and SD in Watts (W) and Kilojoules (kJ), Watts were calculated for heat losses (C+R, C_{res}+E_{res}, E_{req} & E_{actual}) and the sum of the total body heat content (ΔH_b) was calculated in kJ.*Significant difference between L and NL groups ($P<0.01$)

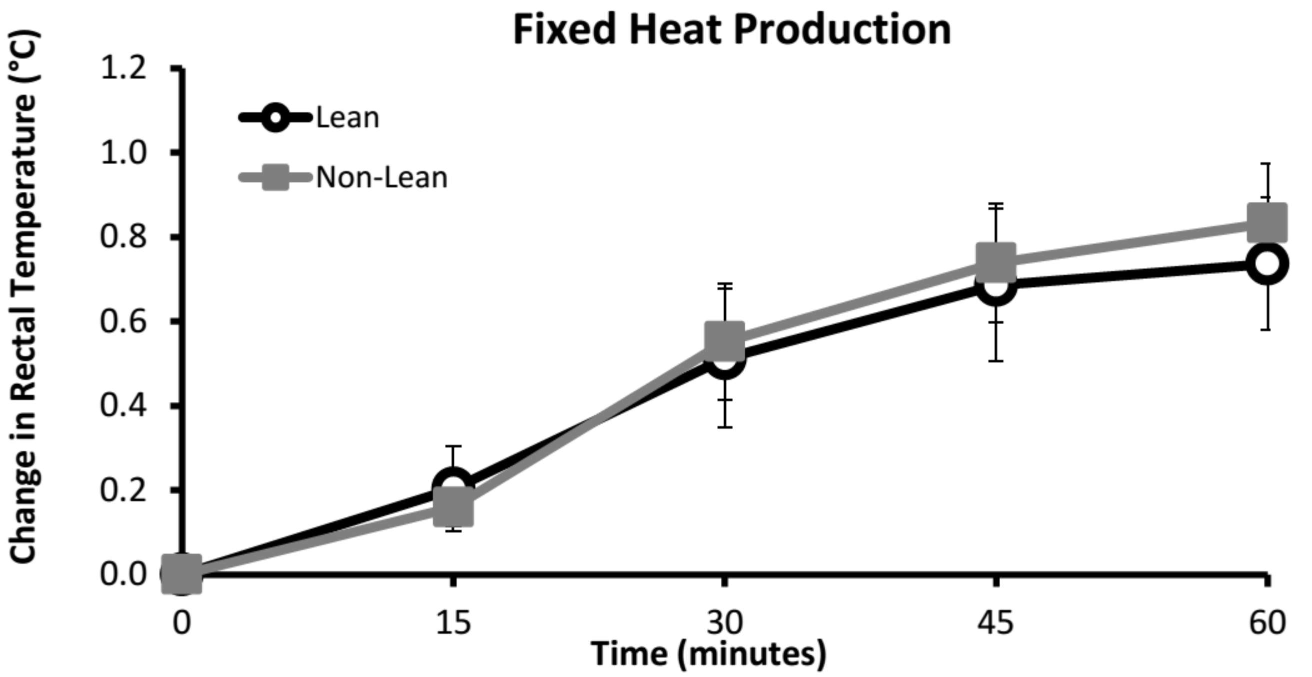


Fig.1. Mean values of changes of rectal temperature for L (~10%BF) and NL (~32%BF) groups of similar total body mass and BSA from rest to the end of 60 minutes of exercise at an FHP of 546 W. Error bars indicate standard deviation.

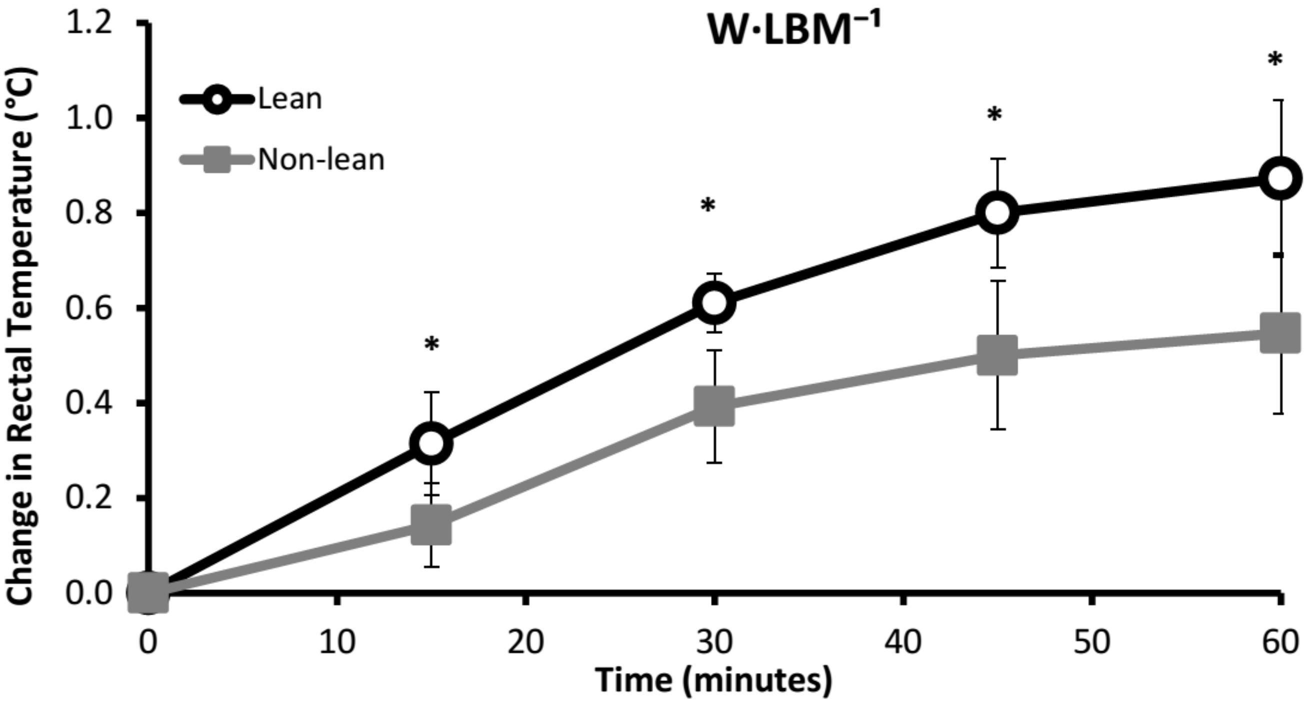


Fig.2. Mean values of changes of rectal temperature for L (~10%BF) and NL (~32%BF) groups of similar total body mass and BSA from rest to the end of 60 minutes of exercise at a heat production of ~7.6 W per unit kg of lean body mass (LBM). *Significant difference between groups ($P<0.01$) and ǂ significant difference between groups ($P<0.05$) at a given time point. Error bars indicate standard deviation.

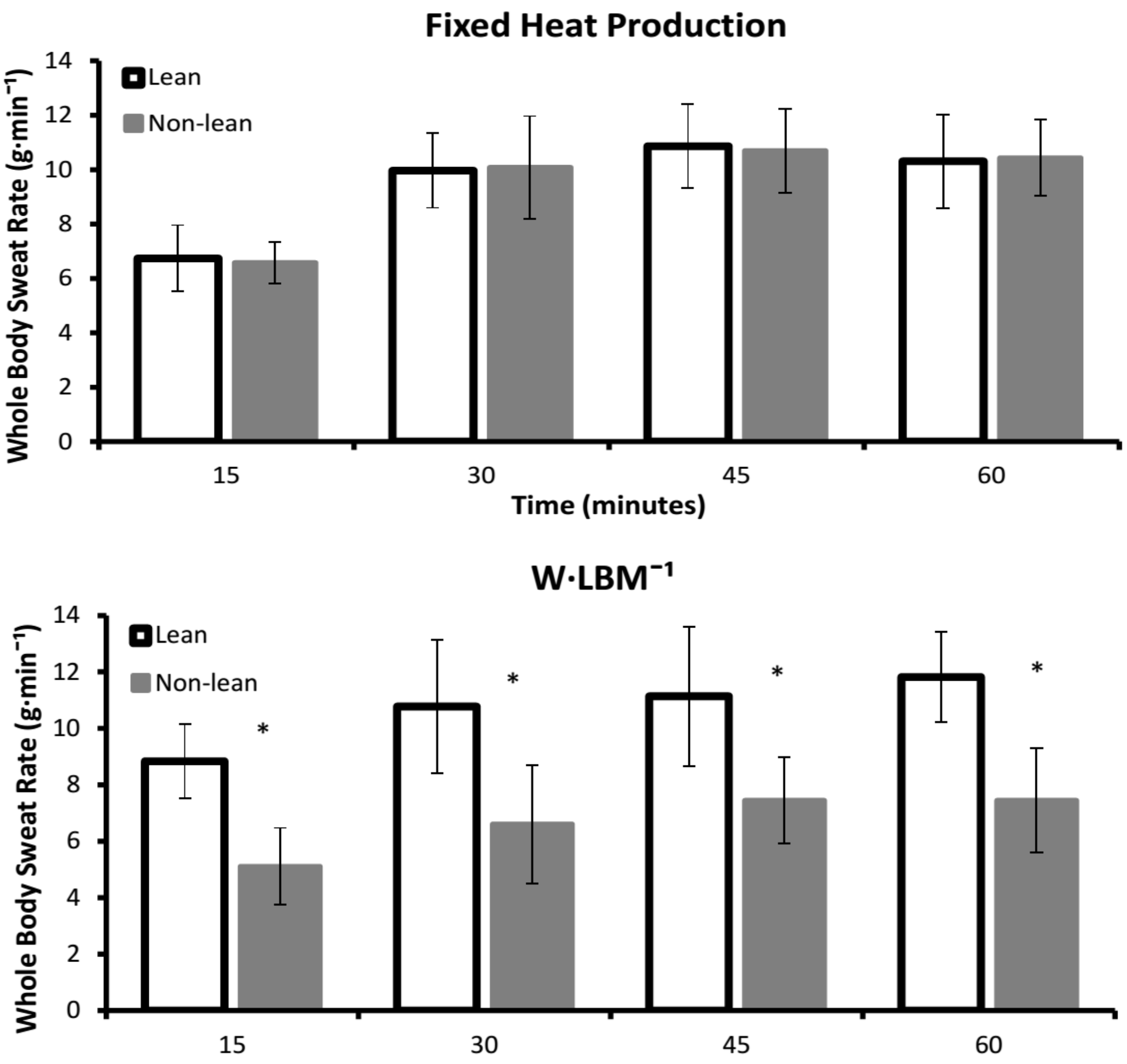


Fig. 3. FHP (~546 W) trial mean whole-body sweat rate across and W·LBM^{-1} of ~7.5 W·kg^{-1} trial mean whole-body sweat rate throughout 60 minutes of exercise in a neutral environment for L (~ 10% BF) and NL (~30% BF) of similar total body mass and BSA. *Significant differences between L and NL groups ($P<0.01$) at a given time point. Error bars indicate standard deviation.

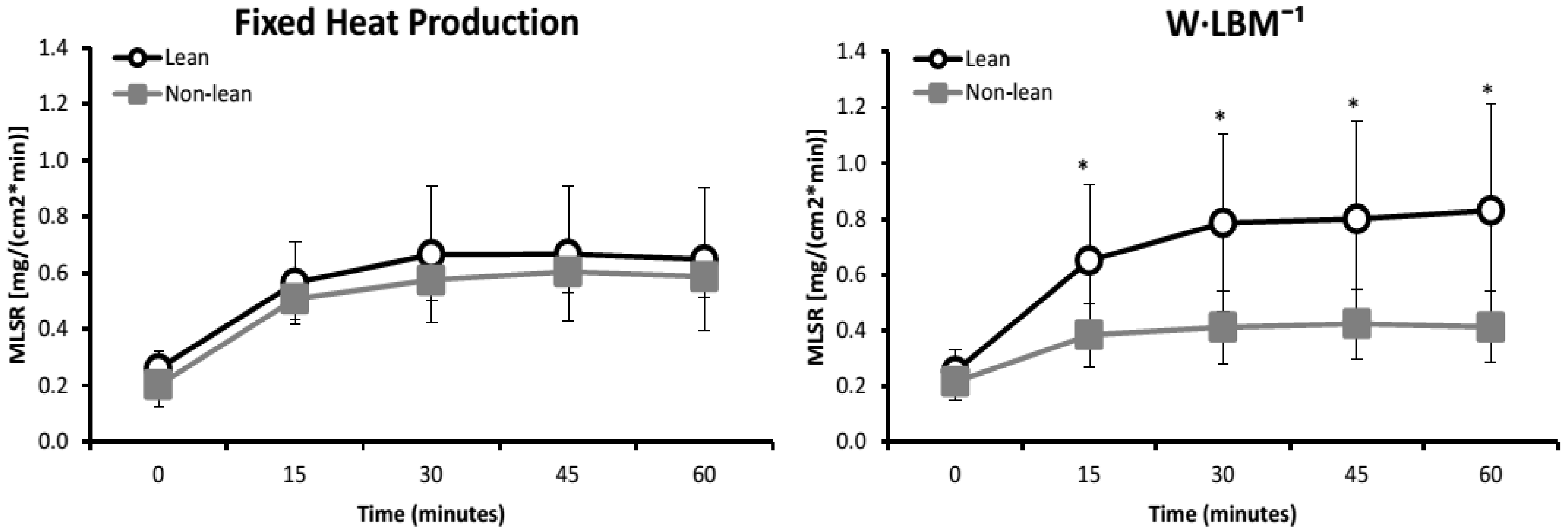


Fig. 4. Mean local sweat rate of the upper back and forearm throughout 60 minutes of exercise in a thermoneutral environment for L (<10% BF) and NL (>30% BF) participants of equal total body mass and BSA at a FHP (546 W) and W·LBM^{-1} of ~7.5 W·kg^{-1} of lean body mass.*Significant difference between L and NL groups (P<0.05) at given time point. Error bars indicate standard deviation.

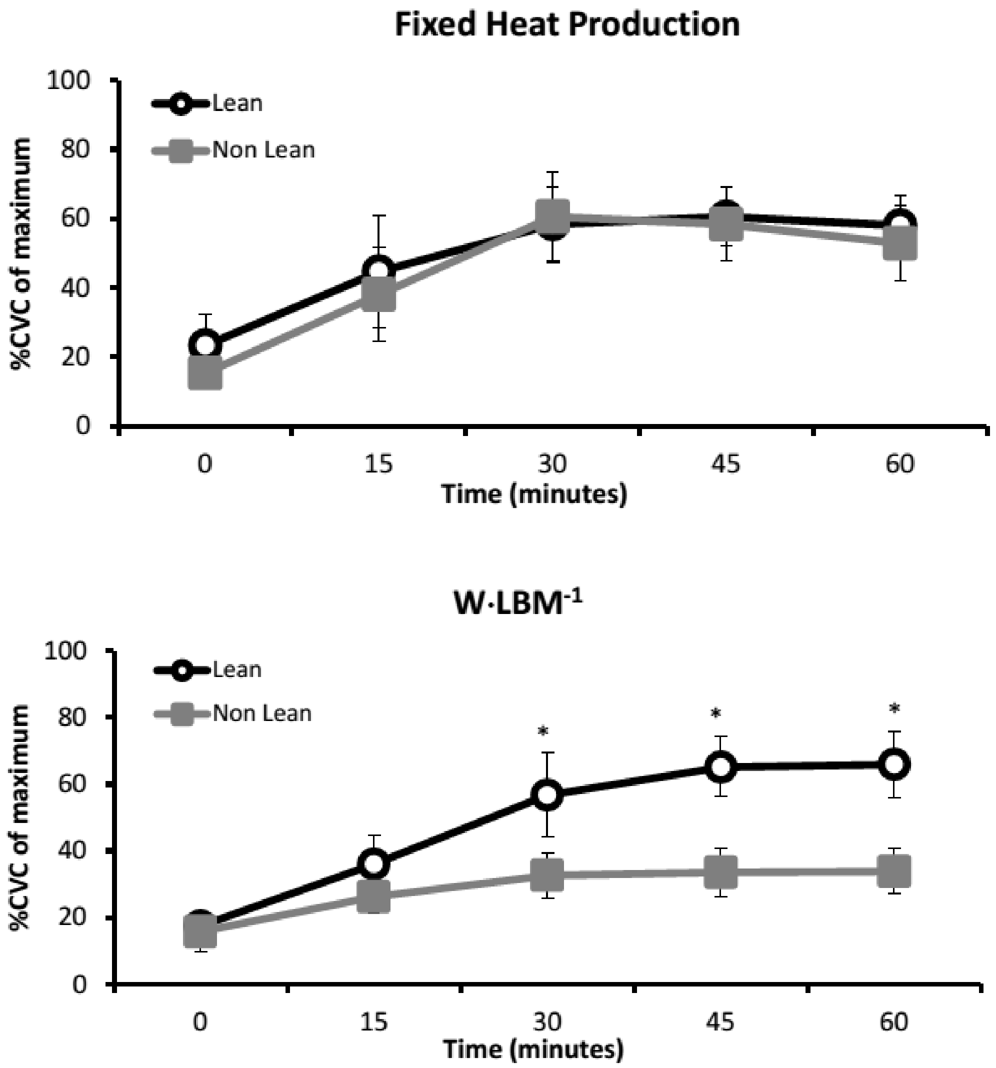


Fig. 5. Cutaneous vascular conductance of the upper back throughout 60 minutes of exercise in a thermoneutral environment for L (<10% BF) and NL (>30% BF) participants of equal total body mass and BSA at FHP (546 W) and $W \cdot LBM^{-1}$ of ~7.5 $W \cdot kg^{-1}$ of lean body mass.*Significant difference between L and NL groups ($P<0.01$) at given time point. Error bars indicate standard deviation.

Chapter IV

Thesis Discussion

Thesis Discussion

The primary purpose of the present study was establish whether variances in changes in core temperature and local/whole body heat loss responses in populations with large differences of percent body fat exist when accounting for confounding differences in total body mass, body surface area and metabolic heat production. The results of the current study clearly demonstrated that such differences do not exist when exercising at a fixed heat production matched for total body mass. Specifically, lean and non-lean participants exhibited similar changes in esophageal and rectal temperatures and whole body sweat losses throughout 60 minutes of exercise. Additionally local heat loss responses including local sweat rate and cutaneous vascular conduction were comparable irrespective of a 20% difference in total body fat between groups.

The alternative experimental session established that a heat production matched for lean body mass does not effectively account for percent body fat due to a significantly greater heat production per unit total body mass in the lean compared to non-lean group and subsequently a greater change in core temperature and whole body sweat loss. Furthermore in the fixed heat production trial, the calculated heat production per unit total body mass was ~6.0 $W \cdot kg^{-1}$ for both groups, which equated to a greater lean body mass heat production in the non-lean (8.7 ± 1.6 $W \cdot LBM^{-1}$) compared to lean (7.1 ± 0.9 $W \cdot LBM^{-1}$) group. Contrarily, in the heat production per unit lean body mass trial both groups maintained ~7.5 $W \cdot LBM^{-1}$, which equated to a greater heat production per total body mass in the lean (6.8 ± 0.3 $W \cdot kg^{-1}$) compared to non-lean (5.1 ± 0.5 $W \cdot kg^{-1}$) group. Based on the given results, heat production per unit total body mass resulted in comparable thermoregulatory responses to exercise irrespective of the large differences in the calculated W per unit lean body mass between lean and non-lean participants. On the other hand heat production based on lean body mass resulted in consistently greater core temperatures and sweat losses in the lean group coinciding with the greater heat production per total body mass in lean compared to non-lean participants. Therefore when comparing the independent influence of a physiological characteristic (e.g. percent body fat) on thermoregulatory responses, an exercise intensity that elicits a heat production based on total body mass should be prescribed in order to effectively isolate the variable.

Although the hypothesis and results of the present study are consistent with previous investigations, it should be noted that the protocols were ineffective at isolating the independent variable of percent body fat[5-8,13,14,37,38,42,52]. For instance, Limbaugh et al [52] measured esophageal temperature and sweat rates in lower body fat (11.3 ± 2.58%) and higher body fat (23.6 ± 3.44%) participants matched for aerobic fitness (lower body fat: 50.72 ± 7.33 $mL \cdot kg\ LBM^{-1} \cdot min^{-1}$, higher body fat: 50.43 ± 5.01 $mL \cdot kg\ LBM^{-1} \cdot min^{-1}$), although total body mass and body surface area were not accounted for because the higher body fat group had a greater mass and body surface area (mass:91.92 ± 14.92 kg, body surface area: 2.11 ± 0.17 m^2) compared to the lower body fat group (mass:78.53 ± 9.37 kg, body surface area: 1.96 ± 0.10 m^2) [52]. Therefore the results cannot be compared between groups because for a given prescribed heat production ($W \cdot m^{-2}$), the higher body fat group has both a greater heat sink as a function of total body mass and available skin surface area for the evaporation of sweat (affecting local and whole body sweat losses).

Implications

The main implication of the present thesis is the observation that fixed heat productions based on total body mass are primary modulators of core temperature and sudomotor activity during exercise in temperate environments. Prior to the current study physiological variables including total body mass and body surface area was not accounted for when testing thermoregulatory responses during exercise[5-8,13,14,37,38,42,52]. A practical implication could insist on reconsidering heat exposure and exercise guidelines for specific populations (e.g. obese populations) to be based on studies that accounted for confounding variables such as mass and body surface area.

It is important to note that the findings of the current study can only be extended to environments that permit the full evaporation of sweat production and to healthy young male populations with an age range of 18 to 36 years and a range of percent body fat from 4.9% to 42.8%. Current guidelines[1] should reconsider the message that fat reduces the capacity of thermal responses to exercise if individuals are young and otherwise healthy, and recognize that when comparing thermal responses to exercise in different populations that biophysical parameters including mass and BSA must be normalized. Prospective research should investigate different environmental parameters (i.e. uncompensable conditions), test weight bearing exercise (i.e. running/walking) and populations with greater than 50% body fat to potentially find a lower limit of influence on thermoregulatory control.

Thesis Conclusion

The current thesis measured if large differences in body fat alter changes in core temperature, whole/local body sweat losses and cutaneous vascular conductance after accounting for confounding differences in physical characteristics and metabolic heat production. Overall, the results show that percent body fat does not influence thermoregulatory responses during exercise.

Chapter V

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