The Biophysics of Human Heat Exchange

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2.1 Introduction

The ability to maintain body temperature within a narrow range during acute or chronic exposure to environmental extremes is paramount for optimal human performance, and ultimately, survival. Muscle contractions during different sporting activities can result in a greatly elevated internal heat production. The subsequent changes in body temperature are managed to an extent by physiologically modulating heat exchange between the skin surface and the surrounding environment via sensible (convection (C), radiation (R) and conduction (K)) and insensible (evaporation (E)) heat transfer. However, the net heat dissipation via these heat transfer avenues is also strongly determined by the physical characteristics of the thermal environment that the sport is performed in. To optimally assess the risk of thermal stress for an athlete performing a given sport in a particular environment, the biophysical processes that govern the dynamic balance between internal heat production and skin surface heat dissipation must therefore be fully considered.

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2.2 Human Heat Balance

The fundamental law of human heat balance illustrates that internal metabolic heat production (M–W) must be balanced by an equal rate of net heat dissipation, i.e. combined sensible and insensible heat losses from the skin (sk) and respiratory tract (res) to the surrounding environment to ensure a rate of body storage (S) of zero (i.e. heat balance):

$$\left(M-W\right)=\left(\pm K_{\text{sk}}\pm C_{\text{sk}}\pm R_{\text{sk}}\right)+\left(C_{\text{res}}+E_{\text{res}}\right)+E_{\text{sk}}\pm S\quad\left[\text{in W m}^{-2}\right] \tag{2.1}$$

2.2.1 Metabolic Heat Production (M–W)

Metabolic heat production (M–W) is the difference between metabolic rate (M) and the external work performed (W). In its most basic form, M is the amount of energy released by hydrolysing adenosine triphosphate (ATP) into adenosine diphosphate (ADP) and an inorganic phosphate molecule. It follows that a proportion of the energy released from this process is then utilised to create W; however, the human body is quite inefficient and about 75–95% of M does not ultimately contribute to W but instead is liberated internally as heat [1–3]. Road cycling is one of the most efficient sporting activities (~30% of M is used for W [4]), so at an external work load of 240 W a metabolic rate of ~840 W is required, with ~600 W of this energy released as heat (Fig. 2.1). Running and walking are among the least efficient activities, especially on a flat surface, where effectively no external work is performed and all metabolic energy is converted to heat [5, 6].

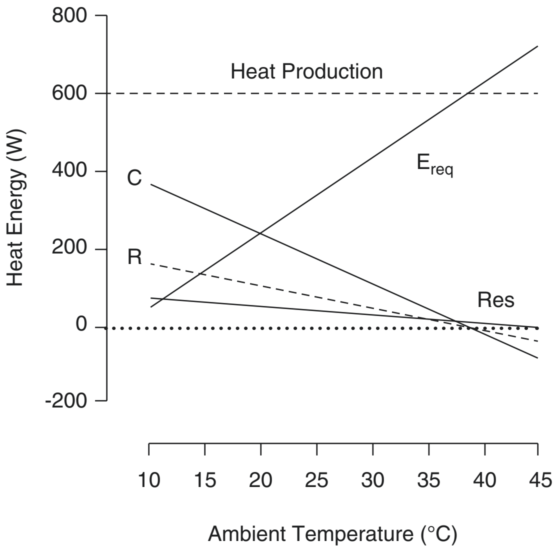

Fig. 2.1 An example of partitional heat exchange for an exercising individual on an upright ergometer. E_{req} evaporative requirements for heat balance, C convection, R radiation, Res respiratory heat loss

Carbohydrates and lipids are the two main substrates utilised by the body to produce ATP, and although ATP can be produced both aerobically and anaerobically within a cell, oxygen consumption is required to restore ATP pools. Thus, *M* can be estimated [7] by measuring the rate of oxygen consumption and carbon dioxide production using:

$$M = \mathrm{VO}_2 \frac{\left[\left(\left(\frac{\mathrm{RER} - 0.7}{0.3}\right) \cdot e_c\right) + \left(\left(\frac{1.0 - \mathrm{RER}}{0.3}\right) \cdot e_f\right)\right]}{60} 1000 \quad [\text{in W}] \tag{2.2}$$

where VO_2 is the rate of oxygen consumption in L min^{-1}, RER is the ratio of carbon dioxide production to oxygen consumption, e_c is the caloric equivalent per litre of oxygen for the oxidation of carbohydrates (21.13 kJ) and e_f is the caloric equivalent per litre of oxygen for the oxidation of lipids (19.62 kJ). To normalise *M*–*W* in W m^{-2}, it must be divided by the body surface area (BSA) of the individual using the Dubois and Dubois equation [8]:

$$\mathrm{BSA} = 0.202 \times \mathrm{mass}^{0.425} \times \mathrm{height}^{0.725} \quad \left[\text{in } \mathrm{m}^2\right] \tag{2.3}$$

where mass of the person is in kg and the height of the person is in m.

2.2.2 Sensible Heat Transfer from the Skin (± K_{sk} ± C_{sk} ± R_{sk})

Sensible Heat Transfer from the Skin (± K_{sk} ± C_{sk} ± R_{sk}) is the sum of conduction (K_{sk}), convection (C_{sk}) and radiation (R_{sk}). These three avenues of heat transfer abide by the second law of thermodynamics, whereby heat energy moves from an area of high concentration to low concentration (e.g. from high to low temperature). During active or passive heat stress, the prevailing temperature gradients for sensible heat transfer may be minimal or even negative, which leads to sensible heat gain through one or more avenue at ambient temperatures above skin temperature (i.e. 35–36 °C) (Fig. 2.1).

2.2.2.1 Conduction (K_{sk})

Conduction (K_{sk}) is the transfer of heat energy through direct contact between the skin and a solid object. From a whole-body heat balance perspective, particularly human heat stress conditions, *K* is generally assumed to be negligible, with the primary means for sensible heat transfer via convection and radiation. However, when a solid object is in direct contact with the skin (e.g. a cold metallic wall), conductive heat transfer can be calculated as:

$$K = kA\left(T_2 - T_1\right) / L \quad \left[\text{in W } \mathrm{m}^{-2}\right] \tag{2.4}$$

where *k* is the estimated thermal conductivity of the object in contact with the skin, *A* is the total surface area of contact between the skin and solid (in m^2), ($T_2 - T_1$) is the absolute temperature difference between the skin and the solid's external surface and *L* is the thickness of the solid object in contact with the skin surface.

2.2.2.2 Radiation (R_{sk})

Heat exchange by radiation is the electromagnetic energy transfer between a relatively cool and warm body. Radiative heat loss from the skin for a nude person can be derived using:

$$R_{\mathrm{sk}} = h_r \left(T_{\mathrm{sk}} - T_r \right) \quad \left[\mathrm{in\,W\,m^{-2}} \right] \tag{2.5}$$

where T_{sk} is mean skin temperature (in °C), T_r is mean radiant temperature (in °C) and h_r is the radiative heat transfer coefficient (in W $\mathrm{m^{-2}\,K^{-1}}$), which is estimated using:

$$h_r = 4\varepsilon\sigma \frac{A_r}{A_D} \left[273.2 + \frac{T_{\mathrm{sk}} + T_r}{2} \right]^3 \quad \left[\mathrm{in\,W\,m^{-2}\;\;K^{-1}} \right] \tag{2.6}$$

where ε is the emissivity of the body surface (usually assumed to be 0.95), σ is the Stefan–Boltzmann constant (5.67×10^{-8} W $\mathrm{m^{-2}\,K^{-4}}$), A_r/A_D is the effective radiative area of the body ($\mathrm{m^2}$) which can be estimated as 0.70 or 0.73 for a seated or standing person [9], respectively, and $T_{\mathrm{sk}} + T_r$ is the sum of mean skin temperature and mean radiant temperature. Mean radiant temperature is assumed to be equal to ambient air temperature when indoors without any substantial sources of radiation. However, in other environments, e.g. outdoor sun exposure, mean radiant temperature of the environment must be estimated using black globe temperature (T_g) measured with a standard 150-mm diameter black globe thermometer placed in a similar location as the exposed individual (e.g. in direct sunlight). T_g will vary depending on the time of day and year due to differences in the angle between the sun and the horizon. However, when interested in calculating radiative heat transfer for an individual wearing clothing, a black globe thermometer may overestimate the effect of a radiative source (particularly the sun) and should therefore be similar in colour to the clothing worn by the individual. Lastly, air velocity (v) in m/s near the black globe thermometer must be measured as greater air flow will alter T_g for a given amount of radiant heat energy. According to ISO 7726:1998 [10], mean radiant temperature (T_r) can be derived as follows:

If $v < 0.15$ m/s:

$$T_r = \left[\left(T_g + 273 \right)^4 + \frac{0.25 \times 10^8}{\varepsilon} \cdot \left[\frac{T_g + T_a}{d} \right]^{0.25} \left(T_g - T_a \right) \right]^{0.25} - 273 \quad \left[\mathrm{in\,^{\circ}C} \right] \tag{2.7}$$

where d is black globe diameter (in cm).

If $v \geq 0.15$ m/s:

$$T_r = \left[\left(T_g + 273 \right)^4 + \frac{1.1 \times 10^8 v^{0.6}}{0.44} \cdot \left(T_g - T_a \right) \right]^{0.25} - 273 \quad \left[\mathrm{in\,^{\circ}C} \right] \tag{2.8}$$

2.2.2.3 Convection (C_{sk})

Convection (C_{sk}) is the transfer of heat to a moving gas (air) or liquid (water), which is increased by the movement of the body in air or water or movement of air or water across the skin. It is directly proportional to the temperature difference between the skin surface and the ambient environment, and air velocity passing across the skin. A warm surface such as the skin can also produce natural convection when a person is still, where the boundary layer movement is a result of differing air densities arising from a temperature gradient (e.g. warm air rises). Alternatively, and more commonly, forced convection pushes air across the skin surface (e.g. a fan) or convection is self-generated as a person moves through an air mass. Convective heat transfer for a nude person can be estimated using [11]:

$$C_{\text{sk}} = h_c\left(T_{\text{sk}} - T_a\right) \quad \left[\text{in W m}^{-2}\right] \tag{2.9}$$

where T_{sk} is mean skin temperature (°C), T_a is ambient air temperature (°C) and h_c is the convective heat transfer coefficient (in W m^{-2} K^{-1}). For natural convection in still conditions, this value can be assumed to be 3.1 W m^{-2} K^{-1} [12]. If air velocity is >0.2 m/s, but <4.0 m/s, the convective heat transfer coefficient can be estimated using:

$$h_c = 8.3v^{0.6} \quad \left[\text{in W m}^{-2}\text{ K}^{-1}\right] \tag{2.10}$$

where v is the mean air velocity around the body in m/s. During physical activity, it may be more practical to consider the mean net air flow across the body surface rather than just the mean ambient air velocity as this accounts for the path of movement relative to wind direction. Indeed, it is evident that the magnitude of self-generated air flow can influence the convective heat transfer coefficient. For example, independent of clothing and equipment, the higher heat strain for American football lineman compared to non-lineman has been attributed to the more static nature of their position-specific activities (e.g. blocking vs. running routes) [13, 14]. Alternatively, self-generated convection during outdoor cycling (>20 km/h) will in most cases be far greater than in laboratory settings [15]. As such, specific equations have been derived for estimating the convective heat transfer coefficient during different modalities of human movement (Table 2.1).

Table 2.1 Estimations of the convective heat transfer coefficient (h_c) for common modalities of exercise

Exercise modality	Equation/constant h_c (W m^{-2} K^{-1})	Comments
Stationary cycle ergometer (50 RPM)	5.4	Ambient air flow <0.2 m/s [16]
Stationary cycle ergometer (60 RPM)	6.0	Ambient air flow <0.2 m/s [16]
Outdoor cycling	$h_c = 8.4\text{v}_{\text{speed}}^{0.84}$	v_{speed}: cycling velocity (m/s) [15]
Walking/Running	$h_c = 8.3\text{v}_{\text{loc}}^{0.531}$	v_{loc}: speed of locomotion (m/s) [16]
Treadmill exercise	$h_c = 8.3\text{v}_{\text{loc}}^{0.391}$	v_{loc}: speed of locomotion (m/s) [16]

All convective heat transfer coefficients presented have been developed for thermal stress at approximately sea level. The relationship between barometric pressure (P_b) and convective heat transfer can be integrated into Eq. (2.9) as follows [17]:

$$C_{\mathrm{sk}} = h_c\left(T_{\mathrm{sk}} - T_a\right)\left(P_b / 760\right)^{0.55} \quad \left[\mathrm{in\ W\ m^{-2}}\right] \tag{2.11}$$

If clothing is worn, combined sensible heat transfer via convection and radiation ($C_{\mathrm{sk}} + R_{\mathrm{sk}}$) can be estimated using:

$$C_{\mathrm{sk}} + R_{\mathrm{sk}} = \frac{\left(T_{\mathrm{sk}} - T_o\right)}{\left(R_{\mathrm{cl}} + \dfrac{1}{h \cdot f_{\mathrm{cl}}}\right)} \quad \left[\mathrm{in\ W\ m^{-2}}\right] \tag{2.12}$$

where T_o is operative temperature (in °C):

$$T_o = \frac{\left(h_r T_r + h_c T_a\right)}{\left(h_r + h_c\right)} \quad \left[\mathrm{in\ ^{\circ}C}\right] \tag{2.13}$$

and h is the combined heat transfer coefficient (in W m^{-2} K^{-1}), i.e. $h_c + h_r$; and f_{cl} is the clothing area factor defined as the surface area of the clothed body divided by the surface area of the nude body and estimated using [18]:

$$f_{\mathrm{cl}} = 1 + \left[\frac{0.31 \cdot R_{\mathrm{cl}}}{0.155}\right] \quad [\mathrm{ND}] \tag{2.14}$$

where R_{cl} is the dry heat transfer resistance of clothing (in m^2 °C^{-1} W^{-1}), which can be obtained from normative tables [18, 19] such as the International Standardisation Organisation (ISO) 9920 standard.

Additionally, convective heat loss by water movement is important for example in swimmers. The convective heat loss is, in contradiction to convective heat loss by air movement, not a function of the water velocity [20]. Due to water turbulence created during swimming in a swimming pool, the effective water velocity around a swimmer does not differ irrespective of swimming speed. As a result, convective heat exchange for swimmers is predominantly determined by water temperature, whereby heat is lost if water temperature is lower than skin temperature, and vice versa. Due to a higher density, specific heat capacity and thermal conductivity [21], convective heat loss is much greater in water than in air [20]. Given exercise is typically performed on land, and detailed equations for convective heat exchange in water are beyond the scope of this chapter. However, for a detailed description we refer readers to the article of Brandt and Pichowsky [22].

2.2.3 Respiratory Heat Exchange ($C_{\text{res}} + E_{\text{res}}$)

Respiratory heat exchange occurs through the convective heat transfer (C_{res}) between inhaled air and the lungs, and evaporative heat loss from the respiratory tract (E_{res}) due to the saturation of air with water vapour when entering the lungs. Net respiratory heat exchange can be estimated using (2.2):

$$C_{\text{res}} + E_{\text{res}} = \left[0.0014M \cdot (34 - T_a)\right] + \left[0.0173M \cdot (5.87 - P_a)\right] \quad \left[\text{in W m}^{-2}\right] \tag{2.15}$$

where M is metabolic rate in W m^{-2}, T_a is air temperature in °C and P_a is the ambient water vapour pressure in kPa.

The rate of respiratory heat loss is dependent on the temperature and humidity of inspired air [23, 24] and minute ventilation [25, 26]. As such, the amount of convective heat transfer through respiration during exercise in the heat compared to the cold is minimal due to the small temperature gradient between ambient and core temperature. Additionally, the amount of evaporative heat loss via respiration is dependent on the humidity gradient between the lungs and the air, and the rate of ventilation which is assumed to have a linear relationship with the rate of metabolic rate (up to 80% of maximum oxygen consumption [26]).

2.2.4 Evaporation from Skin Surface (E_{sk})

The evaporation of sweat (or water) from the skin surface is the largest modifiable avenue of heat loss from the body. During heat stress, sweat evaporation becomes the predominant factor for determining whether heat balance is achieved, and when air temperature equals skin temperature and dry heat loss is eliminated, evaporation becomes the only avenue for dissipating metabolic heat at the skin surface [27]. The latent heat lost for every gram of sweat that completely evaporates from the skin is 2.426 kJ [28]. As such, evaporative heat loss can be estimated using body mass changes corrected for metabolic and respiratory mass losses, as well as any ingested fluids, but only under conditions that permit complete evaporation [29]. Arguably, the most accurate method for estimating evaporative heat loss is direct calorimetry, which measures the difference in absolute water vapour pressure between influent and effluent of an enclosed air space [30]. However, once again the complete evaporation of all sweat from the skin is a necessity and is typically achieved in a calorimeter by ensuring a high and turbulent air mass flow [31].

Under combinations of climate and activity that yield incomplete sweat evaporation from the skin surface, evaporative efficiency (i.e. the proportion of secreted sweat that actually evaporates [32]) can be roughly estimated. It is known that as the sweat saturation level of the skin reaches a maximum, evaporative efficiency rapidly declines [32–34]. First described by Gagge [35], sweat saturation levels can be expressed as a “skin wettedness” value (ω), which is physiologically defined as the fraction of the skin surface that is covered in sweat. It follows that reductions in evaporative efficiency have been reported when $\omega > 0.50$ during passive heat stress [36], and when $\omega > 0.30$ during upright cycling [32]; meaning that while greater levels of skin wettedness permit greater rates of evaporation, this comes at the expense of a disproportionately greater rate of sweating. Mathematically, the ω value required (for heat balance; ω_{req}) is defined as the ratio of the evaporative requirement to maintain heat balance ($\mathrm{E}_{\mathrm{req}}$) relative to the maximum evaporative capacity in the ambient environment ($E_{\max}$):

$$\omega_{\mathrm{req}} = E_{\mathrm{req}} / E_{\max} \quad [\mathrm{ND}] \tag{2.16}$$

By rearranging the conceptual heat balance equation (Eq. (2.1)), and assuming a rate of body heat storage (S) of zero, E_{req} can be estimated as follows:

$$E_{\mathrm{req}} = (M - W) - (\pm K_{\mathrm{sk}} \pm C_{\mathrm{sk}} \pm R_{\mathrm{sk}}) - (C_{\mathrm{res}} + E_{\mathrm{res}}) \quad \left[\mathrm{in\ W\,m^{-2}}\right] \tag{2.17}$$

$E_{\max}$ is determined by the water vapour pressure gradient between the skin and the air, as well as air speed, clothing properties and the maximum proportion of the skin that can be physiologically saturated with sweat ($\omega_{\max}$):

$$E_{\max} = \omega_{\max} \frac{\left(P_{\mathrm{sk,sat}} - P_a\right)}{\left(R_{e,\mathrm{cl}} + \dfrac{1}{h_e \cdot f_{\mathrm{cl}}}\right)} \quad \left[\mathrm{in\ W\,m^{-2}}\right] \tag{2.18}$$

where $\omega_{\max}$ is maximum skin wettedness, which can reach 1.00 for a fully heat acclimated person but only 0.72 in an untrained, non-heat acclimated individual [37]; $P_{\mathrm{sk,sat}}$ is the saturated water vapour pressure at skin temperature (in kPa); P_a is the water vapour pressure measured in ambient air (in kPa); $R_{e,\mathrm{cl}}$ is the evaporative heat transfer resistance of clothing (in $\mathrm{m^2\ kPa\ W^{-1}}$); f_{cl} is the clothing area factor (Eq. (2.14)) and h_e is the evaporative heat transfer coefficient (in $\mathrm{W\ m^{-2}\ kPa^{-1}}$).

Values for $P_{\mathrm{sk,sat}}$ can be derived using Antoine’s equation [38] as follows:

$$P_{\mathrm{sk}} = \mathrm{EXP}\left[18.956 - \frac{4030.18}{T_{\mathrm{sk}} + 235}\right] \quad [\mathrm{in\ kPa}] \tag{2.19}$$

Values for the h_e can be estimated using h_c (from Eq. (2.10)/Table 2.1) as follows:

$$h_e = 16.5 h_c \quad \left[\mathrm{in\ W \cdot m^{-2}\ kPa^{-1}}\right] \tag{2.20}$$

Values for evaporative efficiency (E_{eff}) (i.e. as a fraction of secreted sweat that evaporates from the skin) can be subsequently estimated for a given level of ω_{req} using [39]:

$$E_{\mathrm{eff}} = 1 - \frac{\omega_{\mathrm{req}}^{\ 2}}{2} \quad [\mathrm{ND}] \tag{2.21}$$

Evaporative efficiency can also be estimated by directly measuring the mass of dripped sweat trapped in an oil pan placed on scale directly underneath the participant. However, this technique had been primarily reported during passive heating [36] and is difficult to implement during exercise.

Evaporative heat loss from the skin surface (E_{sk}) can then be estimated using:

$$E_{\mathrm{sk}} = \left(\mathrm{WBSL} \times 2.426\right) \times E_{\mathrm{eff}} \quad \left[\mathrm{in\,kJ}\right] \tag{2.22}$$

where WBSL is whole-body sweat loss over a fixed exercise time (in g).

It is important to acknowledge that the approach described above is especially limited for individuals wearing layered clothing outfits. While trapped sweat can indeed still evaporate, the effective latent heat of vaporisation of this sweat (which is usually assumed to be 2.426 kJ g^{-1}) has been shown to decline dramatically (by up to ~80%) depending on the material properties and most importantly the number of clothing layers [40]. As such, E_{sk} from measured sweat losses, even if sweat trapped in clothing is accounted for, could be overestimated by more than fourfold.

2.2.5 Heat Storage (*S*)

Heat Storage (S) occurs when an imbalance arises between metabolic heat production and the parallel rate of net heat dissipation via sensible and evaporative heat transfer. Typically, at rest in a temperate environment, humans are in heat balance (i.e. $S = 0$) as heat loss from sensible heat exchange via convection and radiation matches resting metabolic rate without any requirement for evaporation other than passively through respiration. However, elevated rates of heat production following the onset of exercise under nearly all environmental conditions lead to a positive rate of heat storage. On the other hand, cold exposure without sufficient clothing insulation can cause high rates of convective and radiative heat loss that exceed metabolic heat production leading to a heat imbalance and thus a negative rate of heat storage. Cumulatively over time, sustained rates of positive or negative heat storage result in changes in internal (i.e. core) body temperature, which if left unchecked can become detrimental to human performance and ultimately health.

The change in heat storage required to alter core temperature is dependent on biophysical factors. Firstly, the body mass of an individual represents their heat sink, meaning that changes in core temperature for an absolute amount of heat stored in the body are negatively correlated, i.e. a smaller rise in core temperature is observed with a larger body mass for a fixed heat storage [41, 42]. Secondly, large differences in the specific heat of the tissues of the body (C_p) caused by marked differences in body composition can also alter core temperature despite a similar heat storage. A C_p of 3.47 kJ kg^{-1} $°\mathrm{C}^{-1}$ is assumed for the average person [43]. However, owing to the different C_p of fat tissue (2.97 kJ kg^{-1} $°\mathrm{C}^{-1}$) and lean mass (3.64 kJ kg^{-1} $°\mathrm{C}^{-1}$) overall C_p can vary depending on adiposity. While small differences in C_p do not seem to meaningfully influence core temperature, it has been recently demonstrated that a ~20% difference in body fat percentage is sufficient to independently yield ~0.2 to 0.3 °C greater rises in core temperature during moderate exercise at a fixed metabolic heat production of 6 W/kg of total body mass in healthy males (mean body fat % of 10.8 versus 32.0%) in a 28 °C environment [44].

2.2.6 Temporal Changes in Human Heat Balance

Reflex physiological mechanisms as described in Chap. 1 aid the maintenance of body temperature within the prescribed limits for human health by modifying heat balance. Autonomic increases in vascular conductance of the skin mediated by a cutaneous vasodilatation, and eccrine sweating, are observed in proportion to elevations in skin and/or core temperature during exercise and/or with heat exposure. Similarly, in the cold, a vasoconstriction response and shivering thermogenesis occur in proportion to reductions in skin and/or core temperature [45–47].

While at rest, mean T_{sk} in a temperate and thermally comfortable environment is typically 33–34 °C [11, 48]. During heat stress, an initial vasodilatation causes an increase in T_{sk}, which alters the temperature difference between the skin surface and the ambient environment and thus increases sensible heat loss (or decreases sensible heat gain if $T_a > T_{sk}$) via convection (Eq. (2.9)) and radiation (Eq. (2.5)) [27]. If net heat loss via convection and radiation (and the small heat losses via respiration) are not sufficient to balance the rate of internal heat production via metabolism (Eq. (2.2)), eccrine sweating must be initiated to enhance evaporative heat loss from the skin. Once sweat is secreted from eccrine sweat glands and reaches the skin surface, the area of skin directly under the sweat is considered to be 100% saturated with water vapour [49]. As such, the gradient between the partial pressure of water vapour at the skin surface (P_{sk}) and in ambient air (P_a), and therefore the rate of evaporative heat loss, is increased by sweating. As sweat gland output increases, skin wettedness (ω) increases until reaching a maximum theoretical value of 1.00 when the entire surface area of the body that is available for evaporation (typically equal to total body surface area in healthy humans) is completely covered in sweat. This level of ω is only possible in fully heat acclimated individuals [39] and has been recently shown to be as low as 0.72 in an untrained, non-heat acclimated individual, and 0.84 in trained but non-heat acclimated people [37]. The ability to saturate ~15 to 25% more of the skin surface following heat acclimation permits an extension of the range of compensable conditions for a given ambient temperature and humidity (Fig. 2.2). Whole-body sweat rate is regulated to ensure that, and if possible, a steady-state core temperature is attained [50]. It follows that for thermal equilibrium to be possible a rate of heat storage of zero must be achieved. As such, whole-body sweat rate is effectively controlled to ensure heat balance, or more specifically the evaporative heat requirement for heat balance (E_{req}) (Eq. (2.17)) [49]. The relationship between whole-body sweat rate and E_{req} becomes non-linear however, once decrements in evaporative efficiency (Eq. (2.21)) are observed; that is, when E_{req} is approximately greater than 50% of E_{max} (Eq. (2.18)).

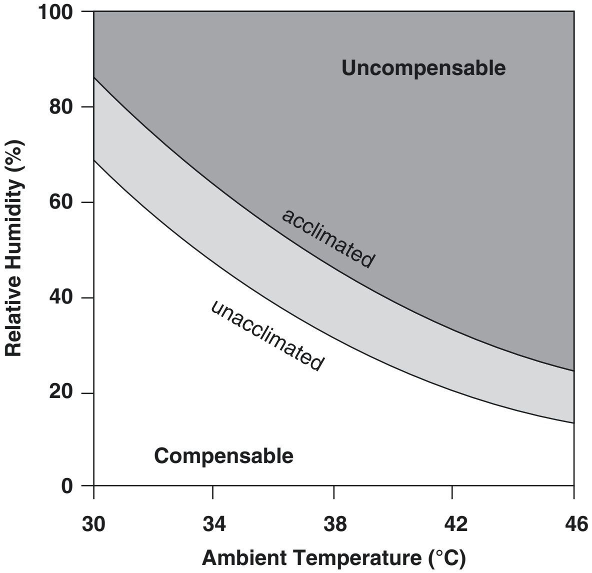

Fig. 2.2 The upper limits of compensability for an exercising individual at 600 W of heat production who is unacclimated (white area) or fully heat acclimated (light grey area). As depicted, the ability to attain a greater maximum skin wettedness following complete heat acclimation permits the maintenance of heat balance in more humid environments (for a given ambient temperature) in comparison to unacclimated

As skin surface sweating is autonomically controlled via a feedback loop using afferent signals from thermoreceptors throughout the body [51], sweating cannot commence without a "load error", i.e. a rise in internal temperature [45, 52], which in almost all circumstances requires heat storage. As a result, the time course of the activation of physiologically mediated changes in skin surface heat dissipation is longer relative to the almost immediate increase in heat production following the onset of exercise leading to a transient heat imbalance. The duration of this imbalance is determined by: (1) the rate at which sweating and skin blood flow increase relative to the rise in core and skin temperature and (2) the maximum physiological capacity to increase sweat production and skin blood flow. The longer this imbalance between heat production and net heat dissipation lasts, the greater S will be for a particular individual, and the greater the rise in internal tissue temperatures.

2.2.7 Compensable and Uncompensable Heat Stress

The risk associated with heat stress or hyperthermia, in terms of the magnitude of rise in core temperature, is greatly dependent on the physiological compensability of the individual in a given environment. While body temperature will eventually plateau if heat balance is attainable (compensable), it will continue to rise without a plateau occurring if heat balance is not possible (uncompensable). Uncompensable heat stress can occur because: (1) metabolic heat production is too high, and/or (2) the physiological capacity to sweat has been reached, and/or (3) the environment/clothing prevents a sufficiently high rate of heat dissipation from the skin. In the context of the previously described heat balance components, whether a given heat exposure is compensable or not is determined by: (a) the amount of evaporation required for heat balance (E_{req}) and (b) the maximal evaporative capacity of environment ($E_{\max}$): that is, if $E_{\mathrm{req}} \leq E_{\max}$ = Compensable and if $E_{\mathrm{req}} > E_{\max}$ = Uncompensable.

The E_{req} and $E_{\max}$ for a given exposure are determined by both environmental conditions and physiological characteristics. A lower E_{req} is observed as: (1) T_a and T_r become lower, (2) v becomes greater apart from when $T_a > T_{\mathrm{sk}}$, (3) M–W is lower and (4) T_{sk} is higher. On the other hand, a higher $E_{\max}$ is observed as: (1) P_a becomes lower and thus drier, (2) v becomes greater, (3) body surface area of the person is greater and (4) $R_{e,\mathrm{cl}}$ of clothing worn is lower. Therefore, the cooler, windier and drier an environment is, the more likely it will lead to compensable heat stress, especially if levels of physical activity are low and/or clothing with a low evaporative resistance is worn. Nevertheless, numerous combinations of activities and climates can yield uncompensable heat stress. Even activities with a low metabolic heat production can result in uncompensable heat stress if the climate is sufficiently hot, humid and still. Similarly, activities with high rates of metabolic heat production can result in uncompensable heat stress even in relatively temperate climates. In sum, for a fixed set of environmental characteristics, the more skin temperature can be increased through elevations in skin blood flow, and the greater the skin wettedness that can be achieved, the more likely an individual will (a) avoid uncompensable heat stress and a continued increase in core temperature and (b) limit the magnitude of heat storage and therefore the increase in core temperature during a compensable heat stress exposure.

2.2.8 Cold Stress

Although the current chapter focuses primarily on heat stress, it will conclude with a brief comment on the biophysical processes associated with cold stress as they follow identical principles. In the cold, large temperature gradients between the cold ambient air and the warmer skin cause extensive sensible heat loss, primarily via convection and radiation. A reduction in skin blood flow via sympathetic vasoconstriction causes a concomitant decrease in T_{sk} [53], and subsequently reduces the temperature gradient between the skin surface and the ambient environment and therefore blunts sensible heat loss for a given air temperature and air velocity. Restricting blood flow to the skin and maintaining blood flow to the body core ensures that the heat produced via metabolism remains close to the deep visceral organs and the brain. As a result, a substantial temperature gradient develops between the body core and peripheral tissues. If skin blood flow does not sufficiently limit dry heat loss and a negative rate of body heat storage persists, shivering thermogenesis will be instigated to increase the rate of metabolic heat production via the asynchronous firing of muscle fibres to produce heat without external work. Heat production during maximal shivering can reach up to 5–6 times resting metabolic rate [54]. Primary input for the magnitude of shivering thermogenesis appears to come from deep body thermoreceptors (i.e. spinal cord, intestines and brain), whereas the onset threshold for shivering is modified by skin temperature [55, 56]. While shivering thermogenesis is an effective means of compensating for a negative rate of body heat storage, shivering has been shown to interfere with the performance of fine motor tasks [57, 58].

2.2.9 Summary

This chapter describes the fundamental factors that influence heat exchange between the human body and its surrounding environment. The bulk of heat exchange takes place at the skin surface via sensible heat transfer (i.e. convection and radiation) and evaporation. With increasing ambient temperature, the gradient for sensible heat transfer declines, meaning that the human body becomes increasingly dependent on the evaporation of sweat for heat dissipation. If the combination of climate (air temperature, radiant temperature, humidity and air velocity) and clothing permit a sufficient level of heat dissipation to counterbalance the rate of internal heat production, elevations in core temperature are moderated (i.e. compensable heat stress). However, if heat production exceeds the upper capacity to lose heat from the skin surface due to high ambient temperatures, humidity, low wind speeds or high evaporative resistance of clothing, a continuous increase in core temperature occurs (i.e. uncompensable heat stress).

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