Supporting Information

Ruxton and Wilkinson 10.1073/pnas.1113915108

SI Text

Section 1: Detailed Description of the Model and Its Biological Justification. Here we give a full description of the model used. Biological motivation for model assumptions can be found in *Methods* or ref. 1.

Thermal environment. We are interested in the period from dawn at 6:00 to dusk at 18:00 on a cloudless day in an environment without cover. Let t be the time in hours, $t = 0$ being midnight. We assumed that the air temperature at a height of 200 cm (T_{200}) varied sinusoidally with a minimum at $t = 5$ and a maximum at $t = 14$. We assume a value of 40 °C for τ_{200} throughout. The minimum value was set at 25 degrees less than τ_{200}. Thus, at any given time t, the air temperature 200 cm above the ground was given by

$$T_{200}(t) = \tau_{200} - 25 + 25Sin\left(\frac{\pi(t-5)}{18}\right). \quad \textbf{[S1]}$$

The ground temperature (T_g) is assumed to reach a maximum that was 5 degrees higher than the maximum air temperature, and to have a daily range of 35 °C. The minimum temperature occurs at $t = 5$, and the maximum at $t = 13$. Thus, the ground temperature at any time (t) is given by

$$T_g(t) = \tau_{200} + 5 - 35 + 35Sin\left(\frac{\pi(t-5)}{16}\right). \quad \textbf{[S2]}$$

The air temperature (T_a) actually experienced by a hominin would depend on its characteristic height. Specifically, we used a parameter (α) to specify this characteristic height, such that

$$T_a = T_{200} + \alpha(T_g - T_{200}). \quad \textbf{[S3]}$$

We assumed the value $\alpha = 0.41$ for a biped and $\alpha = 0.54$ for a quadruped.

Movement relative to the air. We assumed that the air movement past the body is produced by the travel of the individual rather than by wind. Many walkers seem to adopt an energetically efficient walking speed such that their Froude number is ~0.3. If we assume that our organism has a leg length L (in meters), then (because Froude number is velocity squared divided by the product of leg length and acceleration due to gravity), this suggests an energetically efficient walking speed of $1.7\ L^{0.5}\cdot m\cdot s^{-1}$.

Radiation environment. We need to describe daily variation in the intensity of direct solar irradiance incident on a surface at right angles to the ray path (S). Thus, we assume dawn at $t = 6$ and dusk at $t = 18$, and represent S at any time t between dawn and dusk by

$$S = 865Sin\left(\frac{\pi(t-6)}{12}\right). \quad \textbf{[S4]}$$

The intensity of diffuse irradiance resulting from scattering in the atmosphere (s) is suggested to make up 10% of the total incident short wave (S+s); that is,

$$s = \frac{S}{9}. \quad \textbf{[S5]}$$

The fraction of short-wave radiation that is incident on the substrate and is reflected back from the surface to potentially strike the organism is given by the surface reflectivity (r), and we use a value of 0.15 for this.

The downward flux of long-wave radiation (R_{sky}, in $W\cdot m^{-2}$) is given by

$$R_{sky} = 213 + 5.5T_{200}. \quad \textbf{[S6]}$$

We use the same formulation as Wheeler for the flux of long-wave radiation from the substrate (R_g, in $W\cdot m^{-2}$) given by

$$R_g = \sigma(T_g + 273)^4, \quad \textbf{[S7]}$$

where σ is the Stefan–Boltzmann constant (5.67×10^{-8} $W\cdot m^{-2}\cdot{}^{o}K^{-4}$).

We assume that indirect radiation from the sky is incident only on half of the body surfaces (facing upward) and radiation from the substrate is only incident on the other half of the surfaces (facing downward). Thus, the average density of solar energy striking those parts of the surface of the organism not exposed to direct solar radiation is

$$Q_{inc.vert} = 0.5(s + r(S+s) + R_{sky} + R_g). \quad \textbf{[S8]}$$

Thermal properties of the hominin coat. We consider sparsely haired hominids without any clothing. However, like Wheeler, we assume that some parts of the body are covered with thick hair. First we describe the more complex case, for parts of the body where heat lost from the skin must pass through a coat of hair before reaching the environment. The absorptivity (a) of the coat is the proportion of short-wave energy incident on the coat that is absorbed. For haired individuals, Wheeler assumed this value to be 0.8, and assumed that all incident long-wave energy is absorbed. Thus, the radiant thermal energy absorbed by the coat in areas not exposed to sunlight is given by

$$Q_{abs.vent} = 0.5(as + ar(S+s) + R_{sky} + R_g). \quad \textbf{[S9]}$$

In those areas exposed to direct solar radiation, this becomes

$$Q_{abs.dors} = aS + Q_{abs.vent}. \quad \textbf{[S10]}$$

Wheeler considered two values for the thermal conductance of the pelt (C): 5 and 10 $W\cdot m^{-2}\cdot{}^{o}C^{-1}$. The thicker the pelt, the more challenging it is for heat to pass from the skin to the environment, and so the lower the conductance. Both values used by Wheeler are considerably higher than most values measured in mammals, which are rarely above 1 for animals with fur. Indeed, they range from 1.4 to 6 for very fine fur. Because Wheeler assumes implicitly that the pelt is sufficiently thick to prevent wind penetration, we consider both his values to be too high, and adopt a value of 1.0 in our modeling.

Surface temperatures and net environmental heat gain. For haired parts of the hominin, the amount of heat reaching the surface of the pelt (per m^2) Q_{gain} is given by that absorbed at the surface, minus convective and radiative losses, given by

$$Q_{gain} = Q_{abs} - \left[\sigma(T_s + 273)^4 + k\sqrt{v}(T_s - T_a)\right], \quad \textbf{[S11]}$$

where the convection coefficient (k) is 9.8 $W\cdot m^{-2}\cdot{}^{o}C^{-1}$. v is the velocity of the air flowing past the body (in our model, this will be the running speed).

To find the unknown surface temperature of the pelt, we equate heat traveling between the surface of the pelt from the environment with heat flowing from the surface to the animal's skin to the surface of the pelt:

$$C(T_s - T_c) = Q_{abs} - \left[\sigma T_s^4 + k\sqrt{v}(T_s - T_a)\right], \quad \textbf{[S12]}$$

where T_c is the skin temperature, assumed to be 37 °C. Eq. **S12** can then be solved for the pelt surface temperature, and then the rate flux can be evaluated.

Total environmental heat load. We now have two values of Q_{gain}: for those areas of the body that are, and those that are not, exposed to direct sunlight. Wheeler assumed a total surface area of 1.2 m^2 for a 35-kg individual. Because surface area (A in m^2) is likely to vary with mass (M in kg) to the power 2/3, we use a formula that gives the same point estimate as that used by Wheeler but allows us to estimate the surface area for individuals of any mass:

$$\mathrm{A} = 0.11M^{0.67}. \quad \textbf{[S13]}$$

For bipeds, we used the following equation to describe the fraction (β) of the skin surface exposed to the sun as a function of time (t in hours since midnight):

$$\beta_b = 0.23 - 0.15Sin\left(\frac{(t-6)\pi}{12}\right), \quad \textbf{[S14a]}$$

and an analogous equation for quadrupeds:

$$\beta_q = 0.21 - 0.03Sin\left(\frac{(t-6)\pi}{12}\right), \quad \textbf{[S14b]}$$

These equations indicate that the maximum fraction of the surface area exposed to direct sunlight occurs when the sun is low in the sky (near dusk and dawn), being 23% for bipeds and 21% for quadrupeds at that time. The minimum exposure for both stances occurs when the sun is directly overhead, and is 8% for bipeds and 18% for quadrupeds. Thus, the daily change in exposure to direct sunlight is much more dramatic for bipeds, which reduces their exposure considerably when the sun is high in the sky.

Eqs. **S1–S14** allow the total environmental heat load to be calculated on thickly haired parts of the individual.

Effect of hair loss. We assumed that 15% of the body of an individual is still covered in thick hair (this being the head and shoulders). The heat flux through this region is simply considered to be 15% of the total flux through the entire body of a fully haired individual. Wheeler does not assume that the 15% hair is biased toward dorsal surfaces, and so we follow him and assume that 15% of both shaded and unshaded areas of the body are haired. However, our fundamental model predictions are not critically dependent on this assumption.

The rest of the skin surface is treated exactly the same as was the surface of the hair in the description above, except that the temperature is fixed at 37 °C. We consider this a reasonable assumption, because even in sunbathing individuals and those taking vigorous exercise, skin temperature is often lower than core temperature and very rarely more than 1 or 2 degrees higher, although we note that these experiments were only performed on light-skinned individuals.

Metabolic heat load. We used an allometric equation for the total energetic cost of a mammal or bird of mass M moving at speed v:

$$S = 6.03M^{0.7} + 10.7vM^{0.68}. \quad \textbf{[S15]}$$

Thus, the total metabolic heat generated by an active individual (less the 10% lost through respiration) is given by

$$0.9\left(6.03M^{0.7} + 10.7vM^{0.68}\right). \quad \textbf{[S16]}$$

Model summary. The sections above fully specify our modification of Wheeler's model to consider a traveling individual. To evaluate the model for a specific type of hominin, we must specify its mass M kg and leg length L m (morphometric measurements for key hominins of interest are given in the text). With substitution of parameter values, the model will predict the net amount of metabolic heat that must be shed across the skin per unit time (in watts) to avoid core temperature rise. This can be predicted for all times of day between dawn and dusk. Against this, we make the same assumption as Wheeler about the maximum rate at which humans can dump heat by evaporative cooling of sweat from the surface of the skin: 500 $W \cdot m^{-2}$. If the calculated heat energy that is required to be dumped exceeds this maximum value, then the core temperature of the individual will rise.

Section 2: Considering Variation in Body Form. The assumed body mass of 55 kg represents a relatively "robust" individual; the equivalent mass for a more gracile morph with the same 72-cm leg length might be 45 kg (2). Using this value reduces the estimated metabolic heat generation of a walking male to 286 W. However, the estimated skin surface area of this gracile individual is also reduced to 1.41 m^2, and so the maximum rate of heat dissipation through sweating is 131 W for a hair-covered individual and 620 W for an individual with greatly reduced hair. Fig. S1 shows the equivalent model predictions as Fig. 1*B* but for a gracile rather than robust male. The pattern of results is qualitatively identical to that described above for a robust individual. Hence, our model predictions are not sensitive to the particular form of early hominid considered. For hair-covered individuals, the heat load is around 240 W, whereas the predicted heat dissipation is only 131 W; such an excess heat gain of 110 W would be predicted to cause a 1-°C rise in core body temperature of such a 45-kg individual after ∼25 min.

1. Ruxton GD, Wilkinson DM (2011) Thermoregulation and endurance running in extinct hominins: Wheeler's models revisited. *J Hum Evol* 61(2):169–175.

2. Plavcan JM, Lockwood CA, Kimbel WH, Lague MR, Harmon EH (2005) Sexual dimorphism in *Australopithecus afarensis* revisited: How strong is the case for a human-like pattern of dimorphism? *J Hum Evol* 48:313–320.

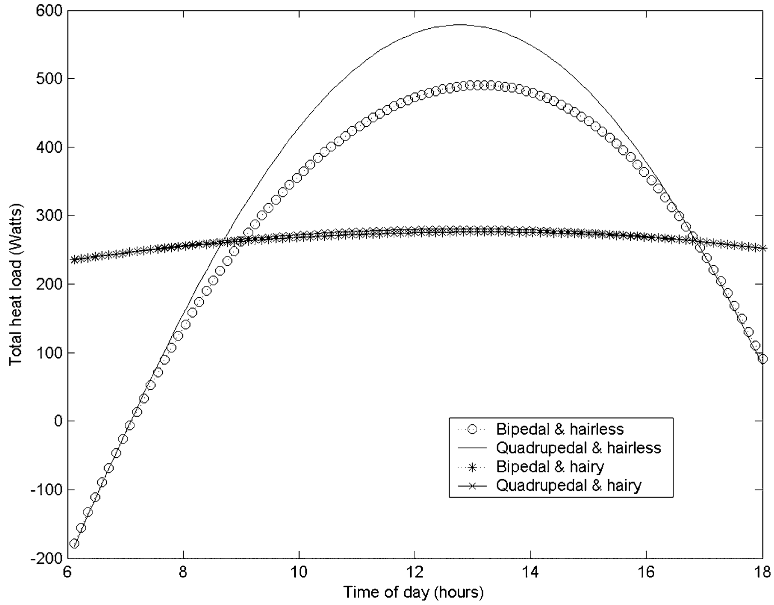

Fig. S1. Model predictions for the amount of heat that must be dissipated by sources other than normal respiration (such as sweating) to maintain heat balance, as a function of time of day for a gracile male hominin. We model four situations involving all combinations of quadrupedal versus bipedal stance and full body hair versus loss of hair to near-modern human levels.