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Energy consumption in buildings and female thermal demand

Boris Kingma* and Wouter van Marken Lichtenbelt

Energy consumption of residential buildings and offices adds up to about 30% of total carbon dioxide emissions; and occupant behaviour contributes to 80% of the variation in energy consumption[1]. Indoor climate regulations are based on an empirical thermal comfort model that was developed in the 1960s (ref. 2). Standard values for one of its primary variables—metabolic rate—are based on an average male, and may overestimate female metabolic rate by up to 35% (ref. 3). This may cause buildings to be intrinsically non-energy-efficient in providing comfort to females. Therefore, we make a case to use actual metabolic rates. Moreover, with a biophysical analysis we illustrate the effect of miscalculating metabolic rate on female thermal demand. The approach is fundamentally different from current empirical thermal comfort models and builds up predictions from the physical and physiological constraints, rather than statistical association to thermal comfort. It provides a substantiation of the thermal comfort standard on the population level and adds flexibility to predict thermal demand of subpopulations and individuals. Ultimately, an accurate representation of thermal demand of all occupants leads to actual energy consumption predictions and real energy savings of buildings that are designed and operated by the buildings services community.

As the built environment is focusing more on design of energy-efficient buildings (for example, near-zero-energy buildings), we argue that indoor climate standards should accurately represent the thermal demand of all occupants. Otherwise there is a great risk that occupants will adapt their behaviour to optimize personal comfort, which may in turn nullify the effects of supposed energy-efficient designs. Furthermore, various fields in commerce, science and policymaking depend on accurate predictions of building energy consumption. For instance, commercial incentives for building renovations premised on energy-saving predictions; scientific climate change simulations require building energy consumption predictions to account for warming effects in winter[4]; and policymaking for resource management requires integrated resource assessments including energy consumption by buildings[5].

The total variation in building energy consumption that is explained by occupant behaviour includes operating the thermostat, windows or air conditioning system[1]. In general, females prefer a higher room temperature than males in home and office situations, and mean values may differ as much as 3 K (males: 22 °C versus females: 25 °C; refs 6,7). Despite this discrepancy in preferred room temperature, no significant gender effect is found with respect to the mean skin temperature range that is associated with thermal comfort (males: 32.8–33.8 °C versus females: 32.4–33.6 °C; ref. 8).

Indoor thermal environment design is primarily based on PMV/PPD (predicted mean vote/percentage people dissatisfied) criteria. The PMV is expressed on the ASHRAE 7-point Thermal Sensation Scale ranging from cold (−3) to hot (+3). This vote is linked to thermal discomfort through the PPD (ref. 9). Two main input variables for the model are metabolic rate and clothing insulation; however, the accuracy of these variables is in general poorly defined[10,11]. Nevertheless, standard reference values for the metabolic rate and clothing are tabulated and used worldwide[2,12,13]. With respect to the metabolic rate, the metabolic equivalent (MET) is used to express the metabolic cost of an activity relative to the resting metabolic rate, and its value ($1\ \mathrm{MET} = 4.186\ \mathrm{kJ\ kg^{-1}\ h^{-1}} \approx 58\ \mathrm{W\ m^{-2}}$) is set by convention based on the resting metabolic rate of only one 70 kg, 40-year-old male[3]. This may have significant consequences because $58\ \mathrm{W\ m^{-2}}$ may overestimate resting heat production of women up to 35% (ref. 3). Similarly, with increasing age, basal metabolic rate decreases[14]. Thus, current indoor climate standards may intrinsically misrepresent thermal demand of the female and senior subpopulations[10,15]. The PMV/PPD model uses the metabolic rate to calculate the environmental conditions that satisfy thermal balance between the body and the environment (see Fig. 1, right part: skin to environment). However, from a biophysical perspective, thermal balance within the body has to be satisfied as well (see Fig. 1).

Thermal balance within the body is dictated by both metabolism and the composite thermal insulation provided by tissues (that is, body composition and skin blood flow). The influence of thermal insulation is especially relevant in the case of lean versus obese. The larger insulation provided by adipose tissue results in greater core-to-skin temperature gradient and a lower mean skin temperature for obese compared with lean[16]. Consequently, these physiological characteristics co-determine the thermal demand from the environment. The PMV/PPD model was published in the 1970s and at that time biophysical models that incorporate the influence of tissue insulation were not widely used. However, since that time several biophysical models of human thermal balance have been developed[17–19]. Therefore, the knowledge gained from these models could be used to enhance the PMV/PPD model.

It has been suggested that thermal balance within the thermoneutral zone is a prerequisite of steady-state thermal comfort[20]. The thermoneutral zone is defined in physiological terms as the range of operative temperatures where an organism can maintain its body temperature without regulatory changes in metabolic rate (for example, shivering or non-shivering thermogenesis) or sweating[21] (see Fig. 2). In relation to thermal comfort this means that operative temperatures that are thermally comfortable (thermal comfort zone) coincide with, or at least form a subset of, the temperatures where the body requires no regulatory metabolic heat production or sweating to maintain thermal balance (thermoneutral zone)[20,22]. The exact positioning of the thermoneutral zone may thus change with activity, body composition (tissue insulation) and clothing level.

In this study we investigate the thermal state of young adult females performing light office work and we use a biophysical modelling approach to test whether these thermal states fall within

Department of Human Biology, NUTRIM School of Nutrition and Translational Research in Metabolism of Maastricht University Medical Center+, PO Box 616, 6200 MD Maastricht, The Netherlands. *e-mail: b.kingma@maastrichtuniversity.nl

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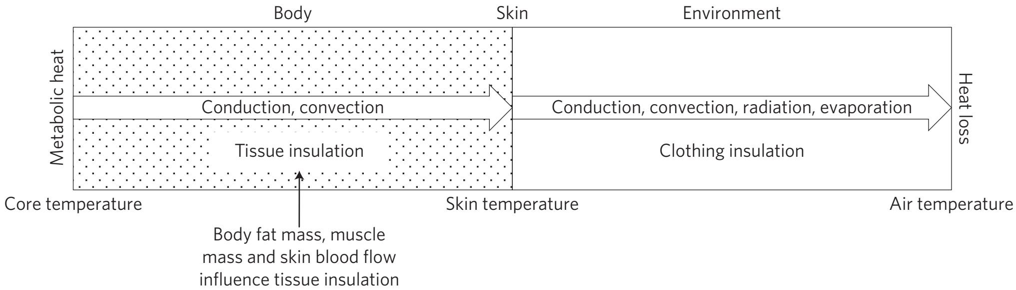

Figure 1 | Schematic view of human heat balance. Heat balance from core to skin (within body) and from skin to air (between body and the environment). The open arrows denote heat flow within the body via conduction through tissues and convection through blood flow; and between the body and environment via conduction, convection, radiation and evaporation. Body tissue insulation provides resistance to metabolic heat within the body and determines the temperature gradient between core and skin. Likewise, clothing also provides resistance to body heat loss and co-determines the temperature gradient between skin and air.

their thermoneutral zone (see Methods and Supplementary Table). With this analysis we aim to point out the importance of using the actual metabolic rate, instead of a standard one based only on a male. Therefore, the biophysical model may provide a constructive way forward from the empirical thermal comfort standard.

The measured group average metabolic rate for young adult females while performing light office work is 48 ± 2 W m^{-2}, which is significantly lower ($p < 0.01$) than the ASHRAE standard values for metabolic heat production associated with this activity (from resting seated: 60 W m^{-2} or 20% overestimation, to seated filing: 70 W m^{-2} or 32% overestimation). The biophysical analyses using both the measured and range of reference values for metabolic rate is shown in Fig. 3 (see Methods for details on how this Figure is constructed). The grey areas in Fig. 3 indicate the thermoneutral zones; that is, they depict the area where heat loss equals measured metabolic heat production. Open circles indicate actually measured mean skin temperature and operative temperature baseline recordings. When using the measured metabolic rate (Fig. 3, right area), measurements are located inside the thermoneutral zone. This is in great contrast to where all model parameters are kept equal except for the metabolic rate for which the standard reference values for light office work are used (Fig. 3, left area).

This biophysical analysis shows that mean skin temperature and thermal environment of young adult females performing light office work falls within their thermoneutral zone, but only if the correct (actual) metabolic rate is used. Furthermore, we confirm that the metabolic rate of young adult females performing light office work is significantly lower than the standard values for the same type of activity. With these results we argue that the current metabolic standards should be adjusted by including the actual values for females to reduce gender-discriminating bias in thermal comfort predictions, and consequently, to reduce prediction bias in building energy consumption.

The body senses its thermal state through temperature-sensitive receptors in core and skin tissues[20]. Various studies have examined skin temperatures that are associated with thermal comfort, and estimates range from wide ($31.5 \leq T_s \leq 35.5$ °C) to more conservative ($32.4 \leq T_s \leq 33.6$ °C) values[8,23]. The former seems to coincide with the entire thermoneutral zone of young adult females performing light office work (see $31.5 \leq T_s \leq 35.5$ °C, Fig. 3), whereas the latter comprises only a subset of the thermoneutral zone (see $32.4 \leq T_s \leq 33.6$ °C, Fig. 3). This discrepancy between studies may in part have been caused by differing number of skin sites that have been measured. In general, more skin sites yields more reliable results. Using a standard that consists of less than 10 skin sites leads to significantly lower reliability[24]. On top of that, within limits imposed by physics and physiology, human psychological factors (for example, thermal adaptation due to geography) may also play a role in what skin temperatures are considered comfortable[25].

Constraining the model results further to skin temperatures that are associated with thermal comfort it is possible to identify a biophysical thermal comfort zone[22]. For the given conditions, the biophysical thermal comfort zone for females ranges from 23.2 to 26.1 °C (for mean skin temperature ranging $32.4 \leq T_s \leq 33.6$ °C).

As introduced, we make a case to use more reliable values for female metabolic rate in thermal comfort prediction. Future technological advances may yield devices that accurately measure individual metabolic rate (for example, via smart watches and so on). Until that time, one way to go forward may be by using resting metabolic rate equations that take into account the effects of age, sex and body size (for example, revised Harris and Benedict equations for resting metabolic rate[26]). The resting metabolic rate can be converted from watt to watt per square metre by using the appropriate equation for body surface area (for example, ref. 27). Furthermore, the resting metabolic rate can also be scaled to the activity type using the MET scaling factors.

The use of more accurate metabolic rates implies that the PMV/PPD model requires recalibration. The reason for this is in the very nature of the PMV/PPD model: it is an empirical model and it has been fitted against thermal sensation votes using the standardized values for metabolic rate. In the long run, recalibration to any unforeseen subpopulation is not a sustainable strategy to maintain. It has been suggested that a better method to improve the PMV/PPD model is to revise its physiological construction[15,28]. This in turn makes it possible to fundamentally understand and take into practice the effects of group and individual differences

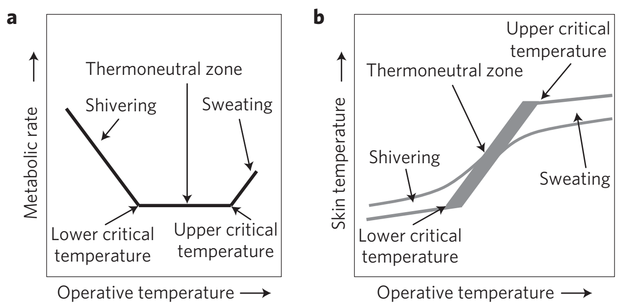

Figure 2 | Two methods to depict the thermoneutral zone. a, The classical method indicating the dependence of metabolic rate versus operative temperature. **b**, The method used in this paper describing the relation between skin temperature versus operative temperature. The range to the left of the thermoneutral zone depicted with 'shivering' indicates that more heat production is required to maintain thermal balance, and the range to the right depicted by 'sweating' indicates that more heat loss is required to maintain thermal balance. Within the open bounds it is possible for the body to maintain core temperature.

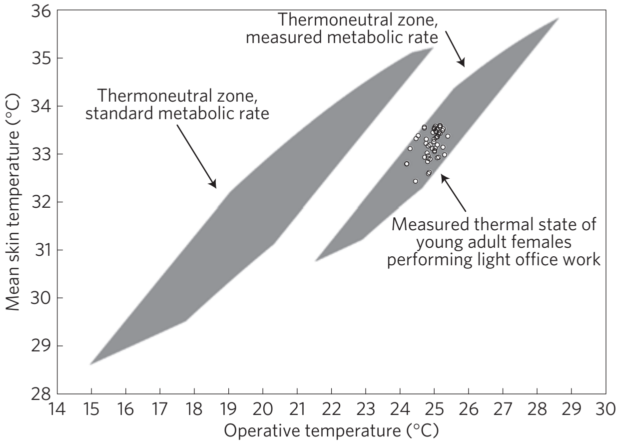

Figure 3 | The steady-state thermoneutral zone (grey areas) and baseline measurements (open circles). The bottom of the thermoneutral zone is associated with maximal tissue insulation, and vice versa for the top. Left area: thermoneutral zone using the standard value for metabolic rate associated with light office work (ranging from 60 to 70 W m^{-2}). Right area: thermoneutral zone using measured metabolic rate of females performing light office work.

in physiological characteristics such as lean versus obese, or the consequences on preferred thermal environment of changes in physiology (for example, ageing, acclimatization or illness).

The biophysical approach in this study is an essential step towards such a revision. In our opinion it allows for a significant improvement of the empirical model because of the physiological construction that includes the constraint for thermal balance within the body. To do so, it is crucial to take into account not only the metabolic rate but also the physiological range of body tissue insulation, which may vary with body composition, gender and age, but also between individuals. Thus, the biophysical model provides insight into thermal comfort boundaries for subpopulations such as females, males, children and seniors. These should be addressed in future studies that measure subjective thermal comfort as well as physiological characteristics such as metabolic rate and tissue insulation. The biophysical approach provides a fundamental substantiation of the PMV/PPD model on the population level and adds flexibility to predict thermal comfort of subpopulations or individuals. Another issue that deserves attention is thermal behaviour. How do physiological characteristics relate to behaviour, and to what extent does a deviation from the thermoneutral zone trigger an action?

The main points here are that thermal comfort models need to adjust the current metabolic standard by including the actual values for females. Consequently, thermal comfort models need either to be recalibrated or enhanced using a biophysical approach as presented here. This in turn will allow for better predictions of building energy consumption, by reducing the bias on thermal comfort of subpopulations and individuals.

Methods

Methods and any associated references are available in the online version of the paper.

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Author contributions

B.K. contributed to experimental work, project planning, data analysis, biophysical modelling, and manuscript writing. W.v.M.L. contributed to project planning, data analysis, manuscript writing and project funding.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to B.K.

Competing financial interests

The authors declare no competing financial interests.

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Methods

The thermoneutral zone. The thermoneutral zone is classically depicted as described in ref. 29: metabolic rate versus operative temperature and bound by the lower critical temperature and the upper critical temperature (see Fig. 2a). From the perspective of thermal balance, thermoneutral operative temperatures near the lower critical temperature correspond to relatively low skin temperatures, and vice versa for thermoneutral operative temperatures near the upper critical temperature. This leads to a new method to depict the thermoneutral zone, which is used in the remainder of this paper (see Fig. 2b). The open range to the left of the thermoneutral zone depicted with 'shivering' indicates that more heat production is required to maintain thermal balance, and the open range to the right depicted by 'sweating' indicates that more heat loss is required to maintain thermal balance. Note that depending on mean skin temperature there is overlap between thermoneutral operative temperatures, and operative temperatures that require extra heat production or extra heat loss. Thermal balance in the thermoneutral zone is always a constellation of skin temperature and operative temperature. Therefore, it may be inadequate to define a thermal comfort zone only by operative temperature.

The exact skin temperature range of the thermoneutral zone is bounded by the metabolic rate and the capacity of the body to regulate tissue insulation[22]. The body regulates tissue insulation by constricting and dilating blood vessels in skin tissue. To preserve body heat the body constricts blood vessels (that is, vasoconstriction), which results in maximal tissue insulation and minimal skin temperatures. To enhance body heat dissipation the body dilates blood vessels (that is, vasodilation), which results in minimal tissue insulation and maximal skin temperatures[30].

Biophysical analysis. For the biophysical analysis a model is used that describes the relation between body core temperature, skin temperature and operative temperature (see Fig. 1)[22]. The model is used to determine core temperature for a range of mean skin temperatures (28–38 °C) and operative temperatures (14–32 °C), whilst satisfying thermal balance. Overall thermal balance is achieved when the following conditions are met: (1) Metabolic heat production equals internal body heat transport. (2) Metabolic heat production equals external body heat loss. These conditions can be rewritten to an equivalent such that internal body heat transport equals external body heat loss. Note that metabolic heat production is then eliminated from the condition of thermal balance, yet still determines the actual body heat transport and heat loss. The model details are described in ref. 22. For the purpose of this paper the steps for constructing the young adult female thermoneutral zone as depicted in Fig. 3 are given below:

Define body surface area (A), clothing insulation (I_{cl}), relative humidity (φ) skin wettedness, (w), wind speed (v_{air}) and Lewis relation (λ).

$$A = 1.88\ \text{m}^2$$

$$I_{cl} = 0.105\ \text{m}^2\ \text{K W}^{-1}\ (\sim 0.68\ \text{clo})$$

$$\varphi = 0.5 (= 50\%)$$

$$w = 0.06\ (-)$$

$$v_{air} = 0.09\ \text{m s}^{-1}$$

$$\lambda = 2.2\ ^\circ\text{C mmHg}^{-1}$$

Define minimal and maximal metabolic rate (M_{min} and M_{max}) based on 99% confidence interval of energy expenditure measurements and correct for respiratory heat loss (that is, consider only heat transfer to and from skin surface; assumed 8% of metabolic rate[31]).

$$M_{min} = (1 - 0.08) \times 84\ \text{W} = 77\ \text{W}$$

$$M_{max} = (1 - 0.08) \times 97\ \text{W} = 89\ \text{W}$$

Define minimal and maximal body tissue insulation ($I_{body,min}$ and $I_{body,max}$), (skin + fat layer ~4 mm)[30,32].

$$I_{body,min} = 0.031\ \text{m}^2\ \text{K W}^{-1}$$

$$I_{body,max} = 0.112\ \text{m}^2\ \text{K W}^{-1}$$

Define minimal and maximal body core temperature ($T_{c,min}$ and $T_{c,max}$).

$$T_{c,min} = 36.5\ ^\circ\text{C}$$

$$T_{c,max} = 37.5\ ^\circ\text{C}$$

Calculate minimal and maximal skin temperature that support internal heat balance ($T_{s,min}$ and $T_{s,max}$) according to ref. 22:

$$T_{s,min} = T_{c,min} - M_{max} \times I_{body,max}/A\ [^\circ\text{C}]$$

$$T_{s,max} = T_{c,max} - M_{min} \times I_{body,min}/A\ [^\circ\text{C}]$$

Define 500 × 500 point grid for T_s and T_a

$$T_s \text{ between 28 and 38 } ^\circ\text{C}$$

$$T_a \text{ between 14 and 32 } ^\circ\text{C}$$

For each point in the grid (T_s and T_a): Calculate combined convective (h_c) and radiative (h_r) contribution to insulation provided by air (I_a) according to ref. 30:

$$h_c = 0.19 \times (100 \times v_{air})^{0.5} \times (298/(T_a + 273.15))\ [\text{clo}^{-1}]$$

$$h_r = 0.61 \times ((T_a + 273.15)/298)^3\ [\text{clo}^{-1}]$$

$$I_a = 0.155/(h_c + h_r)\ [\text{m}^2\ \text{K W}^{-1}]$$

Calculate evaporative heat loss according to ref. 17:

$$Q_e = w \times \lambda \times h_c \times (P_s - \varphi P_{air}) \times F_{pcl}\ [\text{W m}^{-2}]$$

$$P_s = \gamma \times 100 \exp(18.965 - 4{,}030/(T_s + 235))\ [\text{Pa}]$$

$$P_{air} = \gamma \times 100 \exp(18.965 - 4{,}030/(T_a + 235))\ [\text{Pa}]$$

$$\gamma = 0.00750061683\ [\text{mmHg Pa}^{-1}]$$

$$F_{pcl} = 1/(1 + 0.143 \times (h_c/0.155) \times (I_{cl}/0.155))\ [-]$$

Calculate body tissue insulation according to ref. 22:

$$I_{body} = I_{body,max} + (T_s - T_{s,min}) \times (I_{body,max} - I_{body,min})/(T_{s,min} - T_{s,max})\ [\text{m}^2\ \text{K W}^{-1}]$$

where ($I_{body,min} \le I_{body} \le I_{body,max}$)
Calculate T_c satisfying internal and external heat balance according ref. 22:

$$T_c = (I_{body}/0.92) \times ((T_s - T_a)/(I_{cl} + I_a) + Q_e) + T_s\ [^\circ\text{C}]$$

Calculate external heat loss (Q_{out})

$$Q_{out} = A \times ((T_s - T_a)/(I_{cl} + I_a) + Q_e)\ [\text{W}]$$

Keep points for which T_c between $T_{c,min}$ and $T_{c,max}$. Keep points for which Q_{out} between M_{min} and M_{max} and plot remaining points in Figure (T_s versus T_a).

The exact position of the thermoneutral zone depends on the metabolic rate, body insulation and clothing level. Higher metabolic rate and/or clothing level shifts the thermoneutral zone to lower operative temperature and higher body insulation shifts the neutral zone to lower operative and mean skin temperature, and vice versa for lower metabolic rate and/or clothing level and lower tissue insulation.

Accuracy statement. The model in this paper combines the main principles that are important to describe internal and external human thermal balance. Nevertheless, it is a simplification of reality and may not always well-predict temperatures, especially for non-steady-state conditions. Likewise, the model parameters are obtained from elaborate experimental studies, but may include measurement errors. Therefore, to obtain a conservative view of how the thermoneutral zone is situated we used parameter ranges instead of set values for metabolic rate, core temperature and body tissue insulation. All steady-state, comfortable ($32.4 \le T_s \le 33.6$ °C) measurements fall within the computed thermoneutral zone for these conditions (see Fig. 3). When including non-steady-state baseline measurements and skin temperatures outside comfortable skin temperature range, 14% of measurements are situated just outside the model prediction (mean absolute distance from thermoneutral zone for these points is 0.3 K).

Measured data. The data for the analysis were obtained in the context of a larger study performed in our laboratory on thermal preference in young adult females[33].

During the study 16 young female participants were lightly clothed (~0.58 Clo + 0.10 Clo provided by chair), sitting behind a desk and were randomly exposed to room temperature protocols in a climate chamber. For the purpose of this study only steady-state baseline data from these protocols are used.

Operative temperature and relative humidity are measured using wireless sensors (iButton, DS1923, Maxim Integrated Products; accuracy ±0.1 °C). Skin temperature is also measured with iButtons (DS1922L, accuracy ±0.1 °C) at the 14 positions as described by ISO 9886 standard[33]. Energy expenditure of young females performing light office work is measured by indirect calorimetry (Maastricht Instruments, accuracy ±5%). Recordings of baseline CO_2 production and O_2 uptake are converted into their heat equivalent using the Weir equation[34]. The ASHRAE listed values for seated light office work range from 'seated quiet' (60 W m^{-2}) to 'seated filing' (70 W m^{-2}). Measured metabolic rate is compared with the standard values using a one-sample t-test with significance level $\alpha = 0.05$. Data are presented as mean ± s.e.m. Whole body fat percentage is measured through dual X-ray absorptiometry (Hologic, accuracy ±5%).

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