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Considering individual physiological differences in a human thermal model

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Abstract

Physiological differences between individuals can significantly affect human thermal response to the environment. In practice, most thermal models use a single set of physiological data to represent an average person. We have developed a model to translate descriptive data about an individual into a set of physiological parameters which may be used in thermal models. We have incorporated these parameters into a model of human thermoregulation and comfort, which may be used to predict variations in thermal response between individuals. This paper presents this model and examples of its use in thermal simulation. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Modeling; Thermoregulation; Body fat; Body density; Metabolic heat production; Blood flow rate; Skin solar absorption

1. Introduction

Many models of the human thermoregulatory system have been developed over the years. They predict human response to the thermal environment including skin temperature, core temperature, sweating, shivering, vasodilation and vasoconstriction. Although many of these models are capable of considering physiological differences between individuals, they are generally used with data representing a "typical" person because of the complexity in adjusting physiology parameters based on individual information. They often do not adjust basal metabolic heat production for body weight and body type, thermal capacitance and conductance of fat for fat amount, blood flow amount for body type or solar absorption for skin color. Our approach was to develop a model for individual differences based on readily available input data.

Individual differences do impact human thermal responses, and some of these effects have been incorporated in previous models. Nishumura et al. (1993) showed a decrease in skin temperature resulting from a body fat increase. Havenith and Middendorp (1990) presented a relationship between body fat and core temperature in subjects under heat stress. Tikuisis et al. (1988) accounted for the impact of body fat on thermal regulation during cold water immersion. Havenith (2001) developed an individualized model including effects of acclimatization.

There are many ways thermal models could become more useful by considering a range of body types. The challenge is how to use readily-available external measurements of individuals to predict individual variation in thermal response. This paper presents a model for deriving the necessary physiological data from height, weight, body fat, gender, skin color and body type.

2. Body builder model

Body builder defines physiological inputs for human thermal regulation models based on readily measured body characteristics. A number of easily obtainable body characteristics can be used to predict internal thermophysiological parameters based on a set of

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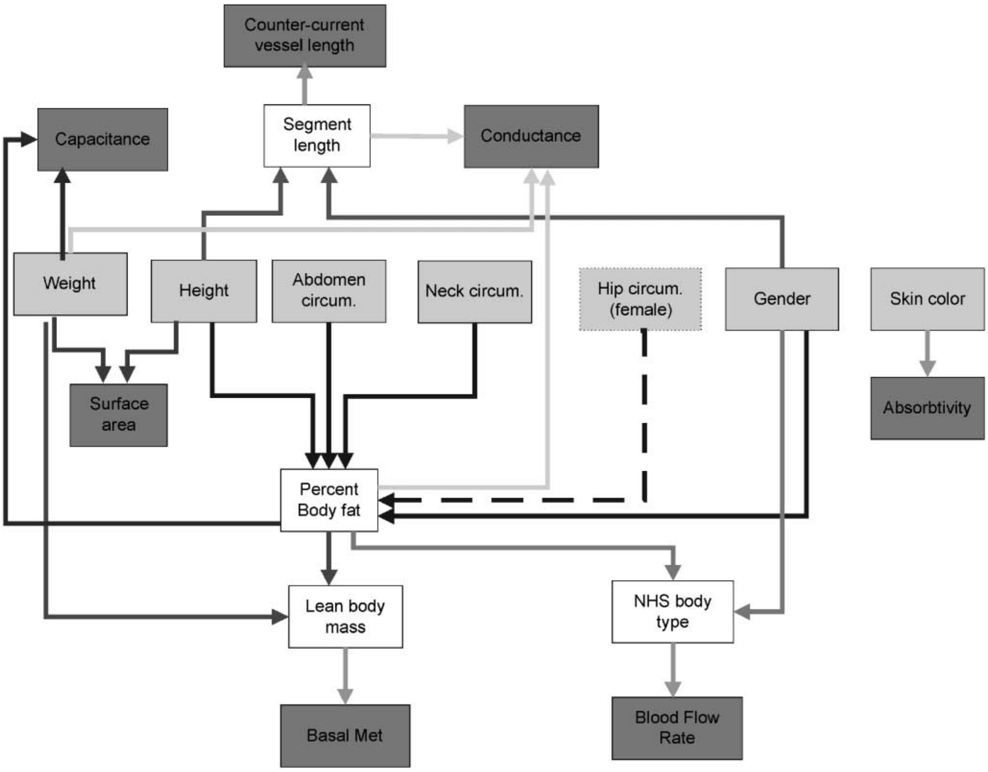

Fig. 1. Flowchart of the *body builder* model.

models we have assembled from the literature. Fig. 1 shows the relationships between the model inputs and the predicted physiological data. The input parameters to the body builder model are the height, weight, gender, body fat (or dimensional information) and skin color. The determined thermal physiological variables are body density, metabolic heat production, body type, blood flow rate, body segment lengths, counter-current blood vessel length in extremities, thermal capacitance, thermal conductance, skin surface area and skin solar absorption. The following sections describe the model in detail.

1. Body fat: The most important thermophysiological differences between individuals result from body fat. Body fat influences both conduction heat transfer and blood flow. Different types of tissues require different amounts of blood, and fat, for example, requires less blood than muscle.

Body fat can be obtained from height and weight for people of normal build. Allen et al. (1956) found that body fat content could be predicted by the weight and the cube of the height. They proposed regression equations giving body fat for men and women, presented in Table 1. The limitation of their method is that it cannot distinguish between normal and unusual body builds, e.g., cases where two people have same height and weight but one has more fat and the other has more lean mass. Such differences in body type require a measurement of the body density. The density of pure lean mass is 1.097 g/ml and the density of pure fat is 0.948 g/ml, so people with more fat have a lower density.

There are many methods used to calculate the percent of body fat (% BF) from body density. We found that Siri's (1961) widely-used formula (Table 1) best predicted the data we have, so we are using it in *body builder* to obtain body fat amount from body density.

2. Body density: The most accurate method of obtaining body density is underwater weighing, in which people are weighed in air and underwater, and the density is obtained via the Archimedes' principle. Since this measurement requires expensive equipment and experienced administrators, there have been frequent attempts to find simpler techniques.

The *skinfold caliper* method is simpler and has been widely used for measuring body fat. Durnin and Womersley (1974) performed regressions of body density versus skinfold thicknesses. The skinfolds were from four body parts: biceps, triceps, subscapular and

Table 1
Body fat, density, and basal metabolic heat production calculation[a]

Outcome measure	Men	Women	Reference
Body fat (kg)	$0.685W-5.86H^3+0.42$	$0.737W-5.15H^3+0.37$	Allen et al., 1956
Percentage of body fat (%)	(a) $100\ (4.95\times10^{-3}/\rho-4.5)$ (b) $0.740C_{\mathrm{u}}-1.249C_{\mathrm{n}}+0.528$	Same as for men	Siri, 1961 Wright et al., 1981
Body density (kg/m^3) by circumferences method	$10^3\{-[0.19077\log 10(C_{\mathrm{u}}-C_{\mathrm{n}})]+[0.15456\log 10(100H)]+1.0324\}$	$-[0.35004\log 10(C_{\mathrm{m}}+C_{\mathrm{h}}-C_{\mathrm{n}})]+[0.22100\log 10(100H)]+1.29579$	Hodgdon and Beckett, 1984
Basal metabolic rate (W) height-and-weight method	$0.0484(66+13.7W+5H-6.8$ age $+$ kilometer $160.9)$	$0.0484(665+9.6W+1.7H-4.7$ age $+$ kilometer $160.9)$	Harris and Benedict, 1919
Basal metabolic rate (W)	$0.0484(19.7\mathrm{FFM}+413)$	Same as for men	Mifflin et al., 1990
Lean-body-mass method	$0.0484(500+22\mathrm{FFM})$		Cunningham, 1980

[a] $W=$ weight (kg), $H=$ height (m), $\rho=$ density (kg/m^3), C_{u}, $C_{\mathrm{m}}=$ circumferences at levels of umbilicus, minimal abdominal width at approximately midway between xyphoid and umbilicus, cm, C_{n}, C_{b}, $C_{\mathrm{h}}=$ circumferences of neck, biceps, hip (cm), kilometer = estimation of average daily running distance (km), FFM = fat-free mass (body weight−fat weight) (kg).

supra-iliac. Equations for body density were found for all combinations of these skinfold measurements. Hodgdon and Beckett (1984) obtained relationships between body density and various *body circumferences*. They re-examined Wright's (Wright et al., 1981) equations (Table 1) for predicting body fat percent from various circumferences and provided improved equations. The measurement locations and regressions for men and women are presented in Table 1.

Hodgdon and Beckett first examined whether or not it was necessary to include skinfold measures and found that the circumferences and height were sufficient for predicting body density. They then cross-validated many existing equations against densities derived by underwater weighting in their data set and found their equations provided the best prediction. For these reasons, and because skinfold caliper measurements may be more prone to error than circumference measurements, we have adopted the Hodgdon and Beckett approach.

3. *Basal metabolic heat production (basal met):* Basal metabolic heat production (or basal metabolic rate, BMR) is often estimated on the basis of height, weight, age and sex using the predictive equations published by Harris and Benedict (1991) (HB) in 1919 (Table 1). However, the HB equations have been found to overestimate BMR for modern populations (Owen et al., 1987; Mifflin et al., 1990).

Mifflin et al. found that the HB equation overestimated measured BMR by at least 15% in their study population, a consequence of marked increase in the mean weights (and fat amount) of their subjects (males, 87.5 kg and females, 70.2 kg) over those of HB (males, 64.1 kg and females, 56.5 kg). The increased fat does not participate much in basal metabolic heat production. We have also found that the HB equation predicts high BMR for fat people and therefore high core and skin temperatures.

Most investigators now believe that the fat-free mass (FFM, or lean body mass) accounts for most of the variance in BMR, both for modern populations and for HB's original data (Cunningham, 1980; Owen et al., 1987). We adopted the Mifflin's model (Table 1) because it is based on FFM and better predicts BMR over a wide range of body fat.

4. *Blood flow rate and body type:* Vasomotor action controls blood flow to the superficial tissues, increasing or decreasing the heat loss of the body to the environment and regulating body temperature. Therefore, accurate prediction of blood flow rate is important in a thermal model of the body. Obese individuals have been shown to have a lower-than-average blood volume per unit weight, whereas thin tall persons have a higher-than-average value (Gregersen and Nickerson, 1950).

Gregersen and Nickerson (1950) measured total blood flow rate (cardiac output) for a number of normal and extreme body types (Table 2). Because classifying these body types required subjective judgement, we defined a relationship between body fat and body type in order to objectively predict blood flow for an individual.

To develop this relationship, we obtained the distribution of %BF for men and women by applying the Durnin's regression equation for body density (1974) to the distribution of arm and intrascalpular skinfold for more than 8000 subjects measured by the US Public

Table 2
Body type and blood flow rate

	Gender	Extreme ectomorph	Ectomorph	Normal	Endomorph	Extreme endomorph	Ref
Cardiac output (cc/min/kg)		90.0	92.0	93.9	69.1	68.0	Gregersen and Nickerson, 1950
Body fat distribution (%)	Men	9.8	13.3	20.9	29.4	34.4	NHS data, 1970
	Women	20.5	25.1	32.1	39.4	43.0	

Health Service (1970). This relationship is shown in Table 2.

5. *Body segment proportion of men and women:* In order to determine the proportions between various body-segment lengths and overall body height, we used detailed body segmentation proportions for 50th percentile adult men and women determined by Tilley and Associates (1993). These proportions are used to get the lengths of segments once the height is known. There are slight differences between men and women in segmentation proportion. Men have a slightly longer chest, calf and foot, while women have slightly longer pelvis region.

6. *Counter-current blood vessel length:* The UCB Physiology Comfort Model simulates the counter-current heat exchanges between the major arteries and veins in the limbs and extremities. These paired blood vessels are assumed to have the same length as their associated segment.

7. *Tissue thermal capacitance and conductance:* The conductivity of fat is about half of that of muscle and core tissues. In the UCB model, fat is concentrated in a layer under the skin, below which are the muscle and core layers, respectively. In *body builder*, the thickness of each tissue layer is obtained from the tissue weight, density, and the length and diameter of the cylindrical segment that the tissue is in.

8. *Surface area:* The surface area of the body is calculated based by the Dubois equation (1927): Area $(\mathrm{m}^2) = 202W\,(\mathrm{kg})^{0.425} \times H\,(\mathrm{m})^{0.725}$.

9. *Skin absorptivity:* The absorptivity of skin varies with skin color in the visible and the near-infrared spectra. Houdas and Ring (1982) provide data for white and black skin absorptivity as a function of wavelength in the spectral bands: ultraviolet, $<0.4\,\mu$; visible light, $0.4–0.7\,\mu$; near infrared, $0.7–2\,\mu$; and far infrared, $>2\,\mu$. For white skin, the absorptivities are: 0.9 (ultraviolet); 0.513 (visible); 0.692 (near infrared); and 0.98 (far infrared). For black skin, they are 0.93 (ultraviolet); 0.737 (visible); 0.777 (near infrared); and 0.98 (far infrared). *Body builder* for now sets brown skin absorptivities midway between those of white and black skin, as suggested by Martin (1930).

10. *Acclimatization and other factors:* It is well known that acclimatization affects thermoregulation (e.g. sweating onset and sweat rate). Acclimatization can increase maximum sweating capacity almost threefold. Fox (1973) found an earlier onset of sweating with acclimatization. Wyndham (1969) did a survey of fatal heat stroke in African gold mines, finding the risk of fatal heat stroke was five times greater in mines not applying acclimatization methods. Havenith (2001) provided equations to account for the impact of acclimatization on sweating threshold, sweating amount and skin blood flow based on the number of acclimation days. The information has not yet been incorporated in *body builder* but will be in the future.

Age is currently considered only indirectly in *body builder*. Body fat and weight have been shown to be correlated with age (Havenith 2001), but our model uses these characteristics as direct inputs.

There are many other factors, such as athletic fitness and the menstrual cycle, that affect thermal responses. We consider our current version of *body builder* a first step and intend to continuously develop it.

3. Applying body builder with the UCB thermal comfort model

In recent years, UC Berkeley has developed a comprehensive human thermoregulatory and comfort model (Huizenga et al., 2000). This model is based on the Stolwijk model of human thermal regulation but includes several significant improvements, including the ability to model unlimited number of body segments (compared to six in the original), and a unique blood flow model including counter-current heat exchange. Clothing heat and moisture transfers are considered. Conduction (such as to a car seat or other surface in contact with any part of the body) is included. Radiative heat transfer is calculated by the view factor method with the body divided into 5500 polygons. It is thus possible to do detailed assessments of complex radiative environments including the effects of solar radiation.

With the addition of *body builder*, individual physiological differences are also considered. The UCB model is capable of predicting physiological response to transient, non-uniform thermal environments and closely reproduces the results of many experiments in the literature.

4. Preliminary comparison of predicted results with measured data

Nishumura et al. (1993) measured skin temperature for two groups of people with different body fat, 10.7% (lean group) and 19.4% (obese group), in order to investigate how body fat affects skin temperatures. The three environmental temperatures were 22°C, 28°C and 34°C. We simulated the experiment based on the published information. The comparisons of the skin temperature for the trunk and the average of the entire body are presented in Fig. 2.

The measured difference in skin temperature for the two groups is 0.5–0.8°C at the environment temperatures 22°C and 28°C. This difference is also shown in the simulations. At the higher environmental temperature of 34°C, the measured difference of skin temperature for the two groups is 0.3–0.7°C, however, the simulated skin temperatures for the two groups are much closer. Vasodilation at the higher temperature causes blood flow to bypass the insulation of the fat layer; our model appears to over-predict this effect.

Hardy and Stolwijk (1966) present average skin and core temperatures for three male subjects exposed to a step change test from 43°C to 17°C to 43°C. The three subjects were similar in stature, tall and slender. We estimated their body fat based on individual information for height and weight and did the simulations for the three subjects. The result is shown in Fig. 3. The average skin temperature at the end of 2 h exposure in 17°C is 0.45°C lower for the subject with 17% BF comparing with the subject with 12% BF. Because the simulated core temperatures for the three subjects are very close, we present an average result.

Hardy and Stolwijk (1966) also provided skin, tympanic and rectal temperatures for eight subjects under stable conditions covering air temperature from 12°C to 48°C. We have individual information of height and weight for six subjects with which we estimated the lowest body fat at 9% and the highest body fat at 32%. The measured skin and tympanic temperatures and simulated data for 9% and 32% BF are also presented in Fig. 3. Many measured skin temperatures are within the range of simulated skin temperatures for 9% and 32% BF. However, the simulated tympanic temperatures are close for both people with these different body fat values. The simulated tympanic temperature does not show as much variation as measured data.

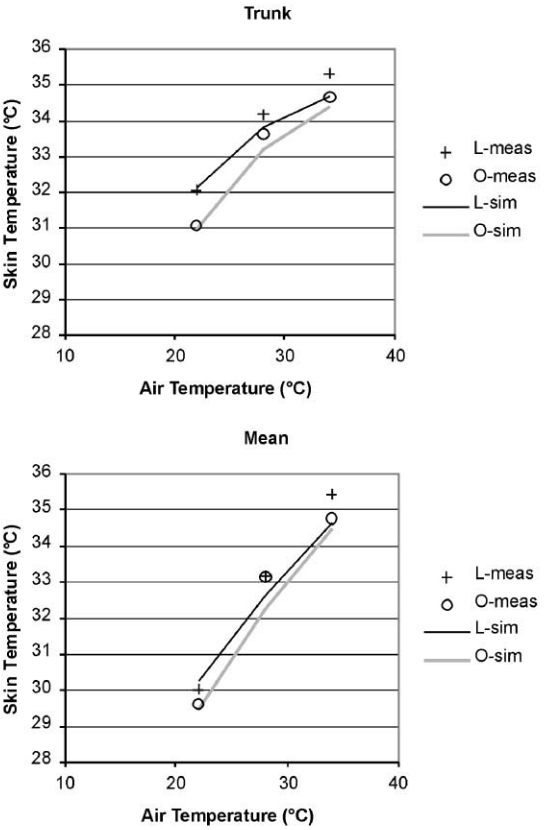

Fig. 2. Comparison of lean and obese subjects' skin temperatures, from measurement (Nishumura et al., 1993) and simulation.

Tikuisis et al. (1991) presented rectal and chest skin temperatures for lean (8.5% BF) and normal (17.9% BF) groups during cold exposure at air temperature 10°C. The measured data is compared with simulated data and the results are presented in Fig. 4. The simulated final skin temperatures are very close to the measured data. However, the simulation does not respond as fast as measured chest skin temperature during the transient process. Both the measured and simulated results show that the normal body fat group has lower skin temperature but higher rectal temperature than the lean body fat group. The differences in rectal temperature are much smaller than in skin temperature.

5. Future work

Our present work has focused on the thermal effects of individual differences. We would like to extend this work to examine the impact of these differences on thermal comfort. To what extent do individual

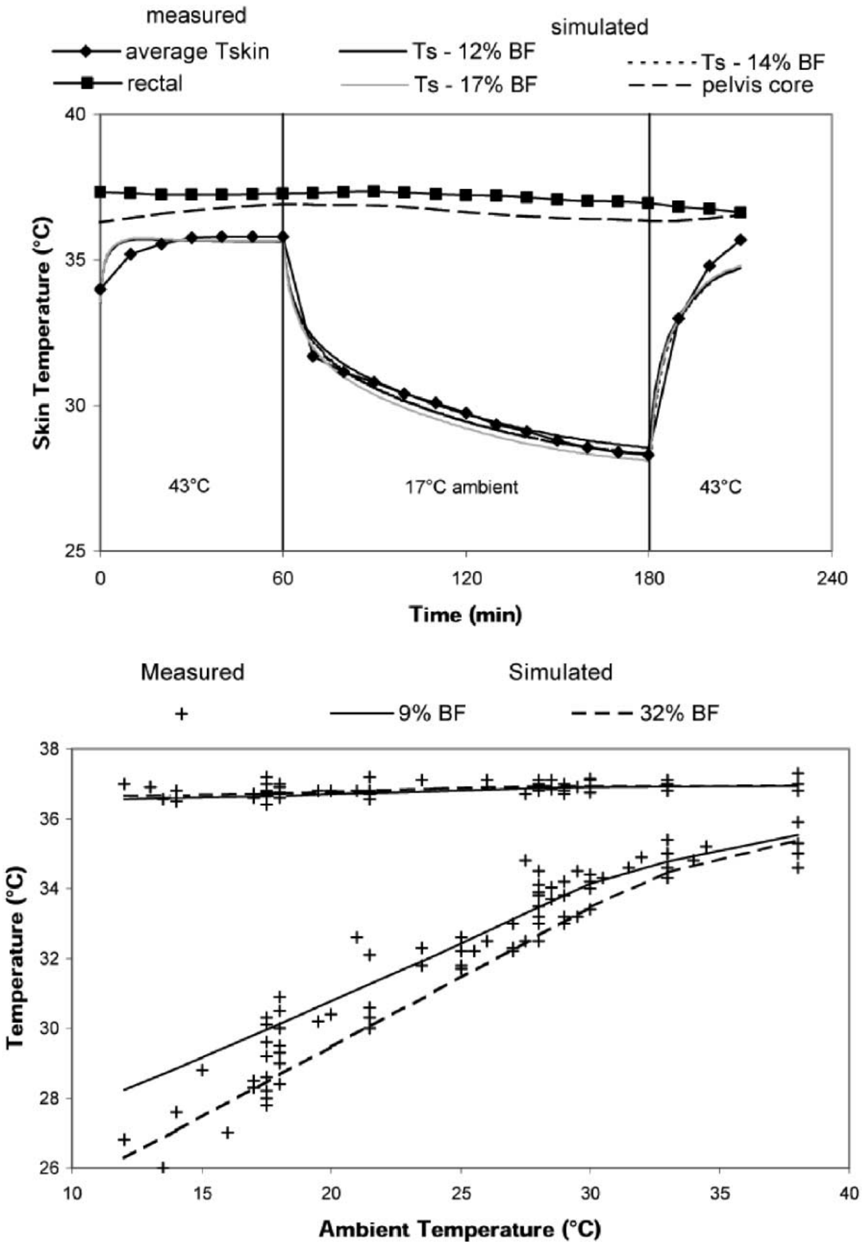

Fig. 3. Comparison of measured (Hardy and Stolwijk, 1966) and simulated skin and rectal temperatures during cold step change and under stable conditions.

physiological differences explain differences in perceived thermal comfort? If differences such as the skin temperature do exist for people with different physiologies, the resulting output from thermal receptors could certainly yield a different perception of the thermal environment.

At this point, the UC Berkeley thermal comfort model has incorporated the *body builder* function. Over time, we intend to incorporate alternative ways of predicting thermophysiological variables found in the literature. We also need to examine the *comfort* implications of body build, via human subject tests. If we find differences in comfort resulting from differences in physiology, we will need to include them in our comfort prediction model so that it not only predicts individual thermophysiology, but also individual thermal comfort response.

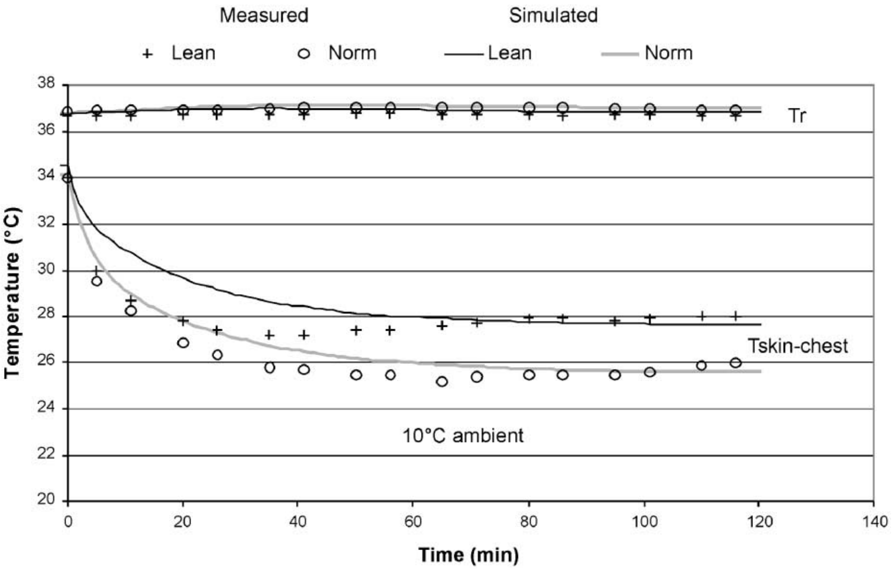

Fig. 4. Comparison of measured (Tikuisis et al., 1991) and simulated skin and rectal temperatures for lean and normal subjects under cold exposure.

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