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Prediction of the average skin temperature in warm and hot environments

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Abstract The prediction of the mean skin temperature used for the Required Sweat Rate index was criticised for not being valid in conditions with high radiation and high humidity. Based on a large database provided by 9 institutes, 1999 data points obtained using steady-state conditions, from 1399 experiments and involving 377 male subjects, were used for the development of a new prediction model. The observed mean skin temperatures ranged from 30.7 °C to 38.6 °C. Experimental conditions included air temperatures (T_a) between 20 and 55 °C, mean radiant temperatures (T_r) up to 145 °C, partial vapour pressures (P_a) from 0.2 to 5.3 kPa, air velocities (v_a) between 0.1 and 2 m/s, and metabolic rates (M) from 102 to 620 W. Rectal temperature (T_{re}) was included in the models to increase the accuracy of prediction. Separate models were derived for nude (clothing insulation, I_{cl}, $\leq$0.2 clo, where $1\ \text{clo} = 0.155\ \text{m}^2 \cdot {}^\circ\text{C} \cdot \text{W}^{-1}$, which is equivalent to the thermal insulation of clothing necessary to maintain a resting subject in comfort in a normally ventilated room, air movement = 10 cm/s, at a temperature of 21 °C and a humidity of less than 50%) and clothed ($0.6 \leq I_{cl} \leq 1.0$ clo) subjects using a multiple linear regression technique with re-sampling (non-parametric bootstrap). The following expressions were obtained for nude and clothed subjects, respectively: $T_{sk} = 7.19 + 0.064T_a + 0.061T_r + 0.198P_a - 0.348v_a + 0.616T_{re}$ and $T_{sk} = 12.17 + 0.020T_a + 0.044T_r + 0.194P_a - 0.253v_a + 0.0029M + 0.513T_{re}$. For the nude and clothed subjects, 83.3% and 81.8%, respectively, of the predicted skin temperatures were within the range of ±1 °C of the observed skin temperatures. It is concluded that the proposed models for the prediction of the mean skin temperature are valid for a wide range of warm and hot ambient conditions in steady-state conditions, including those of high radiation and high humidity.

Key words Skin temperature · Heat stress · Thermal indices · Prediction model · Bootstrap

Introduction

Thermal equilibrium in the human body is achieved through a balance between metabolic heat production and heat loss from the body. Body heat storage will result in an increase in the average body temperature, which is a weighted combination of the core temperature and mean skin temperature (T_{sk}). Changes in the T_{sk} will elicit thermoregulatory responses such as increased skin blood flow through vasodilatation, and will influence the heat exchanges through convection, radiation and evaporation between the human body and the environment. As temperatures vary across the surface of the skin, a mean T_{sk} is commonly calculated by a weighted average of local T_{sk} values. Many different methods have been proposed for this weighting scheme, and ISO 9886 (1992) defines schemes using 4, 8 and 14 local temperatures.

Heat stress indices based on the heat balance equation use either a fixed mean T_{sk} or a prediction model that incorporates some or all physical factors of the thermal environment as well as the clothing insulation and the metabolic rate. The Heat Stress Index (Belding and Hatch 1956) and the Index of Thermal Stress

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(Givoni 1969) use a fixed mean T_{sk} of 35 °C. In situations with intermittent exposure to heat, this can result in severe over- or under-estimations in the heat balance equation (Mairiaux et al. 1986). Many different prediction models have been proposed (Givoni 1967; Hettinger et al. 1986; Missenard 1973). The model used for the Required Sweat Rate index (ISO 7933 1989) was considered to offer the best prediction so far, since it is valid for a wide range of conditions (Mairiaux et al. 1987). This model, however, was criticised for not being valid in conditions of high radiation and high humidity (Mairiaux and Malchaire 1995). Kampmann et al. (1992) showed that this expression was too inaccurate and proposed to include a non-linear interaction term within the convective heat transfer.

The aim of the present paper is to improve the prediction model using a very large database. The study was part of a concerted action in the frame of the BIOMED 2 research programme, and was conducted in co-operation with nine research teams across Europe.

Methods

The basic idea of the project was to use the data that originated from different laboratory and field studies carried out by the partners. The results of these studies have been published elsewhere (Griefahn 1997; Havenith et al. 1995a, b; Hettinger et al. 1991; Holmer et al. 1992; Kaiser 1997; Mairiaux and Malchaire 1995), and details of the experimental procedures applied can be found in the referenced papers. Due to the specific aims of the single studies, not all of these involved exactly the same methods. For example, the laboratory experiments were performed on either a treadmill or on a cycle ergometer, sometimes involving rest periods spent sitting, and not all laboratory experiments involved the measurement of oxygen uptake. The evaluation of clothing insulation was performed according to the ISO standard, or according to what later became the ISO standard.

A common structure was defined so that all of the different data available from the partners could be pooled into one database. All data files included minute-by-minute values of ten parameters of stress and strain: air temperature (T_a, °C), humidity (P_a, kPa), radiant temperature (T_r, °C), air velocity (v_a, ms^{-1}), metabolic rate (M, W), clothing insulation (I_{cl}, clo, where $1\ \text{clo} = 0.155\ \text{m}^2 \cdot °\text{C} \cdot \text{W}^{-1}$, which is equivalent to the thermal insulation of clothing necessary to maintain a resting subject in comfort in a normally ventilated room, air movement = 10 cm/s, at a temperature of 21 °C and a humidity of less than 50%), posture, mean T_{sk} and rectal (T_{re}, °C) temperatures, and sweat loss. A total of 1113 files were gathered (the HEAT database).

Selection of the database

The development of the prediction model required the building of a subset of the HEAT database (the TSK database), which included data that originated only from laboratory experiments. Posture and sweat loss were not taken into account. Using a special graphics program, data points obtained in steady-state conditions were selected from each experiment, based on the following criteria:

1. Steady-state conditions: at least 15 min after any variation of any of the primary parameters (T_a, T_r, v_a, P_a, M, I_{cl}).
2. A minimum of 30 min between two consecutive points from the same experiment to ensure sufficient independency of the values.
3. Randomisation in the selection in order to increase the probability of meeting all possible combinations of the different parameters (in particular for T_{sk}, T_{re} and M), and therefore to minimise the correlation between the independent variables.
4. Exclusion of conditions where the initial value of the core temperature was above 38 °C.
5. Exclusion of conditions in which $T_a \leq 15$ °C.
6. Exclusion of conditions in which $T_{sk} > (T_{re} + 0.5\ °\text{C})$.

Each data record in this subset included the values of the primary parameters (T_a, T_r, v_a, P_a, M, I_{cl}), the observed mean T_{sk} and the observed T_{re}. The TSK database was expanded with other data from laboratory experiments (Forsthoff and Neffgen 1996; Kampmann et al. 1992) lasting 3 h each, which could not be included in the HEAT database since the minute-by-minute values of the primary parameters were not available. They represented mean values of those obtained during the last 30 min of the experiments.

Since few data (less than 10%) were available for women, it was decided to derive the T_{sk} prediction model by using only the data from studies on men. Accordingly, the final TSK database included 1999 data points from 1399 experiments involving 377 male subjects.

The data for nude and clothed subjects were initially treated together in the statistical analysis. It became obvious, however, that the model in this case gave poor predictions, due to the fact that no data were available in the range of I_{cl} values between 0.2 and 0.6 clo. It was therefore decided to separate the TSK database into two subsets, which included 1212 data points for nude subjects ($I_{cl} \leq 0.2$ clo) and 787 data points for clothed subjects ($0.6\ \text{clo} \leq I_{cl} \leq 1.0$ clo). In the subsequent sections we will refer to the subsets "1212 or 787 data points coming from experiments with nude or clothed subjects" simply as the subsets for "nude subjects" or "clothed subjects", respectively.

Each observed mean value for T_{sk} in the TSK database represents a weighted average of 4, 6 or 8 local T_{sk} measurements. In 582 cases (29%), 4 local measurements were used to calculate mean T_{sk} either by referring to Ramanathan's formula (Ramanathan 1964) or using a weighting scheme related to body surface area. A total of 880 (44%) mean values for T_{sk} were determined based on 6 local measurements and averaged according to body surface area. The remaining 537 (27%) mean values for T_{sk} were calculated from 8 local measurements and weighted according to ISO 9886 (1992).

Statistical analysis

The relationship between the mean T_{sk}, the primary parameters, M, and T_{re} was assumed to be represented by an additive model. A multiple linear regression approach was used for the development of the model. A model derived from multiple regression is optimum for the database from which it was derived, but the goodness of prediction may decrease for a different database. If only a small number of data points is added or removed, the regression coefficients or the parameters included in the model may change. The first attempt to avoid involved randomly splitting the database into two subsets for modelling and validation. A different approach would involve using a re-sampling technique such as the non-parametric bootstrap method (Efron and Tibshirani 1993). This type of method overcomes possible violations of implicit statistical assumptions, and achieves a result that is more independent of the database. This re-sampling approach only assumes that the errors are independent. This offers the advantage of robustness to violations of the normality of the error distribution or to heteroscedasticity (non-constant variance). Since the aim of the statistical analysis was not only to obtain estimates of the regression coefficients, but also of their standard errors, this modern statistical approach was particularly relevant.

The bootstrap method described above was used for the multiple regression analysis. A total of 1000 new samples with replacements were drawn from each subset (nude and clothed subjects). The multiple regression was calculated using each of the samples, yielding bootstrap distributions of the regression coefficients for nude and clothed subjects accordingly. The means and standard errors were computed from these distributions.

In multiple linear regression analysis, residuals are usually used for checking model adequacy. However, these residuals are strictly measures of the quality of fit and do not assess the quality of future prediction. Therefore, it may be desirable to have a set of residuals that simulate the conditions under which the model will perform (i.e. for the present models):

$$r(j) = t_{sk\ pred}(j) - t_{sk\ obs}(j) \quad (j = 1, 2, \ldots, n) \tag{1}$$

which can be rewritten as:

$$t_{sk\ obs}(j) = t_{sk\ pred}(j) - r(j) \quad (j = 1, 2, \ldots, n) \tag{2}$$

Assuming independency, which is justified in the present approach by applying the bootstrap procedure, the error in Eq. 1 is truly a prediction error. Calculating a simple linear regression for Eq. 2 offers on one hand the possibility of testing the linear hypotheses that the corresponding slope and intercept are equal to 1 and 0, respectively. On the other hand, the values for the slope and intercept can be used for assessing the quality of prediction.

Results

Descriptive statistics

Table 1 gives the main characteristics (means and standard deviations) of the subjects involved in the studies included in the TSK database. Although this sample is rather young on average, it covers the ranges of age, body mass and height of the general working population.

Figure 1 shows, for each primary parameter, the frequency distribution of the parameter separately for both subsets. The range of conditions is rather broad and includes high values for T_r, P_a and v_a.

Major differences between the two subsets are found for T_a, P_a and M. The range of the mean T_r is larger for the clothed subjects. The observed mean T_{sk} values are, on average, higher for nude subjects [mean (SD) 35.8 (1.4)°C, range: 30.7–38.5 °C] than for clothed subjects [35.2 (1.2)°C, range: 31.1–38.6 °C]. No obvious

Table 1 Individual characteristics of the subjects (n = 377)

Characteristic	Mean	SD	Minimum	Maximum
Age (years)	28.1	10.3	19	59
Body mass (kg)	74.3	9.2	52.0	104.6
Height (cm)	179.9	6.5	162.0	194.0
Body surface area (m^2)	1.93	0.13	1.54	2.25

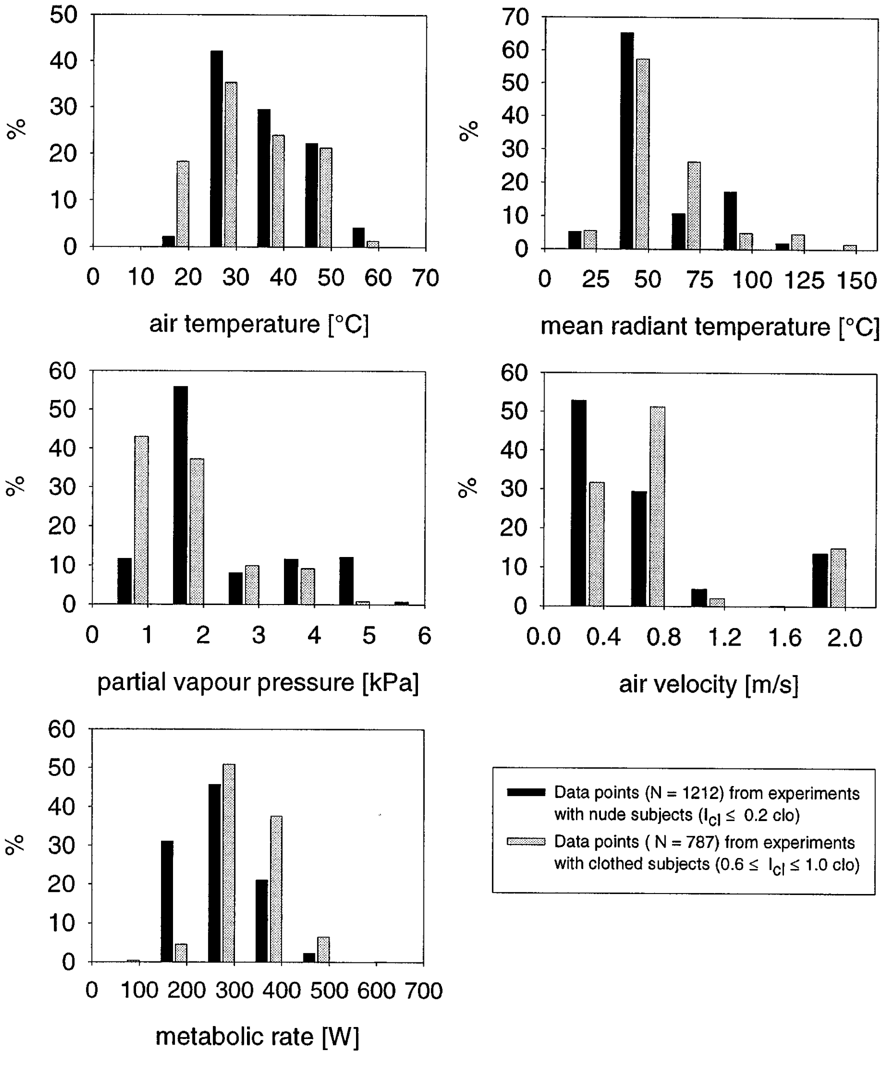


Fig. 1 Frequency distribution of the primary parameters of all experiments in the TSK database separately for the subsets of nude (1212 data points coming from experiments with a clothing insulation, I_{cl}, value of ≤0.2; *black bars*) and clothed (787 data points obtained from experiments for which 0.6 ≤ I_{cl} ≤ 1.0; *grey bars*) subjects

difference was found for the observed mean T_{re}, which was equal to 37.5 (0.4)°C in both subsets.

Pearson correlation coefficients (R) between all pairs of independent variables were calculated in order to take into account a possible problem of multicollinearity for the subsequent multiple regression analysis. Although some of the correlations became statistically significant, only two correlation coefficients were greater than 0.45 (25% of the variance). The higher values of R were observed between:

1. T_r and P_a ($R = -0.43$) for nude subjects: the database includes a lot of points obtained under conditions of high T_r and low T_a and P_a, but no data from conditions with high T_r and high P_a.
2. T_r and v_a ($R = 0.48$) for clothed subjects: the range of v_a was rather small (0.1–2 m/s) compared to the range of T_r (14–145 °C), and most of the conditions with high T_r involved high values for v_a.

Prediction of mean T_{sk}

Nude subjects

A first bootstrap analysis showed that M was not a significant predictor ($P > 0.05$) for mean T_{sk}. Therefore, the analysis was repeated without this parameter. The estimates of the regression coefficients and their standard errors are given in Table 2. All other independent variables contribute significantly ($P < 0.05$) to the prediction of the T_{sk}, and the prediction model is:

$$\mathrm{t_{sk}} = 7.19 + 0.064\ \mathrm{t_a} + 0.061\ \mathrm{t_r} + 0.198\ \mathrm{pa} - 0.348\ \mathrm{v_a} + 0.616\ \mathrm{t_{re}} \quad (3)$$

Figure 2 compares the observed and predicted values for T_{sk}. The corresponding regression equation is:

$$\mathrm{t_{sk\ obs}} = 1.02\ \mathrm{t_{sk\ pred}} - 0.65 \qquad (\mathrm{R} = 0.86) \quad (4)$$

and the multiple correlation coefficient between observed and predicted values for T_{sk} is equal to 0.86. The intercept and the slope in Eq. 3 do not differ significantly from 0 and 1, respectively ($P = 0.287$ and $P = 0.156$, respectively). The figure suggests a slight over-estimation for a few (2.8%) observed values for T_{sk} below 36 °C. But for higher observed values of T_{sk}, which reflect a greater thermal strain, the prediction is within the 95% confidence interval. Of the predicted values for T_{sk}, 83.3% are within the range of ±1 °C of the observed values, and 95.7% are within ±1.5 °C.

Table 2 Means and standard errors of the regression coefficients for nude (1212 data points obtained from experiments with a clothing insulation, I_{cl}, value of ≤0.2) and clothed subjects (787 data points obtained from experiments for which $0.6 \le I_{cl} \le 1.0$). (T_a Air temperature, T_r radiant temperature, P_a vapour pressure, v_a air velocity, M metabolic rate, T_{re} rectal temperature)

Parameter	Nude subjects		Clothed subjects	
	Coefficient	Standard error	Coefficient	Standard error
Intercept	7.191	1.9387	12.165	3.0631
T_a (°C)	0.064	0.0033	0.020	0.0037
T_r (°C)	0.061	0.0011	0.044	0.0016
P_a (kPa)	0.198	0.0191	0.194	0.0311
v_a (m/s)	−0.348	0.0381	−0.253	0.0564
M (W)			0.0029	0.0004
T_{re} (°C)	0.616	0.0530	0.513	0.0828

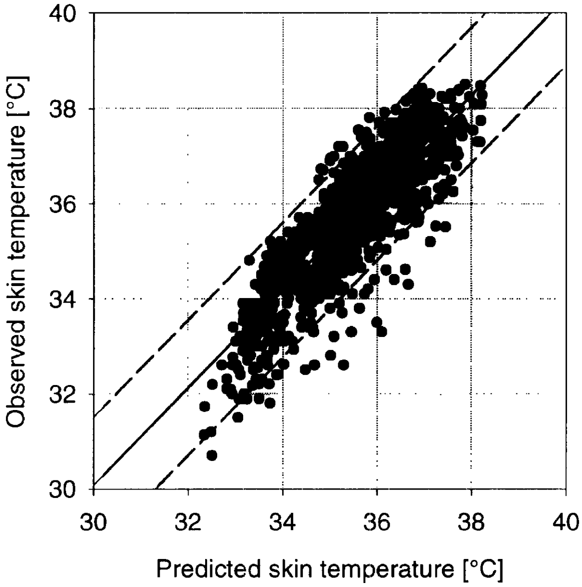


Fig. 2 Regression between observed and predicted mean skin temperatures and the 95% confidence interval (nude subjects: 1212 data points obtained from experiments for which $I_{cl} \le 0.2$)

Clothed subjects

Table 2 gives the results of the bootstrap procedure for the clothed subjects. M contributed significantly, and the final model is:

$$\mathrm{t_{sk}} = 12.165 + 0.020\ \mathrm{t_a} + 0.044\ \mathrm{t_r} + 0.194\ \mathrm{p_a} - 0.253\ \mathrm{v_a} + 0.0029\ \mathrm{M} + 0.513\ \mathrm{t_{re}} \quad (5)$$

Figure 3 illustrates the relationship between observed and predicted values for T_{sk}, and the 95% confidence interval. The regression equation is:

$$\mathrm{t_{sk\ obs}} = 0.99\ \mathrm{t_{sk\ pred}} + 0.33 \qquad (\mathrm{R} = 0.77) \quad (6)$$

with a multiple correlation coefficient between the observed and predicted T_{sk} equal to 0.77. The intercept and slope in Eq. 6 show no significant deviation from 0 to 1, respectively ($P = 0.753$ and $P = 0.727$, respectively). Although the correlation coefficient is lower than for the nude subjects, 81.8% and 94.8% of the predicted values are within the range of ±1 °C and ±1.5 °C of the observed values, respectively.

Conditions of high T_r and high P_a

The ISO 7933 T_{sk} prediction model (1989) was restricted to climates where the mean T_r exceeded only slightly the

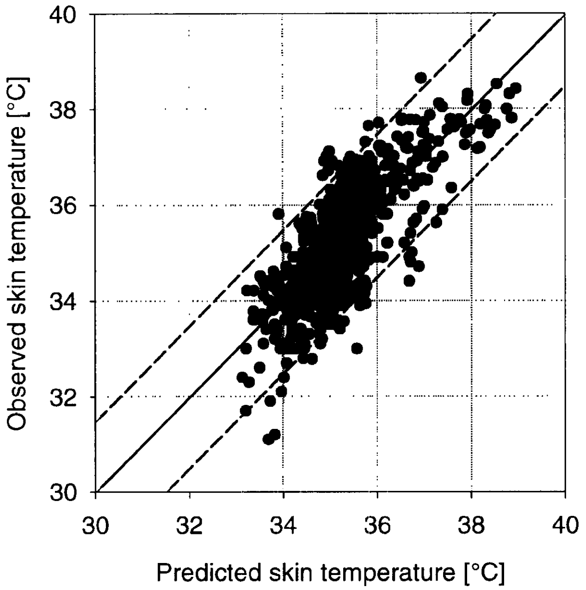


Fig. 3 Regression between observed and predicted mean skin temperatures and the 95% confidence interval (clothed subjects: 787 data points obtained from experiments for which $0.6 \leq I_{cl} \leq 1.0$)

T_a (Mairiaux and Malchaire 1995; Mairiaux et al. 1987). The present model extends to situations with a high T_r, as illustrated in Fig. 4. For both data subsets, climatic conditions with and without additional radiation were separated, and the correlation coefficients as well as the simple linear regression between predicted and observed values for T_{sk} were calculated. The regression equations and the correlations are:

nude subjects:

$$t_{sk\,obs} = 1.06\ t_{sk\,pred} - 2.02 \quad (R = 0.84) \quad \text{if } t_r = t_a \quad (7)$$

$$t_{sk\,obs} = 0.75\ t_{sk\,pred} + 9.45 \quad (R = 0.76) \quad \text{if } t_r > t_a \quad (8)$$

clothed subjects:

$$t_{sk\,obs} = 1.11\ t_{sk\,pred} - 4.07 \quad (R = 0.67) \quad \text{if } t_r = t_a \quad (9)$$

$$t_{sk\,obs} = 0.88\ t_{sk\,pred} + 4.22 \quad (R = 0.78) \quad \text{if } t_r > t_a \quad (10)$$

Apart from Eq. 9, the slopes and intercepts differ significantly from 1 and 0, respectively. In conditions with no additional radiant heat load, a tendency to over-estimate the observed mean T_{sk} is present in both subsets, whereas a minor under-estimation is to be seen in the other conditions with additional heat radiation.

A similar analysis was carried out for evaluating the effects of P_a on the mean T_{sk} (Fig. 5), as the validity of the prediction model used in ISO 7933 (1989) was questioned in conditions of high P_a. The subsets for nude and clothed subjects were divided into two groups for P_a values lower than, or equal to and greater than 2 kPa. The results of the regression analysis are:

nude subjects:

$$t_{skobs} = 1.01\ t_{skpred} - 0.08\ (R = 0.89) \text{ if } p_a \leq 2\text{ kPa} \quad (11)$$

$$t_{skobs} = 1.10\ t_{skpred} - 3.59\ (R = 0.76) \text{ if } p_a > 2\text{ kPa} \quad (12)$$

clothed subjects:

$$t_{skobs} = 0.95\ t_{skpred} + 1.69\ (R = 0.80) \text{ if } p_a \leq 2\text{ kPa} \quad (13)$$

$$t_{skobs} = 1.45\ t_{skpred} - 15.84\ (R = 0.71) \text{ if } p_a > 2\text{ kPa} \quad (14)$$

Under drier conditions (Eqs. 11 and 13), the slope and intercept did not differ significantly from 1 and 0, respectively, for both subsets. This is in contrast to ambient conditions with a humidity level above 2 kPa, where the poorest prediction and lowest correlation was found for clothed subjects (Fig. 5b).

Discussion

The purpose of this study was to derive an improved model for the prediction of mean T_{sk} in warm and hot environments. The resulting models are based on the largest database ever assembled for this purpose, provided by nine research laboratories all over Europe. The database covers a wide range of ambient conditions and it can therefore be anticipated that the models will be valid for most situations in industry and for the general working population.

The methods used by the various laboratories to compute mean T_{sk} differed in the number of measurement points used, their locations, and the weighting schemes used. This should not limit the validity of the prediction model since all of these weighting schemes were validated for warm and hot ambient conditions. However, some experiments used for the TSK database were carried out in climates with a T_a below 20 °C, and Mitchell and Wyndham (1969) have shown that the accuracy of prediction of different weighting formulae decreases as T_a decreases. Nielsen and Nielsen (1984) have compared 11 weighting formulae for a cool environment ($T_a = 10$ °C), and have concluded that at least 7 local T_{sk} measurements are necessary to give a reasonably accurate estimate of the mean T_{sk}. An analysis of the TSK database revealed that 170 out of 1999 data points (8.5%) came from experiments with T_a values equal to or below 20 °C, and that these data points refer mainly to experiments with clothed subjects (85%). Moreover, most of these experiments (93%) were carried out in climates with additional heat radiation where, on average, the mean T_r was 45.6 °C higher than the corresponding T_a. It is therefore concluded that data points coming from experiments carried out in cool environments are represented only marginally in the TSK database, and thus may not have influenced the development of the prediction models significantly.

The comparison between the two models for nude and clothed subjects shows that clothing decreases the influence of the T_a and mean T_r as well as the influence of the v_a. This may be because the dry heat exchanges are reduced. On the contrary, the influence of the level of humidity remains approximately the same, probably due

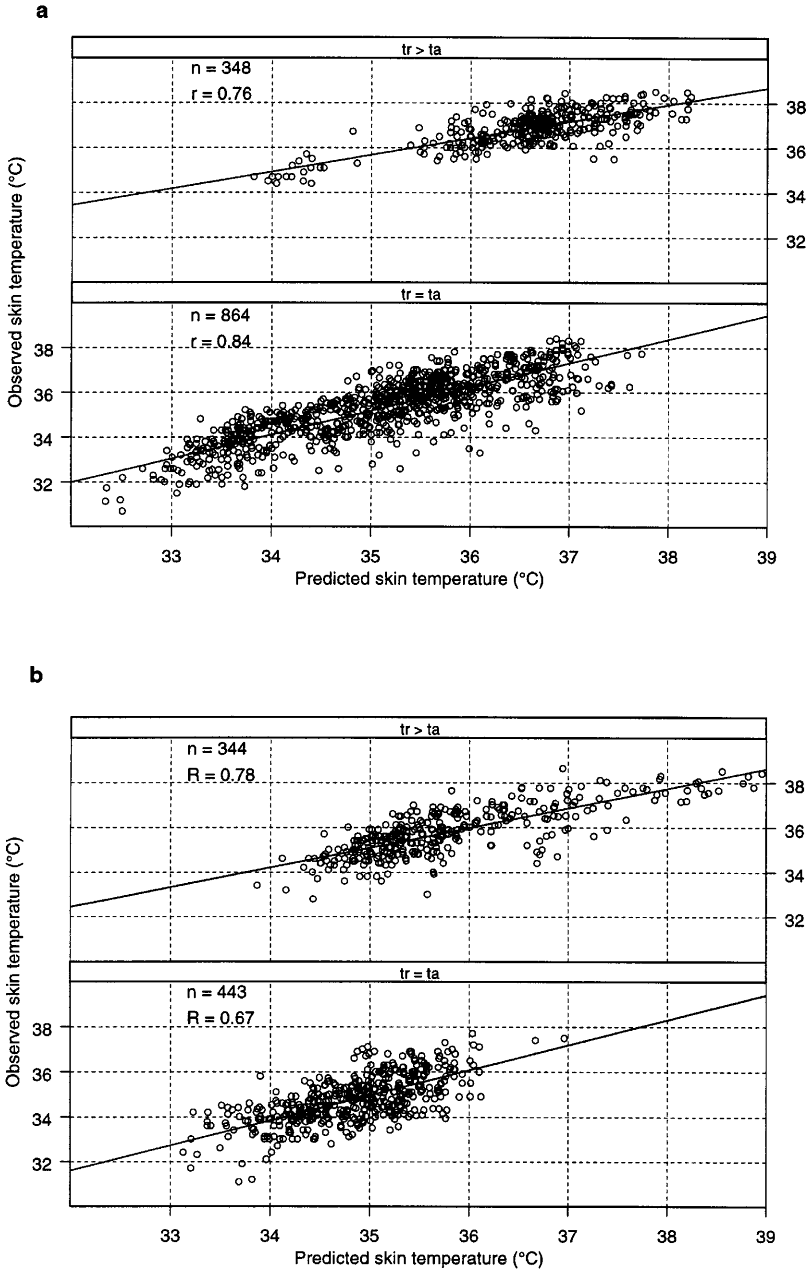


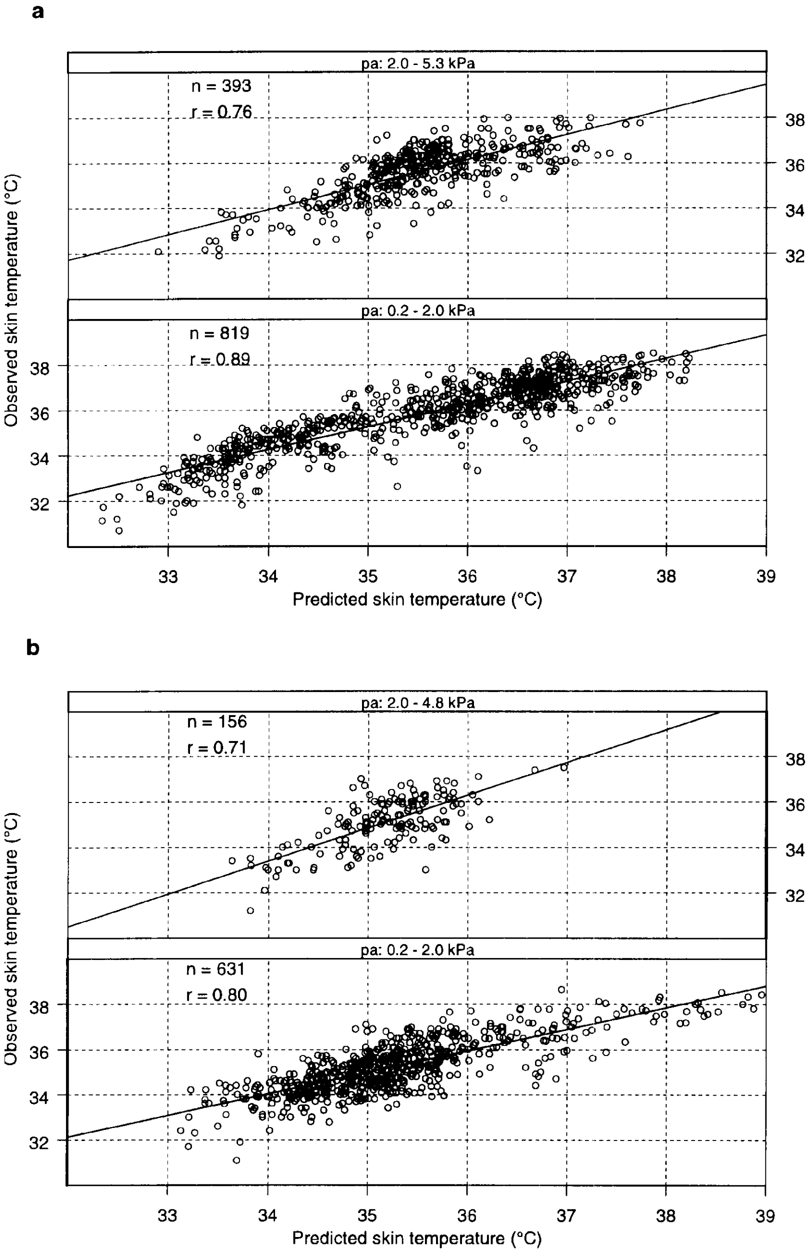
Fig. 4a–b Correlation coefficients and regression lines between observed and predicted skin temperatures separately for climatic conditions without and with additional radiation.
a Nude subjects: 1212 data points obtained from experiments for which $I_{cl} \leq 0.2$.
b Clothed subjects: 787 data points obtained from experiments for which $0.6 \leq I_{cl} \leq 1.0$). (T_r Radiant temperature, T_a air temperature)

to the fact that normal cotton clothes were used in all of the reported studies.

The value of M is a significant predictor for the T_{sk} for clothed, but not for nude subjects. Contradictory results have been reported concerning the influence of M on mean T_{sk}. A decrease in T_{sk} with higher values of M was reported by Hettinger et al. (cited in Peters 1995), whereas others found no relationship between these parameters (Mairiaux et al. 1987). With respect to thermal comfort, Fanger (1970) assumed a decreasing mean T_{sk} with increasing activity level, whereas Nielsen and Nielsen (1965) found no relationship when different work intensities were performed at the same environmental temperature. A reason for this difference is likely to be the correlation between T_{re} and M observed in the present analysis in the data for the nude subjects ($R = 0.22$, $P < 0.05$) and not for the clothed subjects. The influence of M is then likely to be carried by T_{re}. Indeed, M was a statistically significant factor when T_{re} was not taken into account in the model.

The models clearly show an improvement of the prediction accuracy when T_{re} is included. Such an inclusion is justified physiologically, at least for warm and hot environments, because through thermoregulatory mechanisms, the core temperature and T_{sk} are related to each other. This relationship is considered in many models of human thermoregulation (Haslam and Parsons 1994; Havenith 1997; Werner 1989). According to Eqs. 3 and 5, the present prediction models show that, in a given work situation, an increase of 1 °C in T_{re} would

Fig. 5a–b Correlation coefficients and regression lines between observed and predicted skin temperatures separately for climatic conditions with a partial vapour pressure (P_a) lower than and greater than or equal to 2 kPa. **a** Nude subjects: 1212 data points obtained from experiments for which $I_{cl} \leq 0.2$. **b** Clothed subjects: 787 data points obtained from experiments for which $0.6 \leq I_{cl} \leq 1.0$



result in a rise of the mean T_{sk} by 0.6 °C for nude and 0.5 °C for clothed subjects.

To assess the predictive power of the two models, they were each applied to both data subsets and also to the entire TSK database. The correlation coefficients between the observed and predicted values of T_{sk} are given in Table 3.

Applying the model derived from the subset of the nude subjects to the data of the clothed subjects results in a lower correlation coefficient compared to the subset of the nude subjects. An analysis of the residuals reveals a systematic over-estimation of the observed values of T_{sk} by this model, which can be explained by the fact that clothing reduces the effects of T_a and mean T_r. The model derived from the clothed subjects agrees comparably well with the other data sets; the correlation even increases for the subset of the nude subjects.

The question remains as to whether the prediction models derived above represent an improvement compared to the current model used in ISO 7933 (1989). In order to check this, T_{sk} was predicted for each subset and for the whole database, using this last model. The correlation coefficients obtained using the ISO formula (Table 3) are considerably smaller than those obtained using the new expressions, particularly for clothed subjects. The residual variances are also larger, with only 72.1% (nude subjects) and 62.1% (clothed subjects) of the predicted values within ±1 °C of the observed values. The fact that using the ISO expression, the prediction for the nude subjects is much better than for

Table 3 Pearson correlation coefficients between observed and predicted mean skin temperatures (nude subjects: 1212 data points obtained from experiments for which $I_{cl} \leq 0.2$; clothed subjects: 787 data points obtained from experiments for which $0.6 \leq I_{cl} \leq 1.0$; all subjects: 1999 data points), based on the new prediction models and on the one used for ISO 7933 (1989)

Prediction model	Nude subjects	Clothed subjects	All subjects
Nude subjects	0.86	0.72	0.81
Clothed subjects	0.82	0.77	0.78
ISO 7933	0.75	0.56	0.69

clothed ones confirms the limitations already mentioned by Mairiaux et al. (1987).

The relevance of the new expressions can also be tested by comparison with a fixed value of 36 °C for the mean T_{sk}. The average observed T_{sk} in the present entire data set ($n = 1999$) was equal to 35.6 °C, which is rather close to this fixed value. However, the observed values ranged from 30.7 °C to 38.6 °C, and only 50.5% of the observed values were between 35 °C and 37 °C. Since the highest temperatures are observed in the more severe exposure conditions, the under-estimation of T_{sk} encountered when using the fixed value would clearly lead to errors in heat balance calculations, particularly in the evaluation of body heat storage. Since higher values than 36 °C occur rather often, and not only in exceptional cases, as stated by Peters (1995), this could lead to frequent under-estimation of the heat strain, and thus to over-exposure of the workers.

In addition to the parameters discussed above, several other factors have obviously contributed to the differences between observed and predicted values for T_{sk}. Individual factors such as age, gender, physical fitness, skinfold thickness and the state of acclimation were not considered here. This was done deliberately, since the models had to be used in the context of thermal indices for the prediction of strain for an average subject. However, it must be stated that these expressions are only valid for male subjects. How far these can be extended for women remains to be investigated.

The present prediction models will be included in the revision and improvement of ISO standard 7933 (1989). Since few data are currently available in the database for clothing insulation values in the range 0.2–0.6 clo, a linear interpolation between the prediction for nude and for clothed subjects will be used.

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