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ORIGINAL PAPER

Prediction of human core body temperature using non-invasive measurement methods

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Abstract The measurement of core body temperature is an efficient method for monitoring heat stress amongst workers in hot conditions. However, invasive measurement of core body temperature (e.g. rectal, intestinal, oesophageal temperature) is impractical for such applications. Therefore, the aim of this study was to define relevant non-invasive measures to predict core body temperature under various conditions. We conducted two human subject studies with different experimental protocols, different environmental temperatures (10 °C, 30 °C) and different subjects. In both studies the same non-invasive measurement methods (skin temperature, skin heat flux, heart rate) were applied. A principle component analysis was conducted to extract independent factors, which were then used in a linear regression model. We identified six parameters (three skin temperatures, two skin heat fluxes and heart rate), which were included for the calculation of two factors. The predictive value of these factors for core body temperature was evaluated by a multiple regression analysis. The calculated root mean square deviation (rmsd) was in the range from 0.28 °C to 0.34 °C for all environmental conditions. These errors are similar to previous models using non-invasive measures to predict core body temperature. The results from this study illustrate that multiple physiological parameters (e.g. skin temperature and skin heat fluxes) are needed to predict core body temperature. In addition, the physiological measurements chosen in this study and the algorithm defined in this work are potentially applicable as real-time core body temperature monitoring to assess health risk in broad range of working conditions.

Keywords Core body temperature · Skin temperature · Heat flux · Heat stress

Introduction

Human beings have to maintain thermal homeostasis to ensure optimal performance. When working or exercising in hot conditions, heat generated often exceeds heat loss, which disturbs the thermal balance (Brotherhood 2008; Taylor 2006). The accumulation of heat raises the core body temperature and leads to hyperthermia. In such a state, physiological (Cheuvront et al. 2010) as well as cognitive (Nybo 2008) performance may be decreased. Any further rise in core body temperature, particularly in combination with dehydration, increases the risk of suffering exertional heat stroke (Bouchama and Knochel 2002; Armstrong et al. 2007). Early detection of core body temperature gain is key to the implementation of suitable strategies (i.e. cooling) to avoid exertional heat stroke (Epstein and Roberts 2011). The validity, sensor requirements, and application issues of measuring core body temperature at various sites have been reviewed previously (Lim et al. 2008; Togawa 1985; Wartzek et al. 2011; Moran and Mendal 2002; Pusnik and Miklavec 2009). However, on the one hand, existing methods are invasive (inserting rectal or oesophageal temperature probes, etc.) and not convenient for long-term monitoring due to subject discomfort. On the other hand, the

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application of non-invasive measurement methods (tympanic membrane, oral, axillary) have demonstrated only limited accuracy for use in working environments. Furthermore, the telemetric pill is not applicable in daily use or as an operation deployment in response to an emergency due to the uncontrolled measurement site, and the influence of fluid ingestion (Wilkinson et al. 2008) and ingestion timing (Goodman et al. 2009) on accurate measurement.

Previous investigations have examined the use of non-invasive measurement of core body temperature at the skin surface for several applications in hospitals (Yamakage and Namiki 2003). The first non-invasive deep temperature thermometer was reported by Fox and Soleman (1971) using the zero-heat-flow method. This device consists of two temperature sensors, with an insulating layer in between and a heater on the top. The heater ensures that no temperature gradient arises across the insulating layer, thus preventing heat loss from the skin. Given sufficient time, the skin surface temperature will equilibrate with deep tissue temperature (Yamakage and Namiki 2003). The original device has been further modified and improved to be able to record core body temperature during a change in ambient temperature from 30 °C to 10 °C (Togawa et al. 1976, 1979). An insulated skin temperature sensor monitored reliable temperature values for hospitalised infants when compared to rectal temperature (Dollberg et al. 2000; Van der Spek et al. 2009). However, for non-active patients in thermo-neutral conditions, the sensor output differed from rectal temperature by up to 1 °C (Carter and Perry 1977). The same measurement principle was applied in a new prototype sensor published by Zeiner et al. (2010). Their sensor accurately predicted temperature when compared with oesophageal temperature in a clinical setting with hypothermic anaesthetised patients. Furthermore, the sensor was tested under stable, rapidly increasing and decreasing core body temperatures in hot, windless conditions and gave a reliable estimation (rmsd=0.4 °C) of oesophageal temperature (Teunissen et al. 2011). However, as Teunissen et al. pointed out, these kinds of sensors should be used only in stable environmental conditions due to the time they need to stabilise. Cooler and windier conditions would reduce the accuracy of the sensors.

Gunga et al. (2008) applied a methodology called a “double sensor”, which was integrated into firefighter helmets to predict core body temperature in working conditions. This sensor contains two temperature sensors separated by thermal conductive material with known thermal properties to calculate the heat flow. In contrast to the method used by Fox and Solman (1971), the sensor concept has no active heating element. The predicted core body temperature, based on double sensor data, did not in all circumstances meet the requirement of ±0.5 °C when compared with rectal temperature. Particularly in lower ambient temperatures (10 °C), and in intermittent work intensities with rest periods, the predictive value was low. In contrast, during head down bed-rest situations 85 % of the measured data were in the predefined limit of ±0.5 °C (Gunga et al. 2009). Moreover, 98 % of the double sensor values were within ±0.5 °C compared to oesophageal temperature in the study of Kimberger et al. (2009). They concluded that the double sensor was sufficiently accurate and could be considered as an alternative to oesophageal temperature measurement in hospital patients.

To sum up, the methods reviewed above neither meet the requirement of an accurate measurement of the core body temperature (±0.1 °C) nor do they enable the continuous measurement of the core body temperature in changing working conditions. Therefore, the aim of this study was to define the relevant multiple non-invasive parameters, such as local skin temperatures or skin heat flux to predict core body temperature in various working conditions.

Methods

Two human subject studies were conducted that differed in their experimental protocol, ambient environment (10 °C, 30 °C) and human subjects: (1) hot environment study and (2) cool environment study. The protocols and questionnaires used in both studies were approved by the ethical committee of the Canton of St. Gallen (Switzerland).

Subjects: hot environment study

Ten healthy physically active male students were recruited and gave their written consent to participate in this study. Prior to the main trial, each subject underwent a screening that included a health questionnaire, body fat content assessment and a test to determine subjects’ exercise capacity. Body fat content was calculated from the measurement of skin folds at four sites (biceps, triceps, scapula, abdomen) with a calliper (Harpenden Skin folds Calliper (CE 0120) HSK B1, British Indicators, West Sussex, UK) (Durnin and Womersley 1974). The maximal oxygen consumption (VO_2 peak) and the maximal heart rate ($\mathrm{HR}_{\max}$) of each subject were measured using a maximal graded exercise test on the treadmill. Oxygen consumption was determined using a metabolic cart system (Oxycon Pro, Jaeger, Höchberg, Germany). Heart rate was measured using Polar RS800. Ten subjects participated in the study (age, 23.0±3.9 years, height, 180±9 cm; weight, 74.3±8.3 kg; body surface area, 1.92±0.16 m^2; body fat percentage, 11±3 %; maximal oxygen consumption, 57.8±5.3 ml kg^{-1} min^{-1}; maximal heart rate, 193±11 bpm)

In addition, a second submaximal exercise test with constant speed of treadmill (chosen individually by each subject to enable convenient walking) was conducted to set the exercise intensity to 40 % and 60 % of VO_2 peak by the adjustment of the inclination. These two intensities were used in the experimental protocol and were determined for each subject. All subjects confirmed by written consent form that they were non-smokers, were not taking any medications on a regular basis and were free of any known cardiovascular, metabolic and intestinal diseases. In addition, participants were instructed to refrain from drinking alcohol and caffeine, and strenuous exercise 24 h prior to the experimental trial and to arrive in a euhydrated state. They were instructed to drink at least 1.5 l water the day before and on the day of the experiment before every trial.

Experimental protocol: hot environment study

Each subject performed two experimental trials carried out in random order. Experiments were separated by at least 2 days and were conducted at the same time of the day in order to avoid effects of the circadian rhythm on the core body temperature. After attaching sensors (see section on "Physiological measurements") to the subject's skin, subjects were dressed in a two-layered clothing system that included a T-shirt (100 % polyester) and underwear shorts (100 % cotton) as the first layer and trousers (100 % cotton) and a jacket (100 % cotton) as the second layer. They wore their own underwear pants and running shoes. They entered the climatic chamber and first remained in standing position for 3 min on the treadmill. Then, they walked at 40 % VO_2 peak for 40 min in a hot environment (30.0±0.2 °C, 42.9±1.1 % relative humidity, and wind speed <0.3 m/s) (Fig. 1). VO_2 was recorded during the exercise phase to monitor exercise intensity. The exercise session was followed by a 20 min sitting break outside the climatic chamber (25.7±0.2 °C, 19.6±1.0 % relative humidity). After the break, the subjects re-entered the climatic chamber and remained in standing position for another 2 min on the treadmill before completing a 40 min walk at 60 % VO_2 peak. This was followed by a 40 min sedentary rest period outside the climatic chamber.

The duration of experimental trial was up to 145 min. Two trials were conducted for each subject and included the same experimental protocol with and without thermal radiation (simulation of an additional heat source) from the front. The thermal radiation was simulated using a panel of 25 red bulbs adjusted in a square with a power of 150 W for each bulb. The panel was placed in the front of the treadmill and covered the subject's full body height. The amount of direct thermal radiation was measured using a flat heat flux sensor (Captec, Lille, France) on a surface at distance of 1.2 m before the trial. The amount of thermal radiation was held constant at 500 W m^{-2}. The subjects were instructed to always walk at the same distance (1.2 m) from the thermal radiation source during the exercise phase; this area was marked on the treadmill to be checked by the subject himself and the experimenter. According to ethical guidelines, individual trials were stopped when $T_{re}>39.5$ °C or HR>95 % HR$_{max}$ or at the subjects' request.

Subjects: cool environment study

Ten healthy physically active male students aged 24.6±2.0-years (height, 180±5 cm; weight, 75.1±9.1 kg; body surface area, 1.94±0.13 m^2; body fat percentage, 11±2 %; maximum oxygen consumption, 60.2±5.9 ml kg^{-1} min^{-1}; maximal heart rate, 193±9 bpm) participated in this study and underwent the same screening, preliminary physiological tests and got the same instructions as the subjects in the hot environment study. We used a different sample of subjects in this study compared to the hot environment study.

Experimental protocol: cool environment study

The subjects were equipped with sensors and dressed in a three-layer clothing system consisting of a T-shirt (100 % polyester), a long sleeved shirt and trousers (100 % polyester), a jacket and dungarees (50 % polyester, 50 % cotton). They wore their own underwear pants and running shoes.

Each trial consisted of 10 min stabilisation period involving standing on the treadmill, 50 min activity by walking at a velocity and an inclination corresponding to the individual 60 % VO_2 peak calculated from the preliminary test followed by a 60 min of rest phase when the subject sat on a chair (Fig. 2). All tests were performed in a climatic chamber set at 10.1±0.2 °C, 49.5±4.9 % relative humidity and air velocity of 0.5±0.1 m/s. The setup was chosen to mimic military conditions with activity and resting periods.

Physiological measurements

The same physiological measurement parameters were assessed in both studies. The intestinal temperature (T_{int}) was measured

Fig. 1 Measurement protocol of the hot environment study

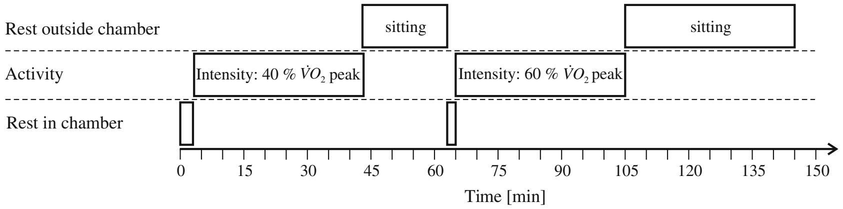
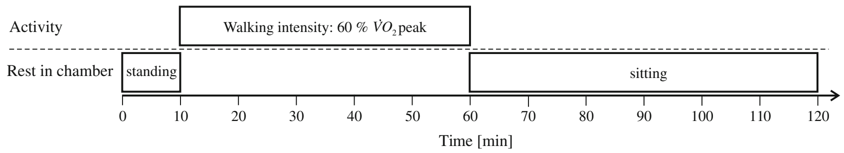


Fig. 2 Measurement protocol of the cool environment study



using a telemetric pill system (CorTemp, HQInc, Palmetto, FL). This method is used widely in athletes (Domitrovich et al. 2010) and is also applicable for workers in hot conditions. As well as the intestinal temperature, rectal temperature was also measured in the hot environment study. It has been shown that, in hot conditions, rectal temperature and intestinal temperature are representative of each other (bias=0.13±0.26) (Teunissen et al. 2012). Rectal temperature (T_{re}) was measured using a rectal thermistor (MSR, Henggart, Switzerland) inserted to a depth of 11 cm past the anal sphincter.

Skin temperature was recorded at nine sites distributed over the whole body surface using iButtons (Type DS1922L, Maxim Integrated Products, Sunnyvale, CA) fixed with surgical tape (Fixomull, BSN Medical, Hamburg, Germany): forehead (T_{head}), chest (T_{chest}), upper back ($T_{\mathrm{u.back}}$), upper arm ($T_{\mathrm{u.arm}}$), lower arm ($T_{\mathrm{l.arm}}$), hand (T_{hand}), abdomen ($T_{\mathrm{abdominal}}$), thigh (T_{thigh}) and calf (T_{calf}). Only the left side of the body was used for temperature measurements.

Additionally, two temperature sensors (iButtons, Type DS1923) were placed between the first and the second layer of the clothing system. These sensors were placed on the chest ($T_{\mathrm{chest\ layer2}}$) and the upper back ($T_{\mathrm{u.back\ layer2}}$) of the right side of the body and fixed on the T-shirt with surgical tape. All temperature data were recorded at 10 s intervals.

Skin heat flow was measured using flat heat flux sensors (Captec, Lille, France) on chest ($\mathrm{HF}_{\mathrm{chest}}$) and upper back ($\mathrm{HF}_{\mathrm{back}}$) fixed with surgical tape. The sensors were thin, light and flat copper-based plates with a width of 1 cm and length of 4 cm. The data were recorded at 10 s intervals.

Heart rate (HR) was recorded using a heart rate monitor (Polar RS800, Polar Electro, Oulu, Finland). The data was recorded at 5 s intervals. All data was reduced to 1 min intervals by picking one sample per minute for the entire experiment.

Statistical analysis

The data set was separated into two parts by random selection by subject. This means that, throughout the experiments, the data of some subjects were used for model development and the remaining data were used for model validation. A linear relationship can be expected for parameters obtained at several body sites. However, for a multiple linear regression model, uncorrelated components are required. Therefore, a principal component analysis (PCA) was conducted (Field 2009). The correlation matrix was applied to the standardised data. An eigenvalue higher than 1.0 was a prerequisite for the components to be included into the model. Multiple iterations were performed to exclude parameters showing communalities lower than 0.6 or complex structure (two or more components with a loading higher than 0.4 for each distinct parameter). Communalities of parameters were considered in a first and loading of parameters in a second iteration. Loadings for the components included are listed in Table 1. The extracted parameters were converted into a factor score for each independent group of dependent factors. In this way, independent principle components were calculated from the physiological measures. Finally, these components were used for multiple linear regression of the core temperature (Field 2009).

Factor scores for each group were calculated using a coefficient of each included variable (Eq. 1). The $\mathrm{coefficients}_{\mathrm{variable}}$ were obtained from the PCA. $\mathrm{x}_{\mathrm{variable}}$ is the measured value of the variable, $\bar{x}_{\mathrm{variable}}$ is the mean value and $\mathrm{sd}_{\mathrm{variable}}$ is the standard deviation of the data. These data have been used for model development and standardisation of input variables.

$$factor\ \ score = \sum coefficient_{\mathrm{variable}} * \frac{x_{\mathrm{vari}able} - \bar{x}_{\mathrm{vari}able}}{sd_{\mathrm{vari}ale}} \tag{1}$$

Coefficients for each variable to calculate factor scores are listed in Table 1. The values used for standardisation of each input variable are listed in Table 2.

Physiological parameters measured non-invasively do not respond immediately to changing experimental conditions. This leads to a delayed prediction of T_{re}. The delay was identified by cross correlation analysis using 10 s values and corrected in the multiple regression model.

The validity of the model was tested by calculating a grand mean of the root mean square deviation (rmsd). This grand mean was reported with ±1 SD. The rmsd was used to measure goodness-of-fit between measured and predicted

Table 1 Component loading after orthogonal rotation. Only the extracted variables based on the explained extracting parameters are listed (see text for explanation). *HF* Skin heat flow

Variable	Factor 1	Factor 2	$\mathrm{Coefficients}_{\mathrm{variable}}$ (factor 1)[a]	$\mathrm{Coefficients}_{\mathrm{variable}}$ (factor 2)[a]
$T_{\mathrm{u.arm}}$	0.918[b]	−0.160	0.327[b]	0.033
$T_{\mathrm{l.arm}}$	0.898[b]	−0.274	0.303[b]	−0.038
$\mathrm{T}_{\mathrm{thigh}}$	0.820[b]	−0.331	0.265[b]	−0.084
Heart rate	0.730[b]	0.246	0.313[b]	0.252
$\mathrm{HF}_{\mathrm{chest}}$	−0.108	0.880[b]	0.084	0.517[b]
$\mathrm{HF}_{\mathrm{back}}$	−0.107	0.875[b]	0.083	0.514[b]

[a] $\mathrm{Coefficients}_{\mathrm{variable}}$ (factor 1 and 2) were used to calculate the factor score (see Eq. 3)

[b] Variables with the strongest loading on the individual factor

Table 2 Mean values and corresponding standard deviations (SD) of the measured data to calculate the standardised variables (see Eq. 1)

Variable	Unit	Mean	SD
$T_{\text{u.arm}}$	(°C)	34.831	3.095
$T_{\text{l.arm}}$	(°C)	34.472	2.389
T_{thigh}	(°C)	35.185	2.681
Heart rate	(bpm)	108.230	29.891
HF_{chest}	(W m^{-2})	201.118	104.627
HF_{back}	(W m^{-2})	328.077	122.751

core body temperature data. Acceptance criterion was set at 0.5 °C as stated in another similar study (Yokota et al. 2012). In addition, the rmsd was compared with the standard deviation of the measured core body temperature. A model bias was calculated to evaluate if the model under- or overestimates the predicted core body temperature (Eq. 2). All statistical analyses were conducted using SPSS 17.0 for Windows.

$$bias = \frac{\sum \left(x_{predicted} - x_{measured}\right)}{number\ \ of\ \ measurements} \tag{2}$$

Model validation

The model was validated using the remaining subject data that had been excluded from the model development data pool and purposely preserved for the validation study. We compared the predicted core body temperature with the measured rectal and intestinal temperature. The calculated rmsd and bias (see "Statistical analysis") were compared with the standard deviation of the measured rectal and intestinal temperature, and compared between the different exposures.

In addition, the model was validated using another data set (mean values of eight subjects available) from a subject study conducted by Mäkinen et al. (2000). They investigated the thermal response of human subjects in different environments and measured physiological parameters as skin temperature and skin heat flux at various sites. In addition, they obtained rectal temperature and heart rate in their experiments. The experimental protocol consisted of a preconditioning of 60 min in a sitting position at two different exposures (cold: −5 °C or thermoneutral: 20 °C). The main exposure consisted of 30 min standing with and without wind in an environment of −10 °C. The chosen exposures in this latter study are listed in Table 3. Eight healthy young males with the following characteristics: age 23±2 years, height 179±4 cm, body mass 73±7 kg, body fat content 14±3 % participated in the study. The calculated rmsd, bias and mean value of standard deviation in rectal temperature were used to test the validity of the multiple regression model.

Table 3 Exposures in the study of Mäkinen et al. (2000) chosen to validate the approach taken in this study

	Ambient temperature (°C), air velocity (m/s)	
	60 min sitting	30 min standing
Exposure 1	20, 0.2	−10, 0.2
Exposure 2	20, 0.2	−10, 5.0
Exposure 3	−5, 0.2	−10, 0.2
Exposure 4	−5, 0.2	−10, 5.0

Results

Principal component analysis

The data was split between model development and model validation. Five subjects from both exposures in hot conditions (with and without thermal radiation) and six subjects from the cold environment study were taken for development of the model. Five subjects from both exposures in hot conditions and four subjects from the cold environment study were used for validation of the model.

PCA revealed two main factors (Table 1). Factor 1 was affected mainly by skin temperatures of the upper arm, lower arm, thigh and heart rate. Skin heat fluxes were expressed in factor 2.

The calculated coefficient matrix is shown in Table 1. For the calculation of the factor score (Eq. 1) the measured values ($T_{\text{u.arm}}$,$T_{\text{l.arm}}$, etc.) have to be standardised based on the individual mean and standard deviation (Table 2) and to be multiplied by the individual coefficient for the respective factor (Table 1). Equation 3 provides an example for factor score 1. These factor scores were then integrated in the multiple regression model as independent standardized variables (Eq. 4).

$$\begin{aligned} factor\ \ score1 = 0.327^{*}\frac{\left(T_{u\,arm} - \overline{T}_{u\,arm}\right)}{sd_{T\,u\,arm}} \\ + 0.303^{*}\frac{\left(T_{l\,arm} - \overline{T}_{l\,arm}\right)}{sd_{T\,l\,arm}} + \ldots \\ + 0.083^{*}\frac{\left(HF_{back} - \overline{HF}_{back}\right)}{sd_{HF\,back}} \end{aligned} \tag{3}$$

Multiple regression model and its validation

Multiple regression analysis revealed a model to predict core body temperature (Eq. 4) with the first part of the data set (split data set) which included the hot environment study (two conditions: with and without thermal radiation) and cold environment study. R^2 of the calculated model was 0.72 (R^2_{adjusted}=0.72). The rmsd was 0.25 °C.

$$\text{Core body temperature} = 0.278 * \text{factor score1} + 0.275 * \text{factor score2} + 37.644 \qquad (4)$$

The mean value of the measured and predicted data was calculated and shown in Fig. 3. The dotted lines indicated ±1 standard deviation of the measured data (see "Model validation"). The model predicted the data obtained in the hot environment with no thermal radiation from the front well for the first 100 min. Afterwards, we observed an underestimation in the cool down phase that was slightly out of the range of 1 SD (Fig. 3a). A similar behaviour was observed in the hot condition with thermal radiation. The underestimation in this case in the second phase of the experimental protocol (−0.49 °C at 105 min) was up to the limit of the acceptance criterion of 0.5 °C (Fig. 3b). However, the cold environment study showed a different behaviour, as the first phase of the experiment was overestimated but afterwards fitted very well (Fig. 3c).

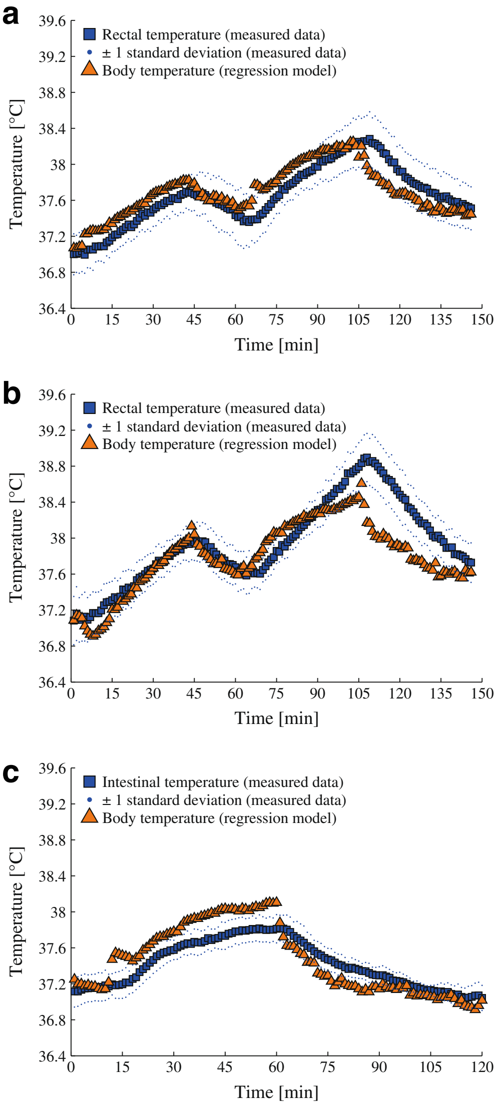


Fig. 3 Mean value for the measured data and the multiple regression model for **a** the trial without thermal radiation in the hot environment study, **b** the trial with thermal radiation in the hot environment study, and **c** the data of the cool environment study

The explained variances for the different conditions were ranging from 70 % up to 73 % (Table 4). This was indicated by the values of R^2. The $\text{SD}_{\text{measured}}$ data was the standard deviation calculated from the measured rectal or intestinal temperature. The $\text{Mean}_{\text{rmsd}}$ was the rmsd average for the included subjects with ±1 SD. The $\text{Mean}_{\text{bias}}$ was the bias (Eq. 2) averaged for the included subjects with ±1 SD.

Rectal temperature measured in the subject study conducted by Mäkinen et al. (2000) and the modelled data are presented in Fig. 4. In addition, the mean standard deviation of the measured rectal temperature and the rmsd of the core body temperature for the exposures are listed in Table 5. The rmsd were smaller than the mean standard deviation of the measured rectal data in three of four exposures. Exposure 3 showed a slightly higher rmsd as the mean standard deviation of the rectal temperature.

Discussion

A multi-parameter statistical approach was chosen to develop a model predicting core body temperature in changing environment and activity levels. We calculated a multiple regression model to predict core body temperature using skin temperatures at different body sites, heart rate and two heat flow sites in hot and cool conditions. PCA extracted the three skin temperature sites, heart rate and two skin heat flux sites to be included in the multiple regression analysis. However, the extraction of factors using PCA depends on a number of physiological variables (e.g. number of skin temperature sites) measured during the experiment. Our investigations showed that data obtained from single exposure (i.e. hot environment study only) led to a different extraction of skin temperature

Table 4 Summary of validation of the multiple regression model with the second part of the split data set. *rmsd* Root mean square deviation

	Hot environment study		Cold environment study
	No thermal radiation	With thermal radiation	
R^2	0.72	0.70	0.73
$\text{SD}_{\text{measured data}}$ (°C)	0.23	0.21	0.13
$\text{Mean}_{\text{rmsd}}$ (°C)	0.28±0.03	0.34±0.07	0.33±0.13
$\text{Mean}_{\text{bias}}$ (°C)	0.04±0.17	−0.17±0.14	0.04±0.28

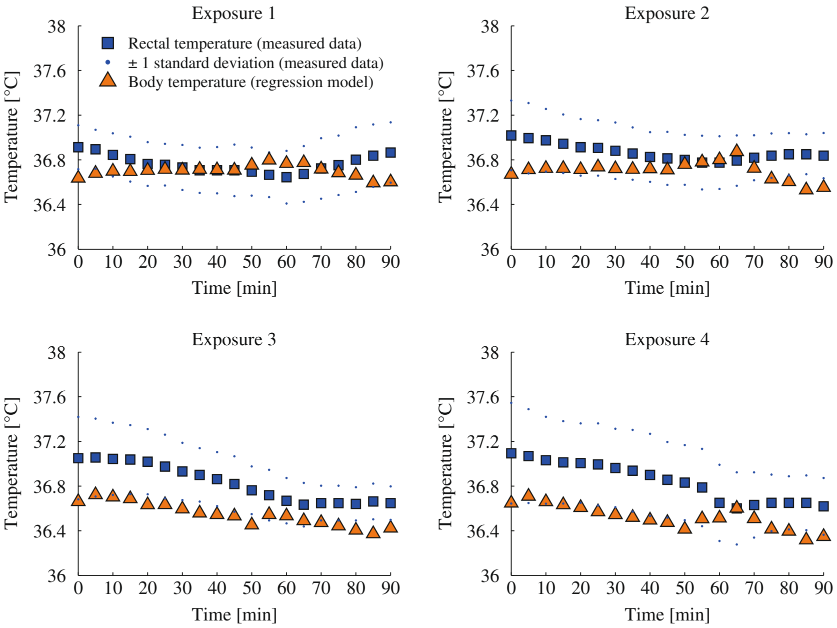


Fig. 4 The four exposures (Table 3) from the study of Mäkinen et al. (2000): *squares* measured rectal temperature, *dots* ±1 SD, *triangles* core body temperature calculated using multiple regression model

sites by PCA compared to the presented approach (including all exposures). However, thigh temperature, heat flow at chest and back and the heart rate were always extracted regardless of the exposure applied. We compared the performance (R^2) of multiple regression models based on different principle components. The best performance (R^2=0.72) was achieved when data from all exposures were included in the PCA. Nevertheless, we suggest that at least three skin temperature sites (T_{thigh} recommended), two heat fluxes and heart rate are used to monitor thermal influences from several body sites to predict core body temperature. Particularly, the measurement of the heat flow at the chest and the upper back provided important information on the heat flux from the body (main determinants of one factor of PCA). In addition, the heat flux measurement on the chest was an important parameter to detect the influence of a thermal radiation source from the front. In addition to the heat flux, the heart rate provides information about the metabolic heat generation of the human body in the model. Therefore, important parameters representing heat loss and heat gain of the human body were integrated in this model. As mentioned above, this approach is limited somewhat by the number of measurement sites used. Therefore, an increase in the number of measurement sites (skin temperatures or heat flux) may change the chosen important parameters of this approach.

Table 5 Mean standard deviation of the rectal temperature ±1 SD from the study of Mäkinen et al. (2000) and the calculated rmsd and bias with the multiple regression model in the current study

	Mean standard deviation ±1 SD of T_{re}, (°C)	rmsd (°C)	bias (°C)
Exposure 1	0.22±0.04	0.14	−0.06
Exposure 2	0.24±0.04	0.20	−0.16
Exposure 3	0.24±0.07	0.29	−0.28
Exposure 4	0.34±0.07	0.33	−0.32

Nevertheless, the presented model was able to explain up to 72 % of the variance and reached rmsd between 0.28± 0.03 °C and 0.34±0.07 °C for the core body temperature depending on three different exposures chosen. It should be noted that, in both conditions (with and without thermal radiation), the hot environment study showed an underestimation in the prediction of the core body temperature in the last one-third of the exposure time. In addition, the cold environment study showed an overestimation at the beginning of the exposure. These deviations of the model cannot be attributed to only one factor as all extracted parameters could have affected the result. This is a clear limitation when using multiple physiological data for a non-invasive prediction. Further, the developed model is valid only for the fitness level, body composition, age and gender of the participating subject. Gender differences, which are explained mainly by fitness level and body composition (Kaciuba-Uscilko and Grucza 2001), have not been included in our model. Further studies are needed to adapt this approach for subjects with lower fitness level and different body compositions.

The acceptance criterion of rmsd less than 0.5 °C for core body temperature for all conditions was achieved. In addition, the rmsd of this study was comparable with rmsd obtained in validation of the leading advanced physiological model, which predicted core body temperature with an average rmsd of 0.32±0.20 °C (Psikuta et al. 2012; Kampmann et al. 2012).

Mäkinen et al. (2000) performed a human subject study in which the same physiological parameters as in the present study were recorded. We used this additional data set to test the validity and robustness of the developed multiple regression model. The obtained rmsd for this data set was smaller compared to the mean standard deviation in rectal temperature in at least three exposures (Table 5). This indicated the validity of the developed model for simulation of the core body temperature in resting human subjects under different environmental conditions levels. However, the trends for core body temperature indicated by the model seem to contradict the observed data in three out of the four chosen exposures (Fig. 4). This deviation can be explained by the accuracy of the model developed here (rmsd of 0.28± 0.03 °C and 0.34±0.07 °C), which is in the same range as the small core body temperature changes in the four chosen exposures (maximum decrease of core body temperature of 0.4 °C in exposures three and four).

Recently, Yokota et al. (2012) used a simple model to overcome problems that arise from physiological computer modeling (many inputs from environmental, physiological and operational conditions). They designed a model to predict core body temperature including heart rate, air temperature, mean radiant temperature, relative humidity and wind speed. They validated the approach using different field test protocols and conditions. Rmsd revealed a range of 0.15 to 0.34 °C, however, with higher rmsd variability than that obtained in our study. This could be explained by the setup of a field test compared to controlled laboratory tests. Buller et al. (2011) used a similar model and measured, in addition to heart rate, heat flow and acceleration non-invasively. They obtained a similar value for rmsd (0.28 °C) in experiments conducted in the laboratory.

Our approach and the approaches of Yokota et al. (2012) and Buller et al. (2011) aimed to develop a simple method for real-time monitoring of thermal status while working in hazardous conditions. The performance of the presented approaches, including our own, was quite similar when comparing the obtained rmsd. The described rmsd or bias values of the approach presented in this study seem to be high. However, the trends of the measured and the modeled data are similar. Therefore, this approach enables a reliable prediction of thermal status while working in hazardous conditions. The higher deviation of the model in even more extreme conditions must first be determined. Nevertheless, the chosen approach is promising for the conditions tested in this study and future studies should focus on identifying important parameters to predict core body temperature in more extreme conditions. We recommend including more heat flux measurement sites instead of the measurement of skin temperature only or environmental factors. The measurement of skin heat flux under various conditions was used in physiological measurements investigating body heat balance (Ducharme and Kenny 2009; Basset et al. 2011; Flouris and Cheung 2009). In addition, it was the one main reliable contributor to successful prediction of core body temperature in our study. Moreover, heat flux measurement is less influenced by environment and attachment method compared to skin temperature measurements (Buono and Ulrich 1998). Environmental factors like microclimate data in clothing layers, which were included in our study, were not extracted by the PCA and therefore did not seem to be important factors. We recommend that physical parameters for prediction of the core body temperature are measured close to the skin rather than distant from the human surface, where the influence on measurement results becomes less controlled.

Conclusions

The multi-parameter approach in this study identified different physical and physiological parameters like skin temperature, heart rate and particularly skin heat flux, that have to be considered for a reliable prediction of core body temperature in different environmental and working conditions. We therefore conclude that multiple physical and physiological parameters at different body sites have to be measured for reliable prediction of core body temperature. Moreover, the real-time physiological monitoring of individual workers can offer information to induce medical intervention when needed. Furthermore, this study showed that, apart from the physiological data obtained non-invasively, no additional environmental data in the chosen range of environmental conditions is needed to predict core body temperature. Therefore, we recommend measuring parameters close to the skin rather than distant from the human surface where the influence of the measurement results becomes less controlled. Our approach showed good reliability and validity for the different environmental conditions chosen in this study. However, the developed model is limited currently to the chosen subject group (fitness level and body composition) and the chosen range of environmental conditions. Therefore, more research is needed to increase the performance (decrease of current rmsd 0.3 °C) of the prediction of core body temperature of this non-invasive measurement approach, and its agreement over a broad range of people and environmental conditions. The studies should focus on extracting important physiological parameters like measurement of skin heat flux and skin temperature at several sites.

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