

# Validation of the thermophysiological model by Fiala for prediction of local skin temperatures

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**Abstract** The most complete and realistic physiological data are derived from direct measurements during human experiments; however, they present some limitations such as ethical concerns, time and cost burden. Thermophysiological models are able to predict human thermal response in a wide range of environmental conditions, but their use is limited due to lack of validation. The aim of this work was to validate the thermophysiological model by Fiala for prediction of local skin temperatures against a dedicated database containing 43 different human experiments representing a wide range of conditions. The validation was conducted based on root-mean-square deviation (rmsd) and bias. The thermophysiological model by Fiala showed a good precision when predicting core and mean skin temperature (rmsd 0.26 and 0.92 °C, respectively) and also local skin temperatures for most body sites (average rmsd for local skin temperatures 1.32 °C). However, an increased deviation of the predictions was observed for the

forehead skin temperature (rmsd of 1.63 °C) and for the thigh during exercising exposures (rmsd of 1.41 °C). Possible reasons for the observed deviations are lack of information on measurement circumstances (hair, head coverage interference) or an overestimation of the sweat evaporative cooling capacity for the head and thigh, respectively. This work has highlighted the importance of collecting details about the clothing worn and how and where the sensors were attached to the skin for achieving more precise results in the simulations.

**Keywords** Thermophysiological model · Thermophysiology · Skin temperature · Temperature sensors

## Introduction

The quantification of thermal strain and comfort is of special interest in fields such as sport physiology (Formenti et al. 2013; Gerrett et al. 2014), clinical research (Lahiri et al. 2012), protective clothing design (Bogerd et al. 2010; Priego Quesada et al. 2015a), automotive industry (Tanaka et al. 1992), building environmental ergonomics (Arens et al. 2006; Zhang et al. 2010), climate impact research, heat and cold health warning systems, urban planning and tourism as it affects human health, performance and comfort. The examination of people directly exposed to the environment of interest provides comprehensive information about physiological responses and perception. However, not all scenarios can be addressed due to ethical reasons and large sample sizes are necessary for reliable conclusions due to inter- and intra-subject variability observed among human beings. As a consequence, human subject trials are time-consuming and cost-intensive.

Mathematical models of the human thermo-physiology are very useful instruments for advancing ergonomics research as they are able to predict human thermal response in a wide range

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of environmental conditions. Several models with different levels of complexity are referenced in the scientific literature, for which the acceptance of their reliability might depend on the specific purpose of the model. For example, models provided in standards in the field of environmental ergonomics strongly simplify human physiology and rely their assessment mostly on heat balance equations (i.e. PHS model (Malchaire et al. 2001) in ISO7933 (2004), IREQ model in ISO11079 (2007) or PMV index based on Fanger's comfort equation (Fanger 1970) in ISO7730 (2005)).

One of the first models approaching human thermal physiology simulation in detail was developed by Stolwijk (Stolwijk 1971). This model considers simplified human body geometry (i.e. cylinders or spheres) divided in six multi-layered segments. Most advanced models presented in the recent decades are based on this model (Smith 1991; Xu and Werner 1997; Fiala et al. 1999; Fiala et al. 2001; Huizenga et al. 2001; Tanabe et al. 2002; Salloum et al. 2007; Kobayashi and Tanabe 2013). Multi-node models are able to predict global and local human thermal response under steady-state, transient and asymmetrical exposure conditions. These models have shown higher agreement with experimental data than the more simplified models (Psikuta et al. 2012). Nevertheless, models usually predict thermal response for a standard person while the thermo-physiological responses are modelled based on statistical regression models rather than physiological principles. Moreover, thermo-physiological models include in general a simplified model for clothing considering a few static parameters whereas complex heat and mass transfer phenomena could occur within clothing layers and air gaps (Jones and Ogawa 1993; Lotens et al. 1995; Li et al. 2004; Havenith et al. 2008; Wu and Fan 2008; Frackiewicz-Kaczmarek et al. 2015). Therefore, the precision of the predictions after these simplifications needs to be quantified by comparing with human subject data.

The validation of thermal physiology models against human experimental data are limited by the availability, accurate description and consistency of human data and the underlying experimental procedures. For example, different measurements methods might affect the temperature readings, especially for the skin temperature measurement due to sensor shape and attachment method (Buono and Ulrich 1998; Tyler 2011; Psikuta et al. 2013a) or due to differences in application of infrared thermography (Zaproudina et al. 2008; James et al. 2014).

Generally, validation studies for the human thermoregulation models are scarce in scientific literature and if available, they do not address complex conditions. Some of the most advanced models were initially validated predominantly based on body global parameters (Stolwijk 1971; Fiala et al. 2001; Psikuta et al. 2012). Although advanced models have been validated based on local skin temperature data and the scenarios included steady-state and transient conditions, they discussed only sedentary conditions (Huizenga et al. 2001; Tanabe et al. 2002; Munir et al. 2009; Zhang et al. 2010; Foda et al. 2011). In

few cases, the validation scenarios included exercising participants but they were limited to low activity rates (Werner and Webb 1993; Xu and Werner 1997).

One of the most extensively validated thermo-physiological models is the mathematical model of the human thermo-physiology by Fiala (Fiala and Havenith, 2015; Fiala et al. 1999, 2001, 2012). This model has been implemented in commercially available software which is constantly under improvement. This model has been already validated for many different scenarios mainly in terms of core and mean skin temperatures. The model by Fiala was presented together with 23 validation scenarios including a wide range of conditions. Moreover, Psikuta et al. (2012) did a further validation study and showed an acceptable accuracy of the model, in a wide range of environmental conditions, clothing and activity level both at transient and steady state. Other parameters such as local skin temperatures or evaporative heat loss were not systematically analysed possibly due to lack of experimental data. Hence, no human thermoregulation model has been widely validated for prediction of local skin temperatures in exercising scenarios so far.

The aim of this work was to evaluate the mathematical model of the human thermo-physiology by Fiala (FPCm5.3 software version, Ergosim, Germany) using a dedicated database for prediction of local skin temperatures in a wide range of scenarios including relevant human and environmental factors, such as cold, neutral and warm environmental conditions, different levels of relative humidity, high wind speed, presence of solar radiation, moderate and high activity levels and protective clothing.

## Materials and methods

### Description of human database

Thirteen different human studies have been selected from literature including relevant human and environmental factors, such as cold, moderate and warm environmental temperature, different levels of relative humidity, high wind speed, presence of solar radiation, moderate and high metabolic rate, and protective clothing (Table 1). A total of 43 exposures with detailed descriptions of the experimental protocol, the environmental conditions and clothing parameters have been included in this study. The maximum and minimum values of the experimental parameters and a detailed description of each exposure can be found in Table 1.

Three out of the 43 exposures took place entirely outdoor and two in a temperature-controlled room, whereas the rest of the experiments were conducted in climatic chambers. Twenty-one out of the 43 included a transient environmental temperature based on participants transferring from a climatic chamber to an adjacent temperature-controlled room. In 23 exposures, participants combined exercise periods at different metabolic rates,

**Table 1** General description of human data base with maximum and minimum

Experiment	Exposure description	Duration [min]	Air temperature [°C]	Radiant temperature [°C]	Relative humidity [%]	Air speed [m s <sup>-1</sup> ]	Solar radiation [W·m <sup>-2</sup> ]	Activity [met]	Mean clothing thermal resistance [m <sup>2</sup> K·W <sup>-1</sup> ]	Mean clothing evaporative resistance [m <sup>2</sup> Pa·W <sup>-1</sup> ]	Number of participants [male/female]	Reference
1	Hot exposure wearing protective clothing	86	40/25	40/25	30	0.5	0	3.3/4.4	0.42	77.29	10/0	Unpublished data from Annahem, Empa, Switzerland
2	Cycling in moderate environments	95	20	20	50	3	0	3.4/7.3 2.8/4.7 3.4/7.3 2.8/4.7 3.4/7.3 2.8/4.7	0.06 0.06 0.05 0.05 0.06 0.06	3.67 3.99 3.72 4.08 3.69 4.01	9/0 0/5 9/0 0/5 9/0 0/5	(Jack 2010)
3	Standing in the cold	90	20/-10	20/-10	50	0.2/0.2 0.2/1 0.2/5 0.2/0.2 0.2/1 0.2/5	0	1/1.2	0.29/0.37	51.55/96.78	8/0	(Mäkinen et al. 2000) and unpublished data from H. Rintamäki, Finnish Institute of Occupational Health, Oulu, Finland
4	Sedentary activity in cold	120	10	10	40	0.05	0	0.8	0.12	5.38	10/0	(Wagner and Horvath 1985)
5	Cycling in warm environment	30	29	29	80	0.2	0	5.1/7.1	0.06	3.39	8/0	(Bogerd et al. 2010)
6	Guard duty in the cold	180	0	0	82	18	0	1.6	0.64	61.74	4/0	Unpublished from I. Mekjavic, Josef Stefan Institute in Ljubljana, Slovenia
7	Hiking in warm conditions	180	22 24	22 24	71 57	1.1 1.2	57 109	4.3 4.2	0.22	16.16	6/0 3/0	Unpublished from I. Mekjavic, Josef Stefan Institute in Ljubljana, Slovenia
8	Walking in the cold	120	10	10	50	0.5	0	1.4/5.9	0.32	27.85	10/0	(Niedermann et al. 2014)
9	Walking in hot conditions	145	30/25.7	30/25.7	40/19.6	0.3	0	4.9/5.9/1	0.21	20.95	10/0	(Niedermann et al. 2014)
10	Cycling in moderate environment	81	21.8 21.2	21.8 21.2	39	0.15/0.44 0.15/0.44	0	2.5/4 2.5/5.3	0.05	2.47	14/0	(Priego Quesada et al. 2015b) and unpublished data from Empa, Switzerland (den Hartog 2002)
11	Cycling in moderate and warm environments	120	20	20	50	0.3	0	1.3/5.3 1.3/1.8 1.3/1.7 1.3/4.6 1.3/1.7	0.16 0.06	17.42 6.63	1/1	Unpublished data from Kuklane, National Institute for Working Life, Sweden. Test conditions and limb cooling are described in (Geing et al. 1998; Kuklane et al. 1998)
12	Sedentary cold exposures	120	3/23 -12/23	3/23 -12/23	n.r	4 8 2 4 6 8 1 2 4	0	1.5	0.50	33.77 48.04	8/0	Unpublished data from Kuklane, National Institute for Working Life, Sweden. Test conditions and limb cooling are described in (Geing et al. 1998; Kuklane et al. 1998)
13	Occupational tasks in the heat	150	34	34	60	0.4	0	1.2/5.1	0.05	3.7	0/5 5/0 14 2	(Lundgren et al. 2015)
	Max		40	96	80	18.0	109	7.3	0.64	96.77		
	Min		-25	-25	20	0.1	0	0.8	0.05	2.44		

and in five out of these 23 exposures, participants experienced changes in environmental temperature in addition to changes in metabolic rate. In 23 out of 43 exposures, wind speeds higher than  $1 \text{ m s}^{-1}$  was applied from front either on the whole body or just locally at some body parts.

### Validation procedure

The FPCm5.3. model (Ergosim, Germany) is the most recent version released in 2015 of the mathematical model of the human thermophysiology by Fiala (Fiala and Havenith, 2015; Fiala et al. 1999, 2001, 2012). This FPCm5.3. model version introduces the possibility of adjusting the fitness level, acclimatization days, body size and percentage of body fat of a simulated person (Fiala and Havenith, 2015).

The validation of the FPCm5.3. model was done by comparing experimental human data with a corresponding simulated virtual exposure. The exposures were built up based on description of the experimental test conditions described by experimenters. Exposures were simulated by providing environmental conditions and activity levels as constant values for a given period of time. For outdoor experiments, environmental parameters were provided as time-dependent values changing every minute within the exposure period (exposures 18–20).

The clothing thermal resistance for the simulations was determined by using either direct measurement with thermal manikins or estimated according to ISO 9920 guidelines if information from direct measurements was not available. Due to reduced information about clothing evaporative resistance in ISO 9920 and the controversy about its determination (ISO9920 2007; Havenith et al. 2008), values were taken from different manikin studies if not similar clothing ensemble data was available in the standard (Wang et al. 2011; Wang et al. 2014).

The metabolic heat production or so-called activity level in the thermo-physiological model was estimated based on the available data provided for each exposure as the difference between metabolic rate and the rate of mechanical work accomplished as required by the FPCm5.3 model. For low-activity levels such as reclining, sitting or standing, metabolic rate was estimated according to the ISO 8996 guidelines. For higher activity levels, metabolic rate was estimated from measured oxygen consumption if available (ISO8996 2004) or workloads required by the cycling ergometer were transformed into oxygen consumption applying a conversion formula (Hawley and Noakes 1992). In exposures taking place on a treadmill, the metabolic rate was estimated based on the treadmill slope and walking speed by applying the empirical equation by Givoni and Goldman (1971). Mechanical efficiency was considered to be close to zero for level-walking, whereas a maximum value of 0.2 was applied for cycling independently of the intensity (Zatsiorsky and Prilutsky 2012). Intermediate mechanical efficiency values were assumed for graded-walking as proposed by Margaria (1968).

In this validation study, body temperatures have been used for assessing the performance of the FPCm5.3. model for predicting human thermal responses. For assessing the prediction of the overall thermal responses, core and mean skin temperatures were investigated. Core temperature was usually assessed based on rectal temperature (only for exposures 21, 24, and 25, intestinal measurements were provided for core temperature monitoring) and mean skin temperature data were available for 33 out of the 43 exposures. Mean skin temperature was mostly provided according to ISO 9886 calculations (8-points for 13 exposures, 14-points for two exposures). For the remaining exposures, non-standard methods based on 15, 7, 6 and 4 points were applied (exposures 10–15, exposure 16, exposures 18–20 and exposures 26–31 and 42–43, respectively). The mean skin temperature predicted by the simulation was calculated using the same body locations and weighing coefficients as used on experimental data. All skin temperature measurements were obtained by contact thermometry sensors attached to skin with clinical tape.

For the assessment of the prediction of local skin temperatures, a single location was selected for representing head site (forehead), three locations were selected on the trunk (chest, abdomen and scapula) and two locations were assigned on the limbs (thigh and calf). This selection of locations was based on the human data mostly available in the included experiments. Skin temperatures measured at arms, hands and feet were discarded from validation as information about the exact position or local insulation values were not carefully controlled or even missing in the experiment description.

All exposures were simulated considering a standard person according to FPCm5.3. except exposures 4–9, 17, 21–25 and 42–43 in which simulations were carried out adjusting simulated person's characteristics for trained athletes upon experimenter's description. The average trained female was represented with  $\text{VO}_2\text{max}$  of  $55.7 \pm 6.2 \text{ ml kg}^{-1} \text{ min}^{-1}$ , height of  $170.8 \pm 1.7 \text{ cm}$ , weight of  $64.7 \pm 8.1 \text{ kg}$ , age of  $27.9 \pm 5.5 \text{ years}$  and fat content of  $26.3 \pm 4.9 \%$  (exposures 5, 7, 9 and 42, see Table 1). The average trained male was represented with  $\text{VO}_2\text{max}$  of  $57.9 \pm 2.0 \text{ ml kg}^{-1} \text{ min}^{-1}$ , height of  $179.0 \pm 2.1 \text{ cm}$ , weight of  $74.5 \pm 1.7 \text{ kg}$ , age of  $27.7 \pm 4.2 \text{ years}$  and fat content of  $14.3 \pm 3.2 \%$  (exposures 4, 6, 8, 17, 21–25 and 43, see Table 1).

### Data analysis

The precision and the accuracy of the FPCm5.3. predictions were statistically assessed by root-mean square deviation (rmsd) and by bias similarly to the study by Psikuta et al. (Psikuta et al. 2013b). Both parameters were calculated for each of the aforementioned body temperatures and for each exposure. The fit of the FPCm5.3. model was considered acceptable when the rmsd was within the standard deviation of the experimental data, typically 0.2 and 1.0 °C for core and

skin temperatures, respectively (Psikuta et al. 2012). Bias should be zero to exclude the presence of systematic errors. Positive bias represented experimental data above simulations, whereas negative bias represented the opposite.

Statistical parameters for each exposure are summarized in Table 2, which corresponded to the simulated core and skin temperatures in the most plausible simulated scenario. Core temperature values from exposures 21, 24 and 25 were not included in overall rmsd and bias calculations as measurements corresponded to telemetric pill registered at intestinal site. Although this measurement method has become very popular in the last time for estimating core temperature due to good agreement with rectal probes measurements, a consistent bias ranging between 0.15 and 0.20 °C has been reported in some studies (Casa et al. 2007; Easton et al. 2007; Teunissen et al. 2012).

## Results

The average rmsd and bias values with standard deviations for each of the target variables are depicted in Fig. 1 for the total of 43 exposures studied in this work. Overall core temperature rmsd and bias values do exclude exposures 21, 24 and 25 as core temperature was exceptionally measured at the intestine site. The figure further includes the average standard deviation observed from experimental data for each body site.

Average deviation (rmsd) in the prediction of core and mean skin temperatures was comparable to typical standard deviation values observed in our database (0.25 °C for core and 0.74 °C for mean skin temperature, respectively) and typically assumed in human subjects trials (0.20 °C for core and 1.00 °C for mean skin temperature (Psikuta et al. 2012)).

Local skin temperatures for all body sites included in this study were predicted on average with a rmsd value of  $1.32 \pm 0.77$  °C. This value was slightly above the average experimental standard deviation found for local skin temperature in the experiments (average  $SD_{exp} = 1.05$  °C). Global rmsd did not show noticeable differences when averaged separately for trunk or for limbs ( $1.22 \pm 0.8$  and  $1.31 \pm 0.68$  °C). Maximum discrepancy between prediction and human data was observed for skin temperatures at the forehead and thigh (rmsd of  $1.63 \pm 0.91$  and  $1.41 \pm 0.75$  °C, respectively), and the minimum discrepancy was found at scapula ( $1.09 \pm 0.76$  °C).

## Discussion

### Prediction of core temperature

The average core temperature rmsd value of 0.26 °C has been found to be comparable to standard deviation observed in the human experiments database ( $SD_{exp} = 0.25$  °C). The bias of  $-0.04$  °C indicated a good matching of simulated results with

real data. The highest deviation was systematically observed for exposures 26–31 which included one male and one female participant in each test only (see Table 1). Core temperature predictions above the experimental data were particularly observed in exposures with participants exercising at moderate to high activity levels if simulating these exposures with the standard person defined in the FPCm5.3. model. Poor agreement was found for exposure scenarios in which well-trained athletes participated. This effect was already observed by Psikuta et al. (Psikuta et al. 2012) and related to a possible mismatch in the fitness level of the simulated person which has been recognized to determine the thermal response. Hence, these specific exposures included the adjustment of the individual characteristics of the simulated person according to experimental data, showing a noticeable improvement in the prediction of core temperature. Figure 2 shows exemplary prediction for exposure 1 and 4 (see description in Table 1). Individual characteristics of participants in exposure 1 corresponded to a standard person whereas they corresponded to a well-trained athlete in exposure 4. The graph providing data for exposure 4 (Fig. 2b) includes simulation cases for both standard person (Std person) and adjusted fit (Fit person) simulated person (see “Validation procedure” section). In this case, discrepancy (rmsd) reduced from 0.39 °C calculated for a standard person to 0.18 °C if simulation considered a well-trained person.

Interestingly, rmsd noticeably differed between exposure 42 and 43 representing the same scenario for females and males (rmsd was 0.28 and 0.1 °C, respectively in Table 2). The females’ experimental temperature started approximately by 0.2 °C above the males’ one whereas similar initial rectal temperature was observed in the predictions for both genders (Lundgren et al. 2015).

### Prediction of mean skin temperature

The rmsd value was  $0.92 \pm 0.47$  °C and the average bias value was 0.37 °C for mean skin temperature, indicating that experimental data were above the predicted mean skin temperature in general. The mean skin temperature was calculated based on different body sites. The prediction of the local skin temperature at these body sites is discussed in the next sections, facilitating the interpretation of the mean skin temperature as well.

### Prediction of forehead temperature

The forehead rmsd value was found to be  $1.63 \pm 0.91$  °C, being comparable to the average standard deviation of our database ( $SD_{exp} = 1.43$  °C). The bias was  $-0.51$  °C, indicating that on average, experimentally measured data were below the predicted skin temperature at forehead.

In cold exposures (i.e. exposures 13–15, see description in Table 1), the deviation was higher than the average value obtained for all 43 exposures. In these particular scenarios,

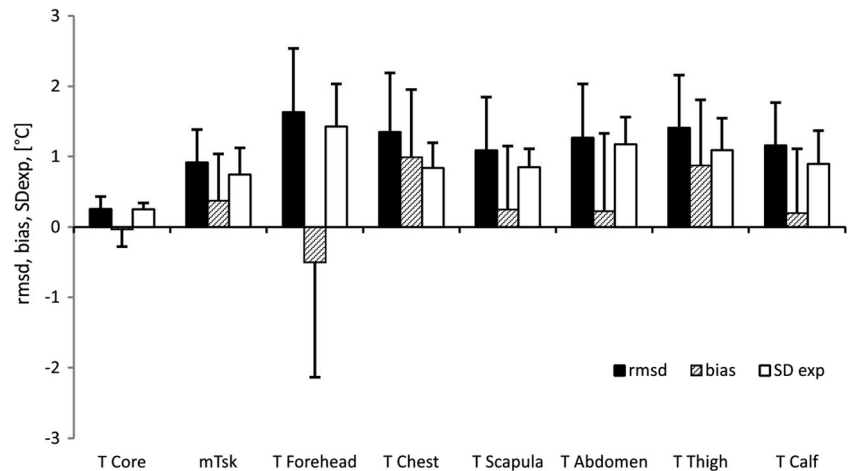


**Table 2** Statistical parameters for measured variables in each exposure. Cases marked with \* provided core temperature at intestinal site and are not included in statistical calculations. *The rectal temperature,  $mT_{sk}$  mean skin temperature*

Database	Exposures	Global			Head			Trunk			Legs						
		T <sub>re</sub> (°C)		mT <sub>sk</sub> (°C)	T Forehead (°C)		T Chest (°C)	T Scapula (°C)		T Abdomen (°C)	T Thigh (°C)		T Calf (°C)				
		Bias	rmsd	Bias	rmsd	Bias	rmsd	Bias	rmsd	Bias	rmsd	Bias	rmsd				
1	Walking in hot environment wearing protective clothing	-0.12	0.14	-0.04	0.36	-0.31	0.47	0.15	0.42	-0.56	0.83	0.05	0.62	0.25	0.50	-0.12	0.57
		-0.18	0.20	-0.01	0.37	-0.48	0.81	0.20	0.47	-0.34	0.60	0.22	0.63	0.38	0.57	-0.09	0.63
		-0.25	0.28	0.05	0.38	-0.25	0.54	-0.23	0.75	-0.37	0.69	-0.57	0.66	0.47	0.79	0.34	0.67
		-0.15	0.18	0.39	0.60	-2.07	2.14	2.16	2.40	0.45	0.65			1.48	1.54	0.55	1.02
		0.00	0.07	-0.44	0.53	-3.12	3.13	0.48	0.67	-0.55	0.95			0.79	1.03	0.53	0.75
		-0.15	0.18	0.70	0.81	-1.93	2.03	3.06	3.29	1.06	1.13			1.52	1.61	0.53	0.91
		0.06	0.07	-0.28	0.49	-4.16	4.16	0.75	0.85	-0.24	0.94			0.34	0.63	0.81	0.91
		-0.17	0.20	0.72	0.85	-1.74	1.90	3.63	3.90	1.50	1.58			1.28	1.32	0.29	0.88
		-0.03	0.06	-0.07	0.34	-3.37	3.38	1.39	1.49	0.05	0.63			0.53	0.76	1.08	1.23
		-0.29	0.30	0.12	0.48	-0.47	0.69	-0.01	0.35	-0.04	0.18	0.09	1.07	0.06	0.60	-0.09	0.78
3	Standing in the cold	-0.18	0.19	0.26	0.49	0.99	1.42	0.27	0.35	-0.07	0.40	0.04	1.02	0.30	0.70	-0.17	0.69
		-0.18	0.20	-0.27	0.66	-0.52	1.00	-0.74	1.19	0.43	0.40	-0.69	1.35	-0.79	1.92	-0.50	0.57
		-0.10	0.12	0.50	0.72	2.70	2.95	0.97	1.11	-0.35	0.40	2.53	2.88	0.69	1.28	0.52	0.78
		-0.09	0.10	0.58	0.76	3.01	3.29	1.06	1.17	-0.12	0.17	1.88	2.18	0.81	1.35	0.67	0.89
		-0.11	0.12	0.03	0.85	1.93	2.54	-0.01	1.51	-0.64	0.68	0.74	1.94	-0.27	1.97	0.29	0.61
		-0.27	0.32	0.53	0.74	1.26	1.44	0.44	0.96					1.97	2.04	-1.96	2.15
		-0.13	0.14	2.11	2.45	1.44	1.67	2.36	2.62	2.54	2.67			2.77	3.13	0.95	1.83
		0.14	0.16	0.64	0.69			0.90	0.94	0.61	0.69			-0.69	0.85	0.72	0.90
		-0.13	0.21	0.42	1.00			1.85	2.03	-1.56	1.82			-0.20	1.29	0.07	1.74
		-0.26	0.48	0.44	1.23			1.96	2.55	-1.56	2.31			0.69	1.40	0.36	1.81
8	Walking in the cold	0.08*	0.17*	-1.09	1.24	-2.20	2.28	-0.36	1.19	-1.84	2.31	-2.16	2.42	1.20	1.37	-1.93	2.03
		-0.19	0.23	0.01	0.43	1.23	1.32	0.73	0.94	1.04	1.57	-0.14	0.57	0.90	1.10	0.59	0.76
		-0.01	0.17	1.30	1.42	0.64	0.89	1.37	1.61	0.99	1.63	0.50	0.88	1.52	1.58	0.73	1.00
		0.42*	0.43*	1.04	1.11	-0.76	0.89	1.10	1.29	1.19	1.27	0.67	0.83	2.42	2.88	1.48	1.57
		0.33*	0.34*	1.11	1.21	-0.87	1.11	1.94	2.33	-0.86	3.82	-0.06	0.69	2.93	3.35	-2.39	3.36
		-0.52	0.83	-0.67	1.13			1.46	2.00							-1.31	1.45
		0.46	0.47	0.77	1.17			1.06	1.39							0.42	0.75
		0.41	0.47	0.64	1.08			1.17	1.75							0.32	1.04
		0.51	0.58	0.35	1.04			0.96	1.02							0.50	1.39
		0.39	0.42	0.53	0.95			0.14	1.28							0.42	1.29
11	Cycling in moderate environment	0.24	0.44	-0.76	1.87			0.27	0.52	-0.33	0.49					0.53	0.67
		-1.52				-1.52	1.63	-0.07	0.60	-0.28	0.54					0.61	0.78
		-1.74				-1.74	1.91	0.63	0.71	0.33	0.59					0.20	1.16
		-1.49				-1.49	1.68	-0.14	0.36	0.39	0.55					0.87	1.41
		-1.09				-1.09	1.33	0.56	0.75	0.16	0.50					0.94	0.75
		-1.05				-1.05	1.32	1.06	1.13	0.27	0.49					0.53	0.67
		-1.21				-1.21	1.60	0.56	0.75	0.27	0.56					0.61	0.61
		-0.80				-0.80	1.23	1.02	1.12	0.27	0.56					1.03	1.20
		-0.34				-0.34	1.05	1.57	1.63	0.77	0.85					1.11	1.30
		-0.53				-0.53	1.24	2.03	2.15	0.84	0.90					0.87	1.41
13	Occupational tasks in the heat	-0.40				-0.40	1.12	1.42	1.60	0.61	0.69					0.53	0.67
		0.27	0.28	1.49	1.57	0.43	0.57	1.75	1.86							0.61	0.78
		-0.03	0.10	1.12	1.23	0.67	0.75	1.04	1.21							0.20	1.16
		-0.04	0.26	0.37	0.92	-0.51	1.63	0.99	1.35							0.87	1.41
		0.25	0.18	0.67	0.47	1.63	0.91	0.97	0.84							0.91	0.61
		0.27	0.28	1.49	1.57	0.43	0.57	1.75	1.86							0.53	0.67
		-0.03	0.10	1.12	1.23	0.67	0.75	1.04	1.21							0.20	1.16
		-0.04	0.26	0.37	0.92	-0.51	1.63	0.99	1.35							0.87	1.41
		0.25	0.18	0.67	0.47	1.63	0.91	0.97	0.84							0.91	0.61
		0.25	0.18	0.67	0.47	1.63	0.91	0.97	0.84							0.91	0.61

Unpublished data from Annenheim, Empa, Switzerland  
 Jaek 2010  
 Mäkinen et al. 2000 and unpublished data from H. Rintamäki, Finnish Institute of Occupational Health, Oulu, Finland  
 Wagner and Horvath 1985  
 Bopgerd et al. 2010  
 Unpublished from I. Mekjavic, Josef Stefan Institute in Ljubljana, Slovenia  
 Unpublished from I. Mekjavic, Josef Stefan Institute in Ljubljana, Slovenia  
 Niedermann et al. 2014  
 Niedermann et al. 2014  
 Pnigo Quesada et al. 2015b and unpublished data from Empa, Switzerland  
 Unpublished from E. den Hartog, TNO Defence, Security and Safety, Netherlands  
 From Kuklane, National Institute for Working Life, Sweden. Test conditions and limb cooling are described in Kuklane et al. 1998 and Geng et al. 1998.  
 Lundgren et al. 2015

**Fig. 1** Overall values for precision (*rmsd*), accuracy (*bias*) and experimental inter-participant standard deviation (*SD<sub>exp</sub>*) for a total of 43 exposures carried out with FPCm5.3

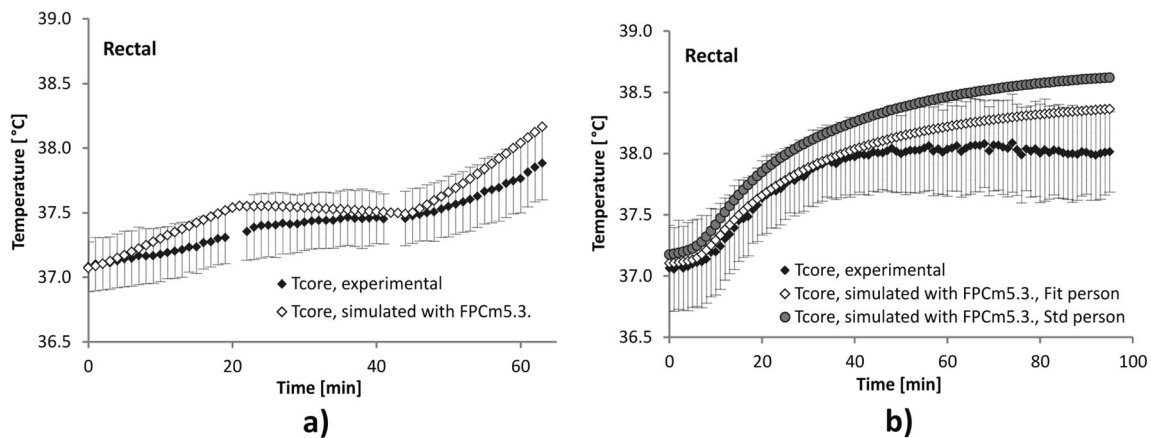


participants usually wore any kind of winter headgear. Depending on the head anatomy, headgear design and wearing style, the forehead area could have been partially dressed for some of the participants. The headgear affected the thermal and evaporative resistances in the areas covered and even covered the thermal sensor. Consequently, this could have had a strong influence on skin temperature recordings. Unfortunately, no details were reported in this respect and even some inconsistencies between participants wearing style could have occurred if it was not carefully controlled. This presumption is supported by the highest experimental standard deviation observed at the forehead among all local skin temperatures.

Figure 3a shows experimental data compared with simulations considering dressed and undressed forehead for exposure 13. In this exposure, the participant wore cold protective clothing, standing for 60 min while exposed to 5 °C followed by a transition to an ambient temperature of -10 °C for another 30 min. No detailed information was given about the

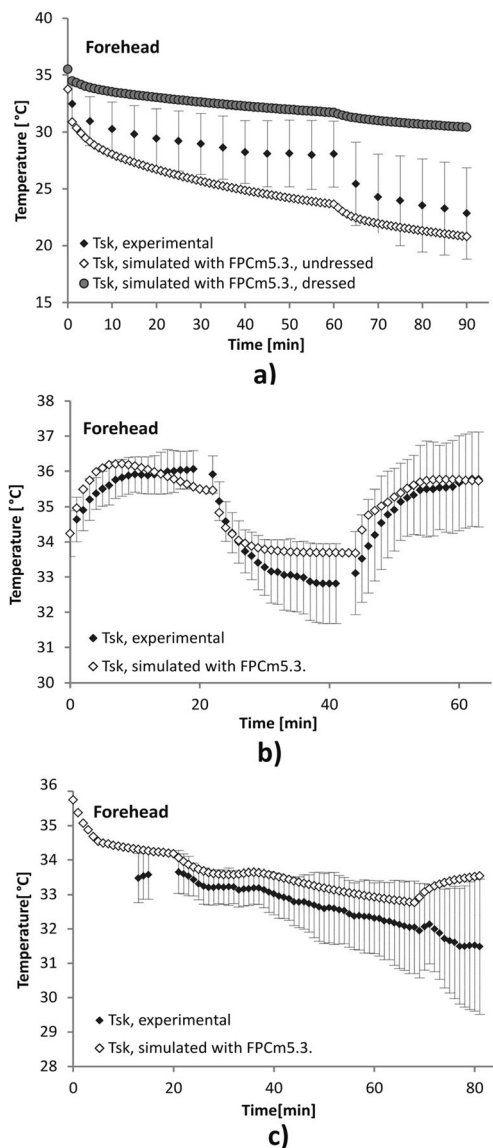
location of the temperature sensor on the forehead site and if it was covered by clothing or not. Moreover, predicted skin temperature at forehead represented the average of the entire forehead surface area, and thus, some inconsistencies with punctual temperature measurements could occur due to temperature heterogeneities. This lack of information of the scenario description might decrease the precision of the simulations. For the global statistical analysis in Table 2, the forehead was considered to be undressed in exposures 10–15.

Looking more closely to forehead temperature for specific exposures including exercise followed by a resting period, it was observed that experimental skin temperature at forehead decreased during the resting period, whereas simulation predicted stabilization or increase during the subsequent resting period. Some illustrative cases from exposure 1 (resting period between minutes 23 and 43) and exposure 24 (resting period from minute 68 until the end) are presented in Fig. 3b, c, respectively. These exposures are described in Table 1. Once



**Fig. 2** Core temperature (*T<sub>core</sub>*) measured in human experiments and predicted using the FPCm5.3 model. **a** Exposure 1: Standard person walking on a treadmill at 3.3 and 4.4 met, air temperature = 40 °C, relative humidity = 30 %, protective clothing worn. Rest period between 20 and 40 min, air temperature = 25 °C, relative

humidity = 30 %. **b** Exposure 4: Well-trained athlete cycling at 7.3 met, air temperature = 20 °C, relative humidity = 50 %, short cycling clothing. Std person corresponds to a standard simulated person and Fit person corresponds to a well-trained athlete. Exposures are described in Table 1



**Fig. 3** Forehead skin temperature (*T<sub>sk</sub>*). **a** Exposure 13: Standard person standing in a cold environment (1 h at air temperature = 5 °C and half an hour at air temperature = −10 °C, still air), cold protective clothing. Experimental data are presented together with simulations that considered dressed and undressed forehead. **b** Exposure 1: Standard person walking on a treadmill at 3.3 and 4.4 met, air temperature = 40 °C, relative humidity = 30 %, protective clothing worn. Resting period between 20 and 40 min, air temperature = 25 °C, relative humidity = 30 %. **c** Exposure 24: Well-trained athletes cycling at 4 met, air temperature = 21.8 °C, relative humidity = 39.4 %, short cycling clothing. Resting period after 68 min. Exposures are described in Table 1

the person was resting after the exercise, the FPCm5.3 model assumed a rapid decrease in sweating and a concomitant reduction of evaporative heat loss. The remaining moisture absorbed by clinical tape or clothing attaching the temperature sensor was possibly underestimated as was the continued

evaporative cooling of the skin surface nearby. Nevertheless, the resting periods were of short duration and the aforementioned effects were not noticeably reflected in the rmsd calculated for the entire exposure duration that is shown in Table 2.

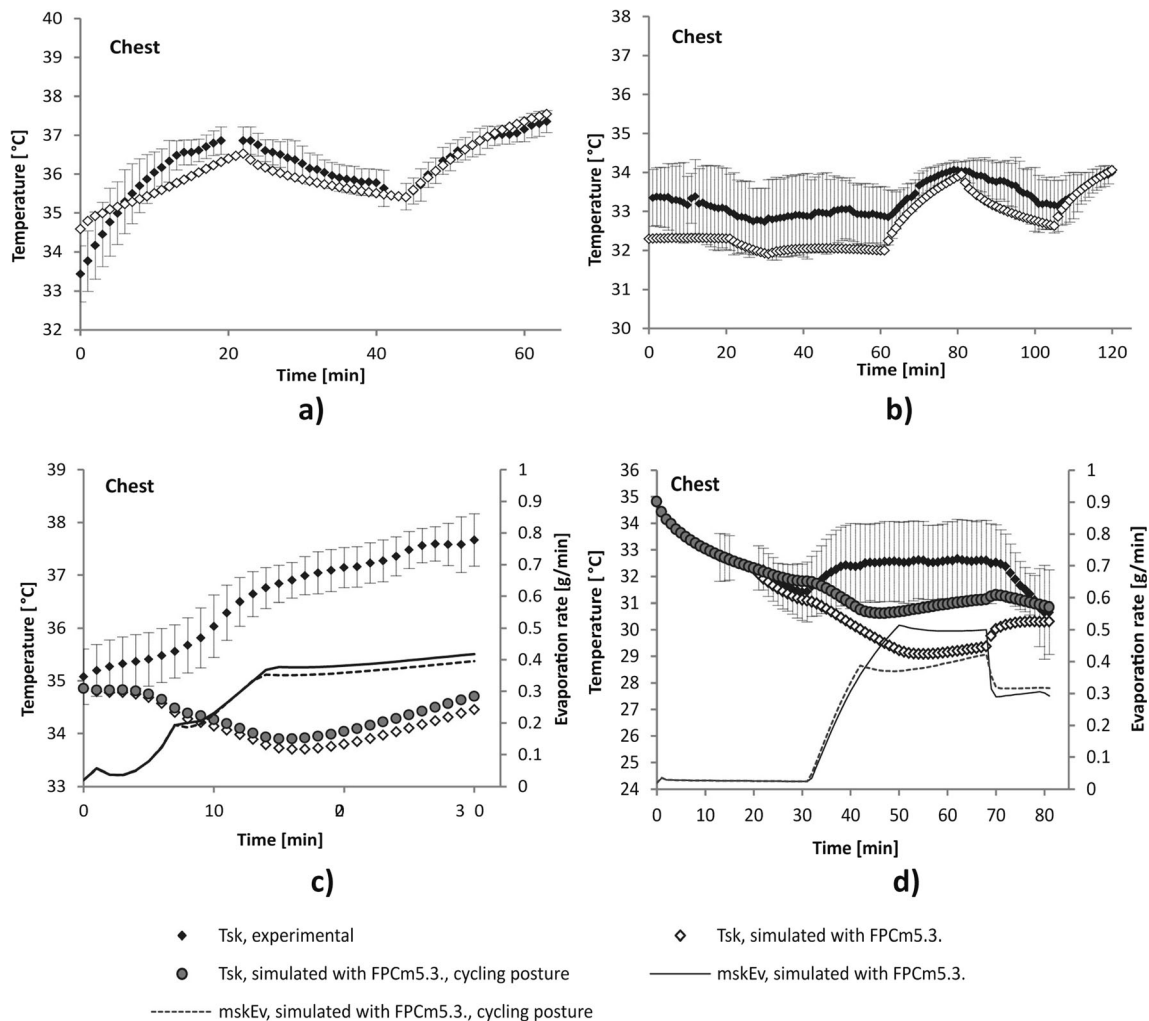
### Prediction of trunk temperatures (chest, abdomen and scapula)

The FPCm5.3. model predicted chest temperature with an average deviation (rmsd) of  $1.35 \pm 0.84$  °C which is above the average standard deviation observed in our database ( $SD_{exp} = 0.84$  °C). Similarly, the FPCm5.3. model predicted abdomen temperature with an average deviation of  $1.27 \pm 0.77$  °C for the exposures included in the database, whereas the lowest deviation among prediction of local skin temperatures was found at the scapula ( $1.09 \pm 0.76$  °C). A bias of 0.99, 0.22 and 0.24 °C was observed for the chest, abdomen and scapula, respectively. Generally, experimental local skin temperature was usually above predicted values at these body sites in this database.

The FPCm5.3. model predicted skin temperature at chest and abdomen with a discrepancy comparable to the average standard deviation observed for corresponding temperature measurements when participants wore protective clothing in still air conditions, while walking on a treadmill in a hot scenario (exposures 1–3, see Table 1) and when sitting or standing in a calm air cold scenario ( $v_{air} < 0.2$  m s<sup>−1</sup>) (exposures 10–11 and 32–37, see Table 1). Figure 4a, b presents exposures 1 and 34, respectively, in which participants were wearing protective clothing in hot and cold conditions, respectively.

However, when frontal wind was applied to participants in a cold scenario, such as exposure 12 (Table 1), the experimental chest and abdomen temperature were noticeable below the predicted values during the second phase of the exposure (i.e. partial bias −2.01 and −2.11 °C at the chest and abdomen for exposure 12, see whole-exposure bias in Table 2). The most probable reason could be an actual reduction in the clothing thermal insulation due to wind compression as previously discussed by Psikuta et al. (2012). In this study, clothing thermal insulation for such exposures was measured on a thermal manikin (Psikuta 2009). Clothing insulation values were, therefore, provided spatially for trunk, upper and lower limbs. Because the correction for wind compression given in ISO 9920 (ISO9920 2007) refers to global total insulation values, they could not be applied locally at the chest where the actual wind compression could have occurred. Seemingly, no effect of wind induced compression was found at the back. In the study by Psikuta et al. (2012), it was shown that not applying the wind compression correction at the back improved the correlation of the simulated and measured back skin temperature.





**Fig 4** Experimental and predicted chest temperature (*Tsk*) and local evaporation rate (*mskEv*). **a** Exposure 1: Standard person walking on a treadmill at 3.3 and 4.4 met, air temperature = 40 °C, relative humidity = 30 %, protective clothing worn. Resting period between 20 and 40 min, air temperature = 25 °C, relative humidity = 30 %. **b** Exposure 34: Standard person exposed in a cold environment at air

temperature = −12 °C, sedentary, protective clothing. **c** Exposure 17: Well-trained athletes cycling at 7.1 met, air temperature = 29 °C, relative humidity = 80 %. **d** Exposure 25: Well-trained athletes cycling at 5.3 met, air temperature = 21.2 °C, relative humidity = 39 % (exercise period between 21 and 68 min). Exposures are described in Table 1

On the other hand, the high rmsd values observed at the chest pointed to some discrepancies between simulation and human data when cycling at moderate-to-high metabolic rates in warm conditions (exposures 4, 6, 8, 17, 24 and 25, Table 1). It has been hypothesised that cycling posture can result in different heat transfer conditions than standing or sitting. The arms are usually separated from trunk side and slightly put forward and trunk is bent towards the thighs. This position can affect the local air speed, local air and radiant temperatures for anterior sectors in the chest, abdomen and thighs due to possible stagnant air layer in the cavity of the bent body. The reflected radiation from sectors facing the body may be different than in standing position as well. Both effects are complex to estimate and were not provided in this database. Based on some single trials in our laboratory, we tried to approximate

the impact of these effects (air speed and air and radiant temperatures in the cavity of the bent body) for conditions as in exposure 24 to rate model sensitivity to such phenomena. In this particular case, we found the local air speed to be reduced by approximately 50 % of the front wind and the local air and radiant temperatures to be increased by 1 °C above ambient air temperature for front body sectors partially facing each other (chest, abdomen and thigh).

Figure 4c, d shows skin temperature and local evaporation rate at the chest site for exposures 17 and 25, respectively, simulated in the following two scenarios: considering similar local environmental conditions than in standing posture and considering the aforementioned modifications of local environmental conditions due to cycling posture. For both scenarios, the experimental skin temperatures were above predicted

values. Interestingly, it can be observed that the opposition between trends of experimental and simulated skin temperatures became more evident as long as local skin moisture evaporation rate increased. It is hypothesised that these differences may occur because of differences in the actual and predicted local moisture evaporation from skin might be different.

The modifications of the local environment due to cycling body posture increased precision of the FPCm5.3. by mainly reducing local convective and radiative heat exchange at these body sectors as well as evaporation rate. For exposure 17, rmsd at chest was reduced from 2.62 to 2.44 °C and for exposure 25, from 2.33 to 1.24 °C. The simulations including adjusted air speed, air and radiant temperatures were not considered for statistical analysis, since our single experiment provided only a rough estimate of the local environmental condition. No information for a precise adjustment is available for the cycling experiments included in the database.

Additionally, forward bending of the trunk could facilitate the sweat dripping off and further reduce the effective evaporation rates. Moreover, how the skin temperature collected could directly affect the temperature readings. The exact position of the sensor on the chest surface could be decisive as locations much closer to the arm can have higher thermal radiation from other body parts or reduced air circulation. Moreover, the attaching method used for skin temperature sensors, particularly different kinds of clinical tapes, can generally impair heat exchange and sweat evaporation at the sensor location, leading to a measured skin temperature value not representative for the body region (Buono and Ulrich 1998; Psikuta et al. 2013a). The impact of this effect might depend on the clothing layers on top of the sensor. If the evaporation was already hindered by clothing layers, the tape could have a minimal effect. However, with gradually thinner layers, the difference could grow between experimental and model predictions. Although less experimental data for the abdomen part was available in our experiments database, experimental data at this body part were as well above the predictions for scenarios in which participants were cycling at moderate intensities in warm conditions (i.e. exposure 24 showed a bias value of 0.67 °C).

In cold scenarios with low activity level, the FPCm5.3. model prediction of scapula temperature fitted to the experimental data better than the average obtained for the total 43 exposures (i.e. exposures 10–15 and 32–41, Table 1). As exposures 17 and 22–23 (Table 1) revealed the highest discrepancy when predicting skin temperature of the scapula, it was found an initial mismatch in the starting temperature value being predicted between 1 and 2 °C below experimental data. This fact produced an artificially higher deviation during the initial phases of the exposures most probably due to an initial increased local vasodilation state of the participants in the experiments. Although thermal initial conditions were

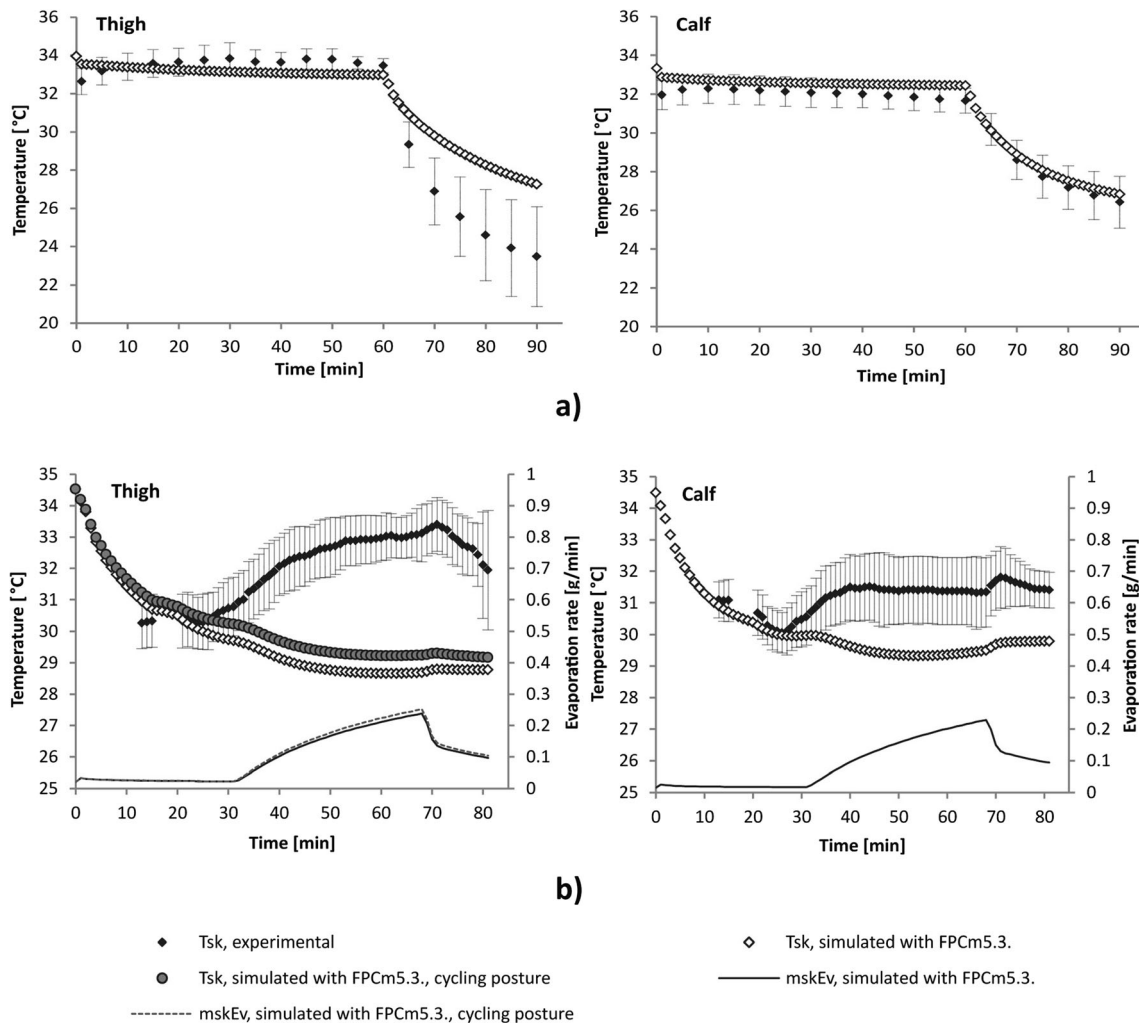
adjusted according to the most probable scenario, some poorly described factors could locally alter some skin temperatures, i.e. leaning against a seatback right before the exposure.

Deviation values for scapula were higher than the average deviation (rmsd) in outdoor scenarios as well, most probably due to changing body orientation along the exposure (exposures 19–20, Table 1). Therefore, as exact information on which body region was exposed to the solar radiation or wind applied at each moment were missing, the discrepancy in local skin temperature prediction increased. Nevertheless, the agreement in core temperature showed rmsd values within and close to the upper limit of the average deviation of core temperature (0.21 and 0.48 °C for exposures 19 and 20, respectively).

### Prediction of leg temperatures (thigh and calf)

Prediction of skin temperature at thigh showed on average one of the highest deviation (rmsd =  $1.41 \pm 0.75$  °C) among local skin temperatures. Average standard deviation in experiments of our database for this variable was found to be 1.09 °C. The observed bias was 0.87 °C, indicating that experimental skin temperature at the thigh was above the predictions. Skin temperature at calf was predicted with rmsd =  $1.16 \pm 0.61$  °C, whereas average standard deviation of experiments was 0.93 °C. The bias for calf temperature prediction was 0.20 °C, demonstrating a good predicting power of the FPCm5.3 model for this location.

As mentioned in the “[Prediction of trunk temperatures \(chest, abdomen and scapula\)](#)” section, the experimental data at chest and abdomen in cold exposures were below the predictions in the period in which  $5 \text{ m s}^{-1}$  frontal wind was applied on the whole body (i.e. partial bias  $-2.01$  and  $-2.11$  °C at chest and abdomen, respectively, for exposure 12, see Table 1 and whole-exposure bias in Table 2). A similar effect was detected for skin temperature at the thigh as well (partial bias  $-3.19$  °C at thigh for exposure 12, see whole-exposure bias in Table 2). At the same time, a deviation lower than the average value at calf in the database was observed for prediction of calf temperature in these cold exposures where frontal wind was applied. From this finding it can be suggested that wind compression could have provided a reduction in clothing insulation at the front parts of the body (i.e. exposures 12 and 15, see Table 1) while rear body regions remain unaffected (such as calf showing partial bias of  $-0.28$  °C for exposure 12, see whole-exposure bias in Table 2). Figure 5a shows skin temperature at thigh and calf sites for exposure 12 in which participants underwent 1 h of thermal adaptation in thermo-neutral conditions (20 °C) followed by half an hour cold exposure ( $-10$  °C) by standing and facing the  $5 \text{ m s}^{-1}$  wind. This simulation is based on measured clothing values and not corrected for wind compression effect.



**Fig. 5** Prediction of thigh and calf temperature (*Tsk*) and sweat evaporation rate (*mskEv*) in exposure 12 and 25. **a** Exposure 12: Standard person standing in the cold wearing cold protective clothing (pre-exposure: 60 min at air temperature = 20 °C, still air/main exposure

30 min at air temperature = -10 °C, 5 m s<sup>-1</sup> frontal wind applied). **b** Exposure 25: Well-trained athletes cycling at 5.3 met, air temperature = 21.2 °C, relative humidity = 39 % (exercise period between 21 and 68 min). Exposures are described in Table 1

Deviation values above the average rmsd observed for the thigh and calf were detected in moderate or warm environments for high activity level during cycling (ranging from 4 up to 7.3 met). The predicted values for skin temperature showed trends differing from the measured participants' skin temperatures at the same both body sites. Similarly to chest and abdomen, the effect of the local environment due to cycling posture on skin temperature of the thigh was explored. Figure 5b shows skin temperature and local evaporation rates for the thigh and calf in exposure 25 (see Table 1). Scenarios with and without correcting the air speed and air and radiant temperatures in the cavity of the bent body due to cycling posture are represented for thigh, but no local effect of cycling posture was assumed for the calf. Figure 5b shows that both simulations, without or with consideration of local environmental effects due to cycling posture, predicted opposite skin temperature evolution if compared with respective experimental data. In addition to body posture in cycling activity, an

additional air flow due to leg movement could affect the thigh temperature differently than the chest temperature.

Interestingly, the observed differences between experimental and predicted values became more apparent at the onset of sweating, and thus, a possible source of this discrepancy could be that either sweat secretion or sweat evaporation efficiency in the experiments might be not as high as assumed by FPCm5.3. No information about sweat secretion rates was available in the respective experiment. However, the simulation of the scenario presented in the study of Smith and Havenith (2011), the model predicted sweat rates that considerably agreed for body parts of interest. The sweat evaporation efficiency from the human skin defined as the ratio of the actual evaporative heat loss to evaporative heat loss calculated based on the mass lost can approximate 100 % only in theoretical cases (all secreted sweat evaporates taking the entire latent energy for evaporation from the body). At this respect, studies on evaporative cooling efficiency of clothing have

highlighted a possible over-estimation of the evaporative heat loss for both hot and cold environments if 100 % evaporation efficiency is assumed (Havenith et al. 2013; Wang et al. 2013). Wang et al. (2013) showed in their study on thermal manikins that in warm environments, 17–49 % of the heat needed for evaporation could have been taken from the surrounding air at 35 °C instead from the manikin surface for thin tight sport garments (thickness less than 1.2 mm). This resulted in a reduced evaporation efficiency due to sweat absorbed by clothing and evaporating at a certain distance from skin surface. Therefore, a similar situation could be expected on human skin. The complexity of different exposures might bring the evaporation efficiency below 100 %. In the reality, some sweat drip-off can eventually occur even for skin wettedness below 1 due to vigorous body movement during exercise. As discussed for the chest region, the sensor attachment method could prevent the local evaporative cooling as showed for convective and radiative heat exchange (Buono and Ulrich 1998; Tyler 2011; Psikuta et al. 2013a) leading to an unrealistic higher measured temperature. On the other hand, the local skin temperature results from the heat balance at skin level. During exercise, metabolic heat produced in the active muscles is brought to the skin by an increased blood perfusion and tissue conduction. The type of activity determines which muscles are active at each body part, and hence, skin blood flow at lower limbs could be different when cycling than during others activities such as walking or running. Although the mechanisms responsible for differences in the efficiency of the exercising legs due to the eccentric-concentric contractions ratio have been analysed (Bijker et al. 2002; Millet et al. 2009), there is still lack of quantitative information for specific modelling of the blood flow in different types of activities.

## Conclusion

Based on a dedicated database containing global and local human physiological data for 43 different exposures, this work provides an evaluation of the precision for global and local skin temperature prediction when using the human thermoregulation model FPCm5.3. Furthermore, it gives relevant insights for a more careful interpretation of the model predictions and about experimental procedures limitations. The FPCm5.3. model has shown in general a good precision when predicting core and mean skin temperatures (rmsd of 0.26 and 0.92 °C, respectively) in different exposures. This was also the case for exposures including well-trained participants exercising at high activity levels due to the possibility of adjusting the individual factors of the simulated person. In general, the model showed good precision when predicting local skin temperatures for most body sites in well-controlled exposures (average rmsd for local skin temperatures 1.32 °C). Nevertheless, the forehead skin temperature (rmsd of

1.63 °C) in general and at the thigh during exercising exposures (rmsd of 1.41 °C) were over-predicted most probably due to the lack of input parameter description. An over-prediction on the local evaporative heat exchange might occur in case the evaporation does not occur with 100 % efficiency in reality as it is assumed by the FPCm5.3. model. In exercising exposures, the sweat evaporation represents one of the principal heat exchange mechanisms any discrepancy in simulation of the evaporative heat loss may bring meaningful consequences for the overall prediction accuracy. As this work focused mainly on the validation of prediction of local skin temperatures, it highlights the need for providing additional local environmental and clothing parameters for an accurate description of heat exchange conditions at the different body parts. This should include details about the clothing worn and how and where the sensors were attached to skin in the experiments. The lack of this information in the literature might have had an impact on the overall model performance evaluation, since often informed guessing and best possible assumptions have been made based on scarce information available rather than providing the actual and precise input parameters.

Scientists and ergonomists can benefit from reliable tool predicting accurately not only core and mean skin temperatures relevant for health, safety and thermal comfort but also local skin temperatures relating to local thermal sensation and comfort. The predictions obtained from thermo-physiological models can be used for a more efficient experimental planning including determination of experimental sensitivity to sought parameters, approximation of safety and ability of sustaining the exposure by human subjects, informed estimation of the exposure conditions to induce the physiological response of interest. Secondly, use of such a model can assist early-stage product development processes, for example, protective and functional clothing systems, body-mapped garments, local environmental conditioning systems such as personal ventilation in offices, ventilated or heated seats and conditioning systems in vehicles and compartments. Therefore, this validation study on FPCm5.3. provides highly valuable information for a careful and critical interpretation of prediction of local skin temperatures, and can assist in increasing the applicability of the model, and hence, accelerating investigations in the field of ergonomics, clothing and environmental engineering.

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Thermal Environment of the Human Being (<http://www.utci.org/cost.php>), especially to Hanu Rintamäki from Finnish Institute for Occupational Health (Oulu, Finland), Igor Mekjavic from Josef Stefan Institute (Ljubljana, Slovenia) and Emiel den Hartog from TNO (The Hague, Netherlands).

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