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ORIGINAL PAPER

Local air gap thickness and contact area models for realistic simulation of human thermo-physiological response

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Abstract
To evaluate the quality of new energy-saving and performance-supporting building and urban settings, the thermal sensation and comfort models are often used. The accuracy of these models is related to accurate prediction of the human thermo-physiological response that, in turn, is highly sensitive to the local effect of clothing. This study aimed at the development of an empirical regression model of the air gap thickness and the contact area in clothing to accurately simulate human thermal and perceptual response. The statistical model predicted reliably both parameters for 14 body regions based on the clothing ease allowances. The effect of the standard error in air gap prediction on the thermo-physiological response was lower than the differences between healthy humans. It was demonstrated that currently used assumptions and methods for determination of the air gap thickness can produce a substantial error for all global, mean, and local physiological parameters, and hence, lead to false estimation of the resultant physiological state of the human body, thermal sensation, and comfort. Thus, this model may help researchers to strive for improvement of human thermal comfort, health, productivity, safety, and overall sense of well-being with simultaneous reduction of energy consumption and costs in built environment.

Keywords Clothing model · Physiological simulation · Thermal insulation of clothing · Air gap in clothing

Introduction

The permanent thermal interaction between the human body and its environment has a significant impact on human thermal comfort, health, productivity, safety, and overall sense of well-being. The largest impact of this interaction is assumed to be related to the indoor environment, since population in economically developed countries spend at least 90% of their time indoors (De Dear et al. 1997; Seppanen and Fisk 2006), and at the same time, 30% of energy use in European countries goes towards comfort control in buildings (Laustsen 2008). To evaluate the quality of the new energy-saving conditioning solutions in terms of occupant satisfaction, thermal sensation and thermal comfort models are often combined with human thermoregulation and clothing models to address both the design stage and retrofit questions. The accuracy of these models is related to accurate prediction of the skin (local and global) and core temperatures that, in turn, are highly sensitive to the local effect of clothing. These crucial input parameters related to clothing need to be detailed and accurate for high quality prediction of the human perceptual and thermo-physiological response. However, till now, they are only roughly estimated or assumed (Veselá et al. 2016).

Not only indoor environment engineering but also ergonomics, medicine, or apparel design may benefit from realistic and comprehensive modelling tools to simulate the thermal interaction of the human body and the environment. Clothing modelling plays an important role in garment prototyping for a dedicated function by increasing the wearing comfort, productivity, development precision, and speeding up the development process (Song 2007; Wang et al. 2006; Öner and Okur 2015). When coupled with a reliable human

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thermoregulation model, the physiological and perceptual effect of the garment in typical or extreme scenarios can be directly predicted.

Manufacturers of clothing have developed a variety of fabrics and membranes that support physiological mechanisms to maintain the thermal balance of the human body and at the same time protect against adverse environmental influence. In these endeavours, a particular attention is put on functional fabrics, whereas clothing fit and pattern are rather considered as elements of aesthetic design than functionality (Öner and Okur 2015). Since the fabric thickness constitutes typically only a small portion of the entire thickness of the clothing system, the air gap thickness is the greatest contributor to the heat and moisture transfer processes within clothing. To take advantage of the fabric properties, a certain garment fit is indispensable. On the one hand, the body contact with the garment is necessary to effectively exploit the moisture management properties of the fabric (Bogerd et al. 2010; Sarkar and Kothari 2014; Wang et al. 2014). On the other hand, air layers trapped underneath and within the clothing layers have a substantial effect on clothing thermal and evaporative resistance (Gupta et al. 2013; Havenith et al. 2013; Wissler and Havenith 2009; Mert et al. 2015). In addition, factors associated with construction and use of a garment, such as air penetration and compression by wind, body posture, and movement, lead to a significant change of these parameters due to the displacement of the air layers and associated lateral heat and mass transfer (ISO 9920 2007; Ke et al. 2014; Morrissey and Rossi 2014; Zhang et al. 2012). Therefore, garment design and the corresponding air gap thickness and contact area between skin and garment are very important factors for heat and mass transfer in clothing. Hence, by a purposeful adjustment of ease allowances (the difference between the body and the garment girths) and garment pattern shape, the thermal and moisture management of a garment can be controlled. And vice versa, the detailed knowledge about the distribution of these parameters will lead to the accurate prediction of the heat and mass transfer through ensemble, and subsequently, human perceptual and thermo-physiological response.

Several studies have attempted to characterise the air layer distribution in a variety of garments. In the first investigations, only an average air gap thickness has been estimated for the whole garment from either the air volume trapped within the garment (Havenith et al. 2010; Lee et al. 2007; Bouskill et al. 2002) or the ratio between clothing and body surface area (Kakitsuba 2004). The distribution of the air layer thickness was recently investigated using a 3D body scanning technique, which combined with a 3D post-processing software offered a high-precision, non-invasive, and fast method to digitalize and analyse the spatial form of the dressed body (Psikuta et al. 2015; Daanen and Ter Haar 2013). To obtain the size of the air gap, 3D scans of the nude and dressed body were aligned, and the air gap thickness was calculated from either a selected number of points or from a discrete number of cross sections through the dressed body (Kim et al. 2002; Song 2007; Xu and Zhang 2009; Wang et al. 2006; Zhang and Li 2011). Further improved 3D scanning methodology (Psikuta et al. 2015) allowed the systematic, accurate, and detailed evaluation of the local and average air gap thickness and for the first time addressed the issue of contact area in ensembles (Psikuta et al. 2012c). Several further studies describing the local distribution of the air gap thickness and the contact area on upper and lower body have been conducted using this method (Bohnet 2013; Frackiewicz-Kaczmarek et al. 2015a, e; Mark 2013; Mert et al. 2016; Mert et al. 2017). They emphasised the regional systematic trends in the distribution of these two parameters in relation to the garment ease allowance at the corresponding body landmarks. Secondly, these trends were consistent and homogeneous between various garment fits and types. This fact together with the observed low standard deviation between 3D scanning repetitions despite complete redressing of the manikin indicated a potential for a precise correlation model. Nonetheless, no comprehensive analysis of the data available in literature has been done until now.

The existing mathematical clothing models available in the literature assume either no or a uniform air gap between the body and fabric layers (Berger and Sari 2000; Fan et al. 2000; Li and Holcombe 1998; Lotens and Havenith 1991). Such a simplification facilitates the computation process but disregards the non-uniform heat, vapour, and liquid water transfer, which depend on the presence of contact between surfaces (Umeno et al. 2001) and on the shape of the air layers trapped within clothing (Bouskill et al. 2002; Mert et al. 2015). The heterogeneous thickness of the air layers within the clothing system influences the local heat and vapour exchange. The air trapped beneath garments and adjacent to the outer layer provides the bulk of both the thermal and evaporative resistances. These parameters depend not only on the air gap average thickness but also on whether the garment surface is folded or smooth (Mert et al. 2015). Typically such a mathematical model would be used in a comprehensive approach together with other models, such as a human thermoregulation model or CFD (computational fluid dynamics) or similar models of the thermal environment for human thermal response and comfort prediction. In any case, the detailed information about thermal and moisture management properties of the clothing system including its air layers is necessary as an input for the human thermoregulation model for accurate thermal prediction of the local physiological response. Likewise, the thermal environment models also often require highly detailed input of the boundary conditions especially when simulating low air velocities, such as in indoor spaces and even small temperature gradients may have a substantial impact on the course of the fluid flow.

The aim of this study was to develop an empirical regression model of the air gap thickness and the contact area in typical casual and protective clothing. The database of 3D scans gathered over several years of research formed a basis for the explorative statistical analysis. The model shall support research and development endeavours in clothing research, indoor environment engineering, thermal comfort in occupied indoor spaces, street canyons, and other outdoor spaces.

Methods

Model development strategy

The model of the air gap thickness and the contact area was developed based on the database of the garments available in the literature. Several studies that used 3D body scanning technique to determine the sought parameters came up from the same laboratory (although measured on two different manikins and using two different 3D scanners), and hence, represented high consistency of methodology and output data. The individual repetitions were gathered in a data pool over which an exploratory data analysis was done showing linear dependence of the air gap thickness and the contact area on the ease allowance at the corresponding body landmarks. In the next step, the linear regression analysis was conducted including the sensitivity analysis. To confirm the relevancy of the regression model for predicting thermal and evaporative properties of fabric-air-layer assemblies as well as thermo-physiological response once applied as clothing characteristics on the human, further error propagation studies were carried out using the fabric assembly model by Mert et al. (2015) and human thermoregulation model by Fiala and Havenith (2016; Fiala et al. 2012). Furthermore, we have hesitated to analyse the effect of air gap thickness on the human thermal sensation due to high discrepancy between trends and magnitudes of predictions using various thermal sensation models (observed differences of up to seven thermal sensation units) as proved by Koelblen et al. (2016). Instead, we have provided information on more basic parameters, such as mean skin and local and body core temperatures that constitute a direct input to several existing thermal sensation models as a more reliable approach. The scheme of the use of models at different complexity level and their inputs and outputs is shown in the figure.

Measurement methodology

The data in all studies were obtained using the same method of gathering 3D scanning data and post-processing, which is scanning and aligning 3D scans of nude and dressed manikin followed by computation of the distance between body and the garment using surface inspection software Geomagic Cotrol (Geomagic Inc., USA), which was developed and validated in our laboratory (Psikuta et al. 2012c; Psikuta et al. 2015). Two different 3D body scanners were used for different clothing sets, such as the stationary scanner VITUS XXL (Human Solutions GmbH, Germany) for garments 1–9 and 29–37 in Table 1 and the hand-held scanner Artec MHT (Artec Group, USA) together with a geometrical reference and a driver built in-house leading the scanner on the spiral-like trajectory around the scanned object for all remaining garments. Two male manikins in a standing straight position served as a human body form for which the proper size of garments was selected (store-bought garments) or designed (garments confectioned for the given study). One manikin was a hard-shell shop window manikin (Fig. 2a; LaRosa, Italy) with a height of 189 cm, a girth of 97.5 cm at the chest, 74 cm at the waist, and 94 cm at the hips (measured according to ISO7250-1: 2008 (ISO 7250 2008)), and the other was an agile manikin made of polyurethane foam with plastic coating (Fig. 2b; Polyform® GmbH & Co. KG., Germany) with the height of 180 cm, a girth of 91 cm at the chest, 77 cm at the waist, and 91 cm at the hips. The manikins slightly differed in body curvature and the position of the legs (Fig. 2). Only 6 out of 51 garments (26–28 and 49–51 in Table 1) were evaluated using the agile manikin (Fig. 2b).

The division into body parts were compatible between studies so that a common range of body parts in the database could be established. The air gap thickness for each body part was defined as an average distance of the garment surface attributed to the given body part to its counterpart region on the body. The contact area was defined as a percentage of the body part area staying in contact with the garment.

Database of garments

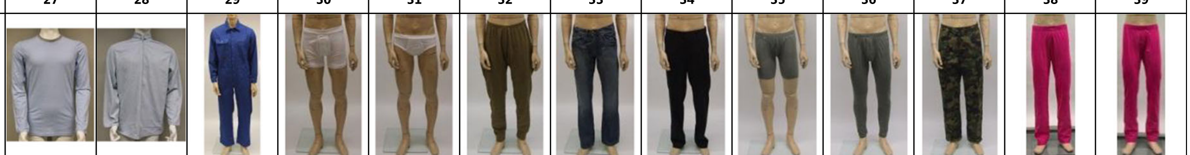
The database of garments was created based on several studies conducted in our laboratory over the past 7 years. Table 1 describes the basic technical parameters of each garment, such as fabric fibre content, fabric weight, and structure as well as the effective ease allowances of garments at standardised body landmarks. The original data was obtained from the following studies:

- garments 1–9 and 29–37 were evaluated in the internal pilot study dealing with variety of casual clothing;
- garments 10–19 were involved in determination of the impact of moisture content on air gap thickness (Frackiewicz-Kaczmarek et al. 2015a);
- garments 10–15 and 20–22 were used in systematic study of garment fit on air gap distribution at upper body (Frackiewicz-Kaczmarek et al. 2015e);
- garments 38–46 were used in systematic study of garment fit on air gap distribution at lower body (Mert et al. 2016);

Table 1 Description of the garments included in the database for development of the air gap and contact area distribution model

No	1	2	3	4	5	6	7	8	9	10	11	12	13
													
Garment type	Athletic shirt	T-shirt	Shirt	Smart shirt	Sweater	T-shirt	Shirt	Jacket	Fleece jacket	Shirt loose	Shirt regular	Shirt tight	Shirt loose
Fibre content (%)*	100 CO	100 CO	100 CO	100 CO	100 CO	100 PES	100 PES	50 PES/50 CO	100 PES	98 CO/2 EL	98 CO/ 2 EL	98 CO/ 2 EL	100 CO
Fabric weight [g/m^2]	145	175	227	124	361	156	259	269	412	188	188	188	251
Fabric structure	1x1 rib	Single jersey	Interlock	Plain weave	Single jersey	Birds eye	Warp knit	Gabardine	Double Fleece	Single jersey	Single jersey	Single jersey	Interlock
EA chest**	-14	12	6	18	13	-8	2	28	16	8	0	-8	8
EA waist**	10	32	30	36	42	16	26	42	40	28	20	10	25
EA hips**	-10	12	10	20	-10	-4	6	26	20	9	1	-9	6
EA biceps**	-	7	6	11	6	2	6	21	10	9	3	1	9
EA lower arm**	-	-	3	10	7	-	4	18	8	-	-	-	-

No	14	15	16	17	18	19	20	21	22	23	24	25	26
													
Garment type	Shirt regular	Shirt tight	Shirt regular	Shirt tight	Shirt regular	Shirt tight	Smart shirt loose	Smart shirt regular	Smart shirt tight	T-shirt loose	T-shirt regular	T-shirt tight	Shirt loose
Fibre content (%)*	100 CO	100 CO	98 PES/2 EL	98 PES/2 EL	100 PES	100 PES	100 CO	100 CO	100 CO	95 CO/5 EL	95 CO/5 EL	93 PES/7 EL	95 CO/5 EL
Fabric weight [g/m^2]	251	251	224	224	232	232	137	137	137	176	176	250	186
Fabric structure	Interlock	Interlock	Single jersey	Single jersey	Interlock	Interlock	Plain weave	Plain weave	Plain weave	Single jersey	Single jersey	Single jersey	Single jersey
EA chest**	5	-2	2	-6	0	-7	18	10	1	12	7	-19	7
EA waist**	19	11	20	10	19	10	39	24	12	39	22	4	15
EA hips**	3	-5	1	-9	2	-9	21	11	1	19	8	-16	3
EA biceps**	3	0	5	2	3	1	14	11	9	10	2	0	7.5
EA lower arm**	-	-	-	-	-	-	10.5	8.5	7.5	-	-	-	4.5

No	27	28	29	30	31	32	33	34	35	36	37	38	39
													
Garment type	Shirt regular	Jacket	Overall	Shorts	Trunks	Long johns	Jeans	Trousers	Shorts	Long johns	Trousers	Sweat pants loose	Sweat pants regular
Fibre content (%)*	95 CO/5 EL	100 CO	60 CO/40 PES	100 CO	100 CO	100 CO	100 CO	60W/ 38PES/2EL	100 PES	100 PES	50 PES/50 CO	98 CO/2 EL	98 CO/2 EL
Fabric weight [g/m^2]	186	345	336	145	145	227	366	202	156	259	269	188	188
Fabric structure	Single jersey	3/1 Twill	2/2 S	1x1 rib	1x1 rib	Interlock	3/1 twill	2/1 S	Birds eye	Warp knit	Gabardine	Single jersey	Single jersey
EA chest**	1	15	2	-	-	-	-	-	-	-	-	-	-
EA waist**	6	23	18	-	-	-	-	-	-	-	-	-	-
EA hips**	1	15	7	-5	-4	10	12	14	-5	6	10	9	6
EA biceps**	3.5	10.5	14	-	-	-	-	-	-	-	-	-	-
EA lower arm**	2.5	10.5	9	-	-	-	-	-	-	-	-	-	-
EA thigh**	-	-	9	-	-	13	3	12	-	3	13	10	6
EA lower leg**	-	-	10.5	-	-	8.5	8.5	15.5	-	-1.5	14.5	12.5	5

No	40	41	42	43	44	45	46	47	48	49	50	51	
													
garment type	Sweat pants tight	Sweat pants loose	Sweat pants regular	Sweat pants tight	Jeans loose	Jeans regular	Jeans tight	Work trousers with pockets	Work trousers	Sweat pants loose	Sweat pants regular	Jeans	
Fibre content (%)*	98 CO/2 EL	100 CO	100 CO	100 CO	100 CO	100 CO	100 CO	60 PES/ 35 CO/ 5 EL	60 PES/ 35 CO/ 5 EL	95 CO/5 EL	95 CO/5 EL	100 CO	
Fabric weight [g/m^2]	188	251	251	251	179	179	179	284	284	186	186	345	
Fabric structure	Single jersey	Interlock	Interlock	Interlock	3/1 twill	3/1 twill	3/1 twill	3/1 twill	3/1 twill	Single jersey	Single jersey	3/1 twill	
EA hips**	6	9	6	6	9	6	6	10	10	17	13	21	
EA thigh**	5	10	6	5	10	6	3	9.5	9.5	8.5	2.5	10.5	
EA lower leg**	-3	12.5	5	-3	12.5	7.5	3.5	7.5	7.5	9.5	1.5	10.5	

**CO*, cotton; *PES*, polyester; *EL*, elastane; *W*, wool

***EA*, ease allowance as a difference between body and garment girth at given landmark

- garments 26–28 and 49–51 were evaluated in various postures including the basic standing straight posture (Mert et al. 2017);
- garments 23–25 were involved in comparison of air gap distribution in male and female T-shirts (Mark 2013);
- garments 47 and 48 were evaluated for the effect of tailor features on air gap thickness (Böhnisch 2015).

In total, the database of garments is comprised of 51 clothing pieces including 28 upper body garments, 22 lower body garments, and one coverall applied every time as a single-layer garment measured at a time.

Statistical analysis

The data analysis was done based on two parameters of interest including air gap thickness and contact area between the garment and the skin. The data from all studies were collected in separate data pools for each body region. Since in all studies the same body division and a similar number of measurement repetitions (four repetitions for garments 26–28 and 49–51 and six repetitions for the remaining 45 garments) were used, there was no need for additional data processing. A corresponding body landmark at which ease allowance was determined was attributed to each body region, such as chest girth to upper and lower chest and back, waist girth to abdomen and lumbus, hip girth to anterior and posterior pelvis, thigh girth to anterior and posterior thigh, lower leg girth to calf and shin regions, biceps girth to upper arm, and lower arm girth to lower arm region. A linear regression analysis was conducted for each body region individually using MS Excel 2010 (linest function), and subsequent determination of the goodness-of-fit and associated standard errors was performed, where ease allowance (cm) was the independent variable and air gap thickness (mm) and contact area (% of total region area) were dependent variables.

Error propagation study

The further analysis of error propagation related to the error in predicting air gap thickness and the contact area was conducted in order to determine its effect on the heat loss calculation. The model of conduction and radiation in the clothing air layer as described in Mert et al. (2015) was used to calculate the variation in thermal and evaporative resistances and the heat loss due to an error in prediction of the air gap thickness. The simulation was done for an air and radiant temperatures of 20 °C, skin temperature of 35 °C, ambient air movement of 0.2 m/s, relative humidity of 50%, and for a single fabric layer with $R_{ct} = 0.05$ m^2 K/W. The simulations were done for an air gap range of 0–50 mm between the skin and the fabric layer and its variation by a standard error. Finally, the uncertainty of the thermal and evaporative resistances as well as heat loss were analysed in relation to the standard error of the air gap thickness.

In the second step, the effect of this uncertainty on the human thermo-physiological response was evaluated using the model of human thermoregulation FPCm 5.3 (Ergonsim, Germany) (Fiala et al. 2012; Fiala and Havenith 2016), which is the most extensively validated physiology model worldwide (Martínez et al. 2016; Psikuta et al. 2012a). A combination of three ambient temperatures of 10, 20, and 30 °C and two metabolic rates of 1.5 and 3 met (metabolic equivalents, 1 met = 58.2 W/m^2) were chosen to represent cold, neutral, and hot environments and typical indoor activities (office work or light physical work), respectively. Two ensembles representing typical indoor clothing in tight and loose fit were chosen as a basis for the simulation. The tight fitting ensemble consisted of tight undershirt and tight jeans (items 10 and 44 in Table 1) and the loose fitting ensemble consisted of loose undershirt and loose jeans (items 12 and 46 in Table 1). The air gaps in the clothing were simulated using the model developed in this study based on the ease allowances of individual garments given in Table 1. Further, the local thermal and evaporative resistances of both ensembles for covered body regions were simulated using the model described in Mert et al. (2015). In addition, the local thermal and evaporative resistances for air gaps with an added and subtracted standard error were computed. Finally, the simulation of all combinations of garments and exposure conditions was performed to analyse the effect of standard error of the estimated air gap thickness on human thermo-physiological response. In addition, the thermo-physiological effect of some typical assumptions found in literature regarding air gap thickness value, such as full contact (air gap thickness equal to zero) and homogeneous air gap applied to the entire body, was compared to the effect of the realistic (measured) heterogeneous (local) air gap in tight and loose fitting ensembles.

Results

Table 2 summarises the linear regression analysis performed for individual body regions at upper and lower body. Figure 3 depicts the air gap thickness and contact area with standard deviation in relation to the ease allowance at the corresponding landmarks of the individual garments including linear regression lines for upper anterior and upper posterior body, arms, and lower body, respectively. In addition, the regression lines provided by Mert et al. for systematically designed garments at lower body regions (dashed line, Fig. 3) were compared in this figure with regression lines obtained for larger amount of lower body garments (Mert et al. 2016).

The mean standard error (mean of absolute residuals) for all body parts and garments approximated 3.6 mm (between 1.2 and 7.2 mm) for the air gap thickness and 10.3% (between 4.8

Table 2 Coefficients of the linear regression analysis for air gap thickness and contact area related to ease allowance for individual body regions at upper and lower body

Body region	Air gap thickness (AGT)						Contact area (CA)					
	Slope mm/cm**	SE_{slope}* mm/cm	Intercept mm	$SE_{intercept}$* mm	R^2 –	SE_{AGT}* mm	Slope %/cm**	SE_{slope}* %/cm	Intercept %	$SE_{intercept}$* %	R^2 –	SE_{CA}* %
Upper body garments												
Upper chest	0.1	0.0	4.4	0.1	0.40	1.7	− 0.6	0.1	33.8	1.2	0.14	14.0
Lower chest	0.2	0.0	5.0	0.2	0.58	2.1	− 1.1	0.1	45.3	0.8	0.57	9.6
Abdomen	0.6	0.0	0.2	0.8	0.69	4.4	− 0.6	0.1	23.9	1.5	0.38	8.8
Anterior pelvis	0.7	0.0	10.1	0.4	0.77	4.4	− 1.2	0.1	23.5	1.1	0.53	12.2
Upper back	0.0	0.0	3.5	0.1	0.03	1.2	− 0.4	0.1	45.5	1.2	0.08	12.7
Lower back	0.3	0.0	8.1	0.3	0.50	2.9	− 1.2	0.1	34.0	0.8	0.61	8.8
Lumbus	1.1	0.0	7.2	1.3	0.75	6.7	− 0.3	0.0	12.0	0.9	0.35	4.8
Posterior pelvis	1.0	0.1	11.6	0.7	0.66	7.2	− 1.0	0.1	20.0	1.2	0.40	12.5
Upper arm	0.9	0.0	2.9	0.4	0.83	2.0	− 1.7	0.1	34.9	1.0	0.74	4.9
Lower arm	1.1	0.1	5.6	0.5	0.86	1.8	− 1.0	0.2	18.9	1.6	0.33	5.5
Lower body garments												
Anterior pelvis	0.3	0.0	4.1	0.3	0.49	2.1	− 1.5	0.1	29.3	1.2	0.55	8.5
Posterior pelvis	0.2	0.0	4.1	0.4	0.19	3.1	− 1.5	0.2	38.3	2.2	0.27	15.6
Anterior thigh	1.1	0.1	−0.6	0.7	0.61	3.2	− 4.6	0.4	59.6	3.0	0.60	13.2
Posterior thigh	1.4	0.1	1.3	0.8	0.67	3.5	− 3.7	0.4	44.1	3.0	0.49	13.3
Shin	1.8	0.1	8.5	0.7	0.82	4.7	− 1.5	0.2	17.9	1.6	0.42	10.0
Calf	0.7	0.1	7.2	1.0	0.28	6.4	− 2.2	0.2	36.3	1.7	0.59	10.5

**SE* standard error, which is the average of absolute residual values

**The units indicate the rate of change of the air gap thickness in mm and contact area in % per unit of ease allowance given in cm

and 15.6%) for the contact area. The trends for the upper body seemed to be slightly more consistent with smaller average standard errors of 3.4 mm (between 1.2 and 7.2 mm) and 9.4% (between 4.8 and 14.0%) than for the lower body with 3.8 mm (between 2.1 and 6.4 mm) and 11.8% (between 8.5 and 15.6%) for air gap thickness and the contact area, respectively.

Figure 3 (dashed line) shows the correlation between ease allowance and air gap thickness for lower body garments based on a systematic study of two kinds of underpants and jeans at three levels of fit introduced by Mert et al. (2016). These trends were repeated to a great extend when including further 14 lower body garments. The trend at the pelvis has slightly changed due to inclusion of tight underwear that was not considered in Mert et al. (2016) study. The trends at the anterior and posterior thigh changed also, since several trousers with larger leg fullness were added to the database. The data for lower leg measured on the agile manikin (garments 49–51, Table 1) were excluded from the analysis, since the position of the lower legs was not anatomically correct during the 3D scanning as in the case of the hard-shell manikin (compare Fig. 1a, b).

Figures 4 and 5 show the results of the error propagation study and demonstrate the influence of the standard error in prediction of the air gap thickness on garment thermal properties and human thermo-physiological response when wearing these garments. In particular, Fig. 4 depicts the thermal and evaporative resistances and exemplary heat loss simulated using model described by Mert et al. (2015) including change of these parameters due to standard error in the model of the air gap thickness. Figure 5 presents the mean and some local skin temperatures as well as body core temperature for tight and loose fitting ensembles (continuous lines) including air gap variation due to standard error in its estimation (dashed lines) for selected combinations of the environmental conditions and activity levels. The upper back and lumbus were chosen for analysis of local skin temperatures due to their distinct trends in distribution of the air gap thickness, namely, low and constant air gap thickness at upper back and large and highly dependent on ease allowance air gap thickness for lumbus.

Figure 6 shows the mean skin, body core, upper back, and lumbus skin temperatures for various approaches to obtaining air gap thickness value and distribution in tight and loose fitting ensembles for a combination of the environmental conditions and activity levels, where (a) assumed full contact vs. measured mean air gap thickness in a tight garment, (b) mean vs. local measured air gap thickness in tight and loose fitting

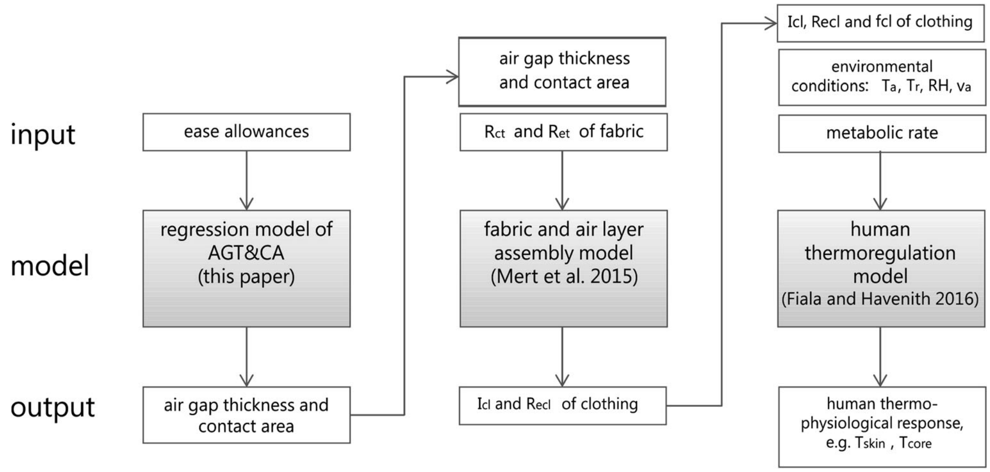


Fig. 1 The scheme of simulation order using a cascade of various models (Fiala and Havenith 2016; Mert et al. 2015) as well as required and resultant input and output parameters, where R_{ct}, R_{et}, I_{cl}, and R_{ecl} are thermal and evaporative resistances of the fabric and clothing at individual body regions, respectively; f_{cl} is the local clothing area factor determined by 3D scanning; T_a, T_r, RH, and v_a are ambient and radiant temperatures, relative humidity, and air velocity, respectively

ensembles, (c) tight vs. loose fitting ensembles with measured local air gap thickness.

Discussion

After the 3D body scanning technique was applied in the clothing research area, it was possible to visualise and quantify the air gap thickness and the contact area distribution in a great detail. This study for the first time summarised the available results on these parameters and provided a statistical model predicting the sought parameters for a number of body regions. This information is necessary for mathematical models of heat and mass transfer in clothing to realistically predict thermal behaviour of the clothing system and its possible impact on human thermal response. Secondly, since air gap significantly affects thermal and evaporative resistances and can greatly vary over the body, detailed information about local thermal clothing properties at least corresponding to the body resolution of physiological models is needed. The studies that served as a basis for the air gap and contact area model developed in this study provided the necessary fine body resolution matching to the body division of the majority of the human thermoregulation models. The ease allowance, which is the difference in circumference between the body and the garment at corresponding landmarks, was chosen as an

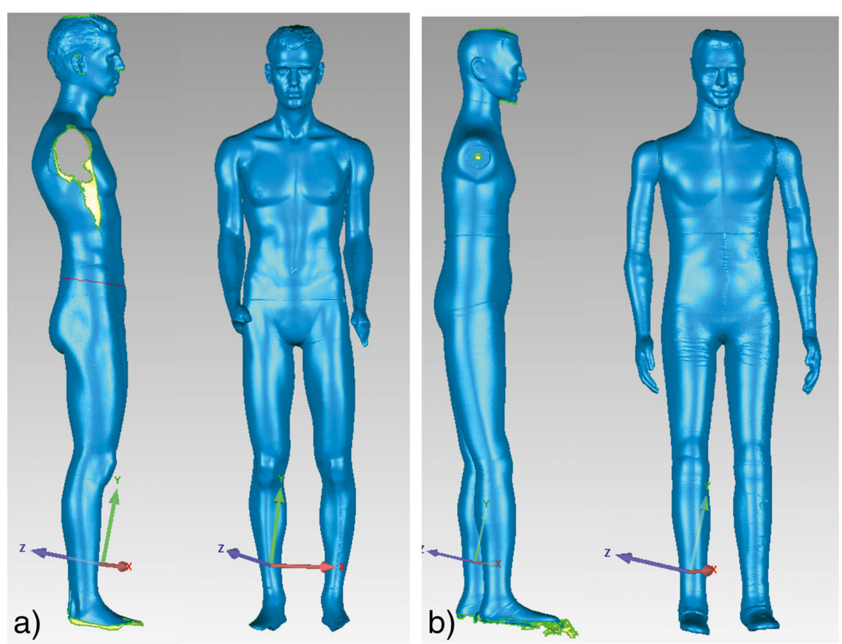
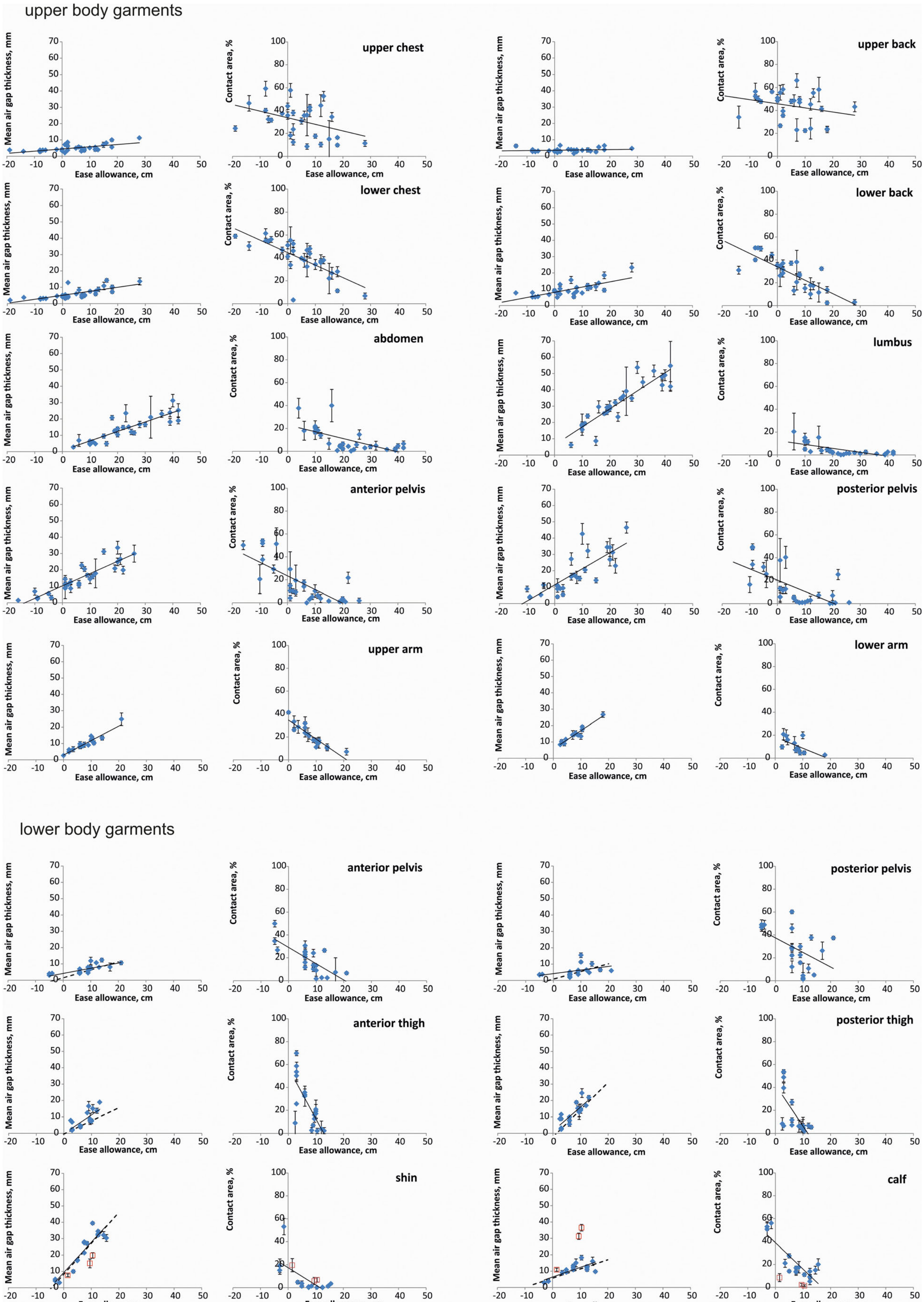


Fig. 2 Profile and frontal view of manikins used in evaluation of garments. **a** Hard-shell manikin. **b** Agile manikin


upper body garments
upper chest
upper back
lower chest
lower back
abdomen
lumbus
anterior pelvis
posterior pelvis
upper arm
lower arm
lower body garments
anterior pelvis
posterior pelvis
anterior thigh
posterior thigh
shin
calf
Mean air gap thickness, mm
Contact area, %
Ease allowance, cm

◀ **Fig. 3** Air gap thickness and contact area with standard deviation in relation to the ease allowance at the corresponding landmarks of the individual garments for upper and lower body including linear regression lines (continuous line) included in the model in Table 2. In addition, linear regression line according to Mert et al. (dashed line) and data points not included in the analysis (red squares) were marked in the graphs (Mert et al. 2016)

independent parameter representing reliably clothing fit as shown in various studies (Frackiewicz-Kaczmarek et al. 2015a, e; Mert et al. 2016; Bohnet 2013; Mark 2013).

Linear correlations for air gap thickness for upper and lower body garments were observed at all body parts. At some body parts such as upper and lower chest and back as well as anterior and posterior pelvis, the dependence of the air gap thickness on ease allowance is minimal, approximating 0.1–0.3 mm/cm of ease allowance (Table 2). This means that regardless of the garment fit and the fabric used, the air gap thickness remains nearly constant at these body parts. This is because the clothing rests on these inclined body parts due to gravity force (upper chest and back) or needs to be snugly adjusted to the body for garment to stay in place (pelvis) (Psikuta et al. 2012c). At the remaining body parts, the air gap thickness increased proportionally with the increase of the ease allowance at the rate between 0.6–1.8 mm/cm of ease allowance (Table 2). The strength of this linear trend is also indicated by high correlation coefficients between 0.61 and 0.86. Whenever garment is hanging at the edge of the protruding body part (e.g. below breast, shoulder blades, and buttocks) or below a fixed point (e.g. waistband), the garment fullness represented by ease allowance and originating folds increase the distance of the fabric from the skin (Frackiewicz-Kaczmarek et al. 2015e; Mert et al. 2016).

The linear trends were also observed for the correlation between contact area and ease allowance with the reverse proportionality (negative slope, Table 2). That means that the contact area between the body and the garment decreases with the increase of the ease allowance. The lowest dependence of the contact area on ease allowance was observed for the upper chest and back, abdomen, and lumbus and approximated less than −0.6%/cm of ease allowance (Table 2). The uniformity of contact area at the upper chest and back through variety of garments is due to gravitational force compelling the fabric to rest on the body, whereas the concavity of the body under protruding body region is responsible for low contact area at lumbus and abdomen. For the remaining body parts, the slope of the contact area was between −1.0 and −4.6%/cm of ease allowance indicating sensitivity of this parameter to the garment design decisions at these regions.

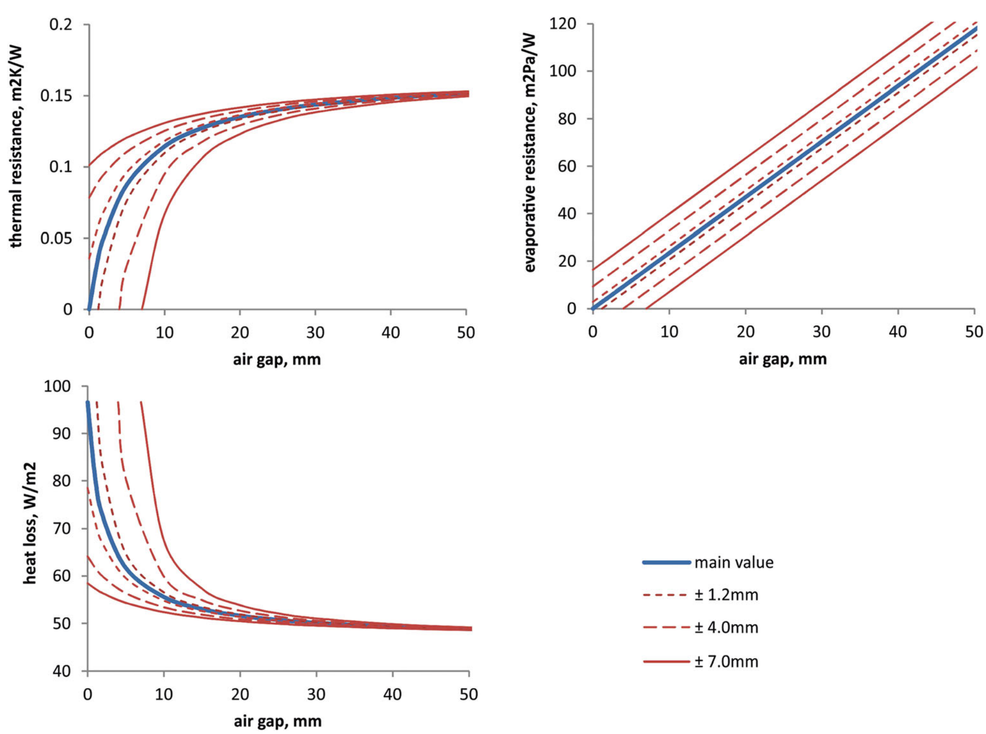
The heat loss is insensitive to the contact area until this parameter reaches value of about 50–60% (Mert et al. 2015). In this study, such high contact area was approached only at several body parts, such as upper and lower chest, upper back, and anterior thigh. In all these cases, the contact area was not higher than 70%. Even in wet state when the fabric weight, rigidity, and affiliation to surfaces are affected by moisture, the contact area observed in tight undershirts did not exceed 60% (Frackiewicz-Kaczmarek et al. 2015a). Therefore, the assumption made by some mathematical clothing models of the full contact for tight garments (Fan et al. 2000; Li and Holcombe 1998; Lotens and Havenith 1991) is not valid within the range of typical casual and protective clothing included in this database.

The analysis of the error in predicting air gap thickness and contact area was conducted in order to determine their effect on the heat loss calculation. Such sensitivity study is necessary to estimate the final uncertainty of predicting the heat transfer, because the air provides the main bulk of thermal and evaporative resistance in the clothing system and its even small change in thickness may lead to a large alteration in heat loss. Since dry heat transfer in the air layer with increasing thickness is a non-linear phenomenon, the effect of error in air gap thickness prediction is expected to be varying with the air gap thickness as well. The available model of conduction and radiation in the clothing air layer (Mert et al. 2015) was used to calculate the variation in thermal and evaporative resistances and heat loss due to an error in prediction of the air gap thickness. The standard error in the air gap thickness approximated between 1.2 mm for upper back and 7.2 mm for posterior pelvis (Table 2). The theoretical impact of this standard error on thermal and evaporative resistances and heat loss is depicted in Fig. 4 for an exemplary exposure at ambient temperature of 20 °C (T_{skin} = 35 °C, v_{air} = 0.2 m/s, for single fabric layer with R_{ct} = 0.05 m^2 K/W). The effect of the standard error on thermal resistance changes for various air gap thicknesses, which is related to non-linear radiative heat transfer according to Stefan-Boltzmann law. This means that the same absolute standard error value will have larger effect for small air gaps and nearly negligible effect at large air gap thickness range (see Fig. 4). The evaporative resistance is uniformly affected by the prediction error throughout the different air gap thickness. This is related to the linear influence of the air gap thickness on water vapour diffusion between limiting clothing layers. Due to the high sensitivity of the dry heat loss on the prediction error, the body parts with generally small air gap are prone to an inaccurate estimation of the heat transfer. On the other hand, these body parts, such as lower and upper chest and back for upper body garments and anterior and posterior pelvis for lower body garments with air gaps being typically below 10 mm, showed the lowest standard errors approximating 1.2–3.1 mm. The largest standard errors approximating 4.7–7.2 mm were observed for body parts with typically the largest air gaps being typically above 15 mm and up to 60 mm, such as lumbus, posterior pelvis, shin, and calf. In this range of the air gap thickness, the effect of prediction error is substantially lower (Fig. 4). In conclusion, it seems that the effective uncertainty in thermal resistance for body parts with larger error and, at the same time, larger typical air gaps, i.e. errors between 4 and 7 mm for air gaps 15–50 mm in Fig. 4 is comparable to or lower than that at the body parts with lower standard error and lower typical air gap thickness, i.e. errors between 1.2–4 mm for air gaps 0–15 mm in Fig. 4.

To evaluate the consequence of the uncertainty in the thermal and evaporative resistances on the human response, a further modelling step was undertaken using physiology model and a combination of environmental conditions and activity levels. Figure 5 shows that both predicted mean and local skin temperatures were noticeably affected by this uncertainty by up to 1.4 and 1.5 °C between lower and upper bounds of temperature, respectively, resulting from the standard error in air gap thickness prediction for the presented examples. The core temperature, which is one of the most inert physiological parameters, was also affected by up to 0.16 °C between lower and upper bounds. These bound ranges represent roughly half of a typical intra- and inter-subject standard deviation observed in human experimental studies, which is a state-of-the-art reference for assessment of the goodness-of-fit in physiological model validations (Psikuta et al. 2012a) (i.e. 0.5–1.0 °C for mean skin temperature, 0.2–0.3 °C for body core temperature, 1–2 °C for local skin temperatures). This means that the effect of standard error in air gap thickness prediction on the thermo-physiological response presented in Fig. 5 is lower than the aforementioned differences observed between healthy humans.

The majority of clothing models reported in the literature assumes full contact between the garment and the body or a certain (arbitrary) homogenous air gap. The problem of unknown air gap was addressed at first by Bouskill et al. (Bouskill et al. 2002; Bouskill 1999) who used a tracking gas method to estimate total air volume trapped underneath the clothing. Based on this measurement and the covered body surface area, the average air gap thickness could be calculated. Some detailed fabric models with integrated physiological model suggested using no air gap for tight clothing assuming that the entire garment is in full contact with the body or some arbitrary values for an average air gap thickness, e.g. 5 mm (Li and Holcombe 1998; Fan et al. 2000). However, in reality, the air gap thickness is much larger. For example, an ensemble consisting of tight undershirt and tight jeans (items 10 and 44 in Table 1) represents an average air gap thickness of 6.8 mm, and another ensemble consisting of loose undershirt and loose jeans (items 12 and 46 in Table 1) represents an average air gap thickness of 16.6 mm. Such a difference has a substantial impact on heat and mass transfer through the air gap and the entire clothing system. Referring to the example shown in Fig. 4, the dry heat loss may decrease by a third when using an average air gap of 6.8 mm instead of suggested 0 mm for tight

Fig. 4 Thermal and evaporative resistances and exemplary heat loss simulated using the model described by Mert et al. (2015) at $T_{air} = 20$ °C, $T_{rad} = 20$ °C, RH = 50%, $T_{skin} = 35$ °C, $v_{air} = 0.2$ m/s, for single fabric layer with $R_{ct} = 0.05$ m^2 K/W and variable air gap thickness including change of these parameters due to added or subtracted standard error to the predicted value of the air gap thickness



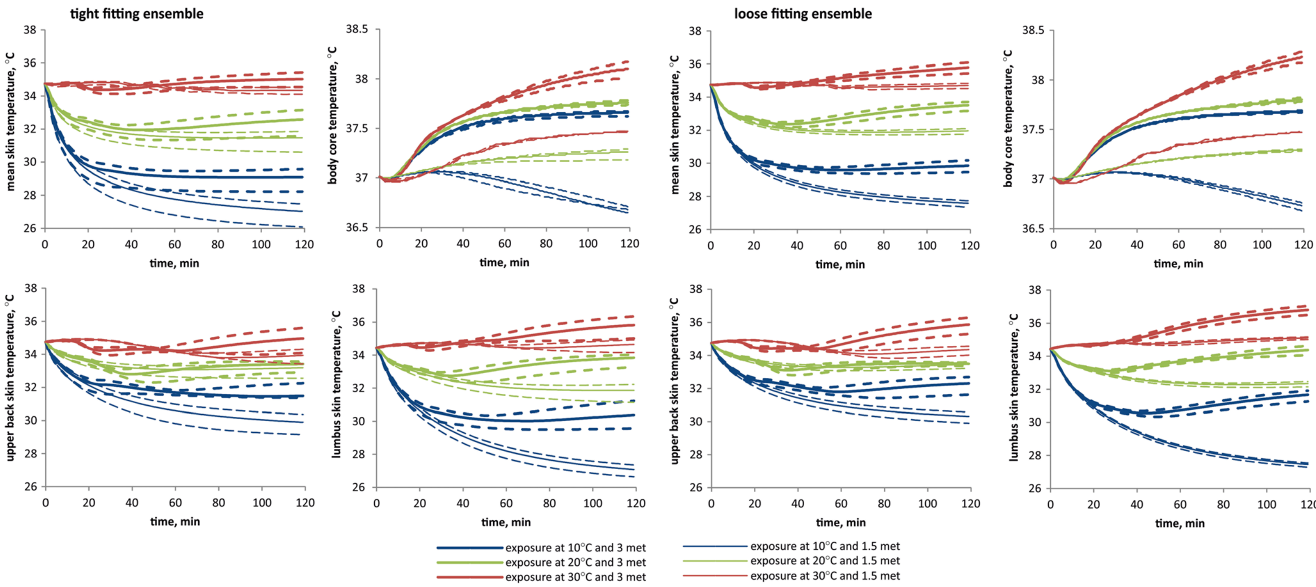


Fig. 5 Mean skin, body core, upper back, and lumbus skin temperatures for tight and loose fitting ensembles (continuous lines) including air gap variation due to standard error in its estimation (dashed lines) for chosen combinations of the environmental conditions and activity levels

garments (at ambient air temperature of 20 °C, skin temperature of 35 °C, and still air conditions). Secondly, the fit of clothing can have a great impact on thermal properties of the clothing system even if the fabric used for confection remains the same. In the case of the example from Fig. 4, the difference in heat loss between tight and loose ensembles at ambient temperature of 20 °C approximates 10 W/m^2. However, this difference may increase substantially for more thermally challenging environments according to the change in the thermal and evaporative resistances for various fits (Fig. 4).

Since both thermal and evaporative resistances are greatly affected by the magnitude of the air gap thickness, it is expected that this effect will be also pronounced in human thermal response when wearing various ensembles. We evaluated several assumptions used for the air gap thickness estimation that researchers have available at the moment to demonstrate the improvement of the simulation accuracy when using the presented air gap distribution model over practice and data available up-to-date. A frequent assumption found in literature is attributing 0 mm air gap thickness to tight fitting clothing (Spencer-Smith 1977; Li and Holcombe 1998; Fan et al. 2000; Lotens and Havenith 1991). As seen in Fig. 3, this assumption is not represented by any garment included in the database of this study. In the simulated example in Fig. 6a, the mean and local and body core temperatures' comparison between garment with 0 mm air gap and realistic tight garment with an average air gap of 6.8 mm are shown. The observed differences approximated between 0.5–2.3, 0.7–3.2, 1.2–5.8, and 0.02–0.26 °C for mean skin, upper back, lumbus, and body core temperatures, respectively. Such substantial differences are physiologically relevant and may lead to false estimation of the resultant thermo-physiological state of the human body. Secondly, assuming the average air gap thickness for the entire body, such as in the case of estimating the air gap thickness based on volume measurement including trace gas or 3D scanning methods, the local skin temperatures and possibly also mean and global body thermo-physiological response may be inaccurate. In the case of the tested scenarios (Fig. 6b), these differences were up to 0.3 and 0.4 °C for mean skin temperature, 0.03 and 0.04 °C for body core temperature, 0.7 and 0.9 °C for upper back skin temperature, and 1.1 and 1.0 °C for lumbus skin temperature for tight and loose ensembles, respectively. In addition, the trends at upper back and lumbus were reversed, since the air gap thickness at the upper back is lower and at the lumbus greater than the mean air gap thickness for the entire ensemble. Although the differences for mean skin and body core temperatures were rather small (within experimental error in human studies), the local skin temperature differences can be critical for local and overall thermal sensation and comfort prediction. Finally, the effect of the clothing fit was evident in the thermo-physiological response showing the differences of up to 0.9, 0.13, 1.3, and 0.6 °C for mean skin, body core, upper back, and lumbus temperatures, respectively, in the tested scenarios (Fig. 6c). This comparison proves that the dedicated design of the clothing can have an influence on the human thermo-physiological response beyond the statistical error, and hence, can be used to customise and to support the desired thermal clothing effects.

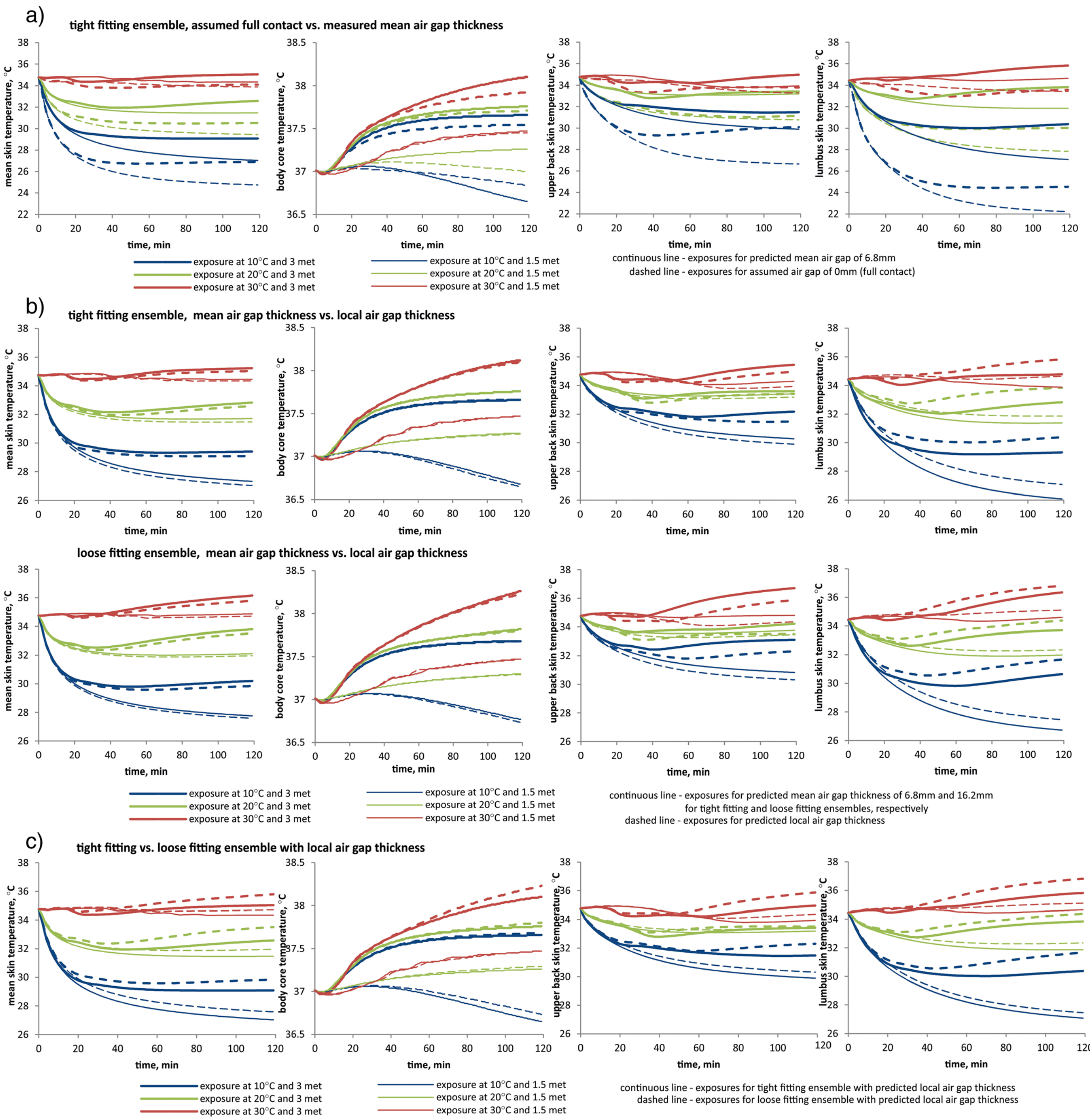


Fig. 6 Mean skin, body core, upper back, and lumbus skin temperatures for various approaches to air gap thickness value and distribution in tight and loose fitting ensembles for a combination of the environmental conditions and activity levels, where **a** assumed full contact vs. measured mean air gap thickness in a tight garment, **b** mean vs. local measured air gap thickness in tight and loose fitting ensembles, and **c** tight vs. loose fitting ensembles with measured local air gap thickness

Conclusions

This paper presented the advanced model of air gap thickness and contact area able to predict the distribution of the sought parameters locally and reliably. For the first time, the available results on these parameters were summarised and further compiled into a statistical model predicting the air gap thickness and contact area for 14 body regions based on the ease allowances for the given landmarks. Not only the thermal processes in the clothing but also their impact on human thermo-physiological response in relation to the air gap thickness was analysed to demonstrate the comprehensive approach to the human response simulation in the context of his thermal environment. It was found out that the effect of the standard error in air gap thickness prediction on the thermo-physiological response is lower than the differences between healthy humans, which demonstrate the credibility of this new model for predictions of thermo-physiological responses and evaluation of thermal clothing properties. Such a reliable and detailed model is crucial for mathematical models of heat and mass transfer in the clothing to realistically predict thermal behaviour of the clothing system and its possible impact on human thermal and perceptual response. It was demonstrated in several selected scenarios including different clothing fit levels that the up-to-date assumptions and methods for determination of the air gap thickness can produce a substantial error for all global, mean, and local physiological parameters, and hence, lead to false estimation of the resultant physiological state of the human body, and consequently, the thermal sensation and comfort. The greatest advantage of the air gap thickness model is visible when used in combination with a cascade of other powerful models to increase their accuracy by providing more accurate input parameters. Thus, the use of this detailed model shall contribute to the improvement of simulation of human thermo-physiological and perceptual response to the thermal environment for the evaluation of energy-saving conditioning technologies, and enhance the clothing design for protective and functional apparel to balance the environmental and bodily influence on clothing performance. Secondly, the advantage of this model over thermal manikin method for determination of clothing properties is that it provides the information about the share of various heat transfer phenomena useful for trouble-shooting of the garment performance and conscious design for the intended functionality. A selection of theoretical designs can be efficiently simulated, and the best design can be selected for confectioning and further evaluation, possibly with thermal manikins or human subjects, which makes manikin measurement and modelling not competing but complementary methods used for various research questions. Hence, this tool shall help researchers to strive for improvement of human thermal comfort, health, productivity, safety, and overall sense of well-being with simultaneous reduction of energy consumption and costs.

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