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ORIGINAL PAPER

Contribution of garment fit and style to thermal comfort at the lower body

Emel Mert[1,2] · **Sonja Böhnisch**[1,3] · **Agnes Psikuta**[1] · **Marie-Ange Bueno**[1,2] · **René M. Rossi**[1]

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Abstract The heat and mass transfer between the human body and the environment is not only affected by the properties of the fabric, but also by the size of the air gap thickness and the magnitude of the contact area between the body and garment. In this clothing-human-environment system, there is also an interaction between the clothing and the physiological response of the wearer. Therefore, the aim of this study was to evaluate the distribution of the air gap thickness and the contact area for the male lower body in relation to the garment fit and style using a three-dimensional (3D) body scanning method with a manikin. Moreover, their relation with the physiological response of the lower body was analysed using the physiological modelling. The presented study showed that the change in the air gap thickness and the contact area due to garment fit was greater for legs than the pelvis area due to regional differences of the body. Furthermore, the garment style did not have any effect on the core temperature or total water loss of the lower body, whereas the effect of garment fit on the core temperature and total water loss of lower body was observed only for 40 °C of ambient temperature. The skin temperatures were higher for especially loose garments at thigh than the tight garments. Consequently, the results of this study indicated that the comfort level of the human body for a given purpose can be adjusted by selection of fabric type and the design of ease allowances in the garment depending on the body region.

Keywords Air gap thickness · 3D body scanning · Heat and mass transfer in clothing · Thermal comfort · Lower body

Introduction

The human body is always in a direct interaction with its surrounding environment in which it attempts to keep its core temperature at around 37 °C, which indicates that the heat balance between the human body and the environment has been achieved (Parsons 2003). In this human-clothing-environment system, the clothing has a basic function to help the body to achieve this thermal balance, e.g. to protect the human body from especially harsh environmental conditions. Heat and mass transfer through the garment is not only dependent on the properties of the fabrics used in the garment but also on the change in the contact area and the air gap thickness between the garment layers and outer adjacent air layer (Spencer-Smith 1977; Mert et al. 2015). In these air layers, a number of physical processes occur, such as dry heat transfer (conduction, convection and radiation), evaporation and wicking of liquid sweat from the skin (where the contact areas are) and influence the thermal balance of the human body. Moreover, the fabric, which is in a direct contact with the body can take up the sweat from the skin and spread it to the larger area on the fabric, where the heat loss may increase due to evaporation (Umeno et al. 2001 ; Wang et al. 2014). The thickness of air layers and the magnitude of contact area can be affected by the mechanical properties of the fabric and the garment properties (various ease allowances due to the different fits and styles) (Mah and Song 2010; Frackiewicz-Kaczmarek et al. 2014a), moisture content, for example due to rain or excessive sweating,

✉ Agnes Psikuta
agnes.psikuta@empa.ch

[1] Empa, Swiss Federal Laboratories for Materials Science and Technology, St. Gallen, Switzerland

[2] Laboratoire de Physique et Mécanique Textiles, Ecole Nationale Supérieure d'Ingénieurs Sud Alsace, University Heute Alsace, Mulhouse, France

[3] Hochschule Albstadt-Sigmaringen, Albstadt, Germany

(Frackiewicz-Kaczmarek et al. 2014b), body posture and the movement of the limbs (Kirk and Ibrahim 1966), which can lead to heterogeneous heat transfer in clothing.

The garment is a 3D shape made from 2D pattern to cover the complex geometry of the human body. Depending on the garment style (difference in garment pattern) and fit (ease between the garment and the body), either the garment conforms to the body geometry or sags according to the mechanical properties of the fabric (drapability, bending rigidity) affecting the distribution of the air gap thickness and the contact area over the body. As it has been shown in previous studies, the air gap thickness and the contact area varied over body parts and formed mostly heterogeneous shape (Psikuta et al. 2012b). Moreover, the air gap thickness and the contact area are affected by different garment properties. Therefore, previous studies evaluated the effect of garment size (Chen et al. 2004; Lee et al. 2007; Lu et al. 2014), garment fit and style (Psikuta et al. 2012b; Frackiewicz-Kaczmarek et al. 2014a, 2014b) on the distribution of the air gap thickness. The garment size is designed only for a narrow range of body dimensions and one garment size is confectioned only for one body dimension (Daanen and Reffeltrath 2007). For example, the shoulder width, waist band length or sleeve length will stay the same for various garment fit levels, but they will vary among garment sizes. Therefore, using several garment sizes for one body shape (e.g. used manikin) for evaluation of air layers is unrealistic and incorrect. The garment fit, which is a relation between the body and the garment dimensions, is important for needed garment functionality, e.g. freedom of movement. Till now, the effect of the garment fit and style on the distribution of the air gap thickness on the upper body was analysed since the upper body is the largest and warmest body part and even small changes in the air gap thickness and contact area may have a large overall effect on the body thermal balance. However, the lower body is also important to maintain the body core temperature in extreme conditions. Therefore, the effect of the properties (fit and style) of the lower body garments on the distribution of the air gap thickness and their relation with the physiological response of the human body should also be investigated to understand the importance of the lower body garments with various fit and style in various ambient temperatures.

The extremities, especially the legs, are the first body parts, which are affected by the extreme ambient conditions. The role of extremities (legs and arms) is similar to help human body to maintain its core temperature. However, the surface area of legs is around 50 % higher than the surface area of arms (ISO 9920: 2007), which means that legs have two times higher importance than arms to support the balance of the core temperature at a desired level. Moreover, under cold conditions, legs and feet have the lowest skin temperature over the whole body and unless they are not protected against the harsh environmental conditions, cold injury may occur on these body parts frequently (Parsons 2003 ; Makinen et al. 2000). In these situations, the large leg muscles, such as quadriceps muscles on the anterior thigh, contribute greatly to the shivering thermogenesis (Charny 1992; Pearson et al. 2011). Furthermore, in the hot environments, vasodilation at the legs helps to increase the heat loss and to reduce the heat impact on the core temperature. The organs important for the immune system, which are also located at the pelvis area, are covered by trousers (40 % of whole trunk). They should be protected from external hazards. Moreover, around 25 % of sweat rate is released from the lower body in comparison to the sweat rate for the whole body with different sweating ratios for individual lower body regions (Smith and Havenith 2011). The moisture can then lead to excessive heat loss or wet discomfort, which can be prevented by garments that allow wicking of the moisture away from the skin. Therefore, controlling the heat transfer at the lower body by the air gap thickness (additional insulation) and the contact area (wicking of moisture) in the purposefully designed protective and functional garments can greatly contribute to the well-being of the wearer.

The aim of the study was to evaluate the effect of garment style and fit on the thermal comfort at the lower body. For this reason, the distribution of the air gap thickness for the lower body at different garment fits, such as tight, regular and loose fit, and styles, such as trousers and sweatpants, were determined using advanced 3D scanning and post-processing method developed in previous study and a stationary standing male manikin. The obtained air gap was used to derive the local thermal and evaporative resistances of garments for individual body regions. Finally, the obtained parameters were used in the physiological simulation to determine the differences in the physiological and sensational reaction of the whole body and local body parts individually, in relation to various garment designs.

Methods

Fabrics and garments

The fabrics used in this study provide a range of typical textiles, which are mostly used to make casual garments. Knitted single jersey (98 % cotton (CO) and 2 % Spandex (SP)), interlock and 3/1 twill weave fabrics (100 % CO) were used to make the sample garments for the lower body as described in Table 1. The single jersey knitted fabric with Spandex and the interlock fabric were chosen to simulate the indoor garment, whilst the woven fabric was used to represent the outdoor casual garment. To analyse the effect of fabric properties on the distribution of the air gap thickness and the contact area, a knitted fabric with Spandex, a knitted fabric without any elastane and a woven fabric were used to make the sample garments. All fabrics were washed one time to remove any foreign materials and the tension of the manufacturing process

Table 1 Properties of fabrics used in the study and ease allowances between girths of the nude manikin and the sampled garment used in the present study

Fabric	Fibre content	Mass (g/m^2)[a]	Thickness (mm)[b]	Drape coefficient (DC) (%)[c]	Thermal resistance (R_{ct}) (m^{2}K/W)[d]	Water vapour resistance (Ret) (m^{2}Pa/W)[d]	Garments	Fit	Ease allowances (cm)[e]		
									Hip	Thigh	Calf
Single Jersey	98CO / 2SP	188	0.87	41	0.0221	3.2	Sweatpants	Tight	6	3	−3
								Regular	6	6	5
								Loose	9	10	12.5
Interlock	100 CO	251	1.31	23	0.0307	4.4	Sweatpants	Tight	6	3	−3
								Regular	6	6	5
								Loose	9	10	12.5
3/1 Twill weave	100 CO	179	0.67	63	0.0191	3	Trousers	Tight	6	3	3.5
								Regular	6	6	7.5
								Loose	9	10	12.5

[a] (ISO 9073-1: 1989)

[b] (ISO 5084: 1996)

[c] (ISO 9073-9: 2008)

[d] (ISO 11092: 2014)

[e] (ISO 8559: 1989)

at 40 °C (ISO 6330: 2012), gently ironed to remove any crease and left for conditioning in the standard atmospheric conditions (ambient temperature 20 °C, relative humidity (RH) 65 %, (ISO 139: 2005)) for at least 24 h before confectioning. The mass, thickness, drape coefficient, thermal and water vapour resistance of the fabrics were measured using dedicated devices in the relevant standards (Table 1). The thickness of the fabric was measured using Frank 16,502 thickness meter according to ISO 5084: 1996. The drape coefficient of the fabrics, which is a ratio of a projected pleating fold area formed by the sample fabric with 15 cm of radius under its own weight to the original area of this sample fabric without draping, was measured using Cusick Drape tester according to the ISO 9073-9: 2008. The measurements of the thermal and water vapour resistances of fabrics were carried out using sweating hot plate according to the ISO 11092: 2014.

A casual trouser made of 3/1 twill woven fabric and two casual sweatpants made of jersey and interlock knitted fabrics were confectioned for the present study. The classic casual trousers were designed with two front pockets, a zipper, and a yoke at the back of the trousers. The sweatpants were confectioned from one pattern piece with one inner side seam. All garments were designed in tight, regular and loose fit (Fig. 1 and Table 1). Before measurements, the garments were washed one time at 40 °C (ISO 6330: 2012) and gently ironed to remove any creases and stored in the standard atmospheric conditions (ambient temperature 20 °C, RH 65 %, (ISO 139: 2005)).

The maximum girth of the relevant landmarks at the lower body (hip, thigh and lower leg) on the nude manikin and garment were measured using measurement tape. Ease allowances of the sampled garments were calculated by subtracting the girth of the nude body (maximum girth of the hip, thigh and lower leg) from the girth of the garment (maximum girth of the garment at hip, thigh and lower leg) (ISO 8559: 1989) (Table 1). Since, both jersey and interlock sweatpants were designed with the same pattern to evaluate the effect of fabric's type on the distribution of the air gap thickness and the contact area, ease allowances of the corresponding fit are the same.

Measurement protocol

In the presented study, a motionless male manikin was chosen with the height of 190 cm, waist girth of 74 cm, hip girth of 94 cm, thigh girth of 53 cm and calf girth of 35.5 cm. Measurements of the manikin were taken in the standing upright posture and provided a basis for the patterns, which were used to confection the garment samples (ISO 8559: 1989).

The manikin was scanned nude and clothed with the selected garments using Artec MHT 3D body scanner (Artec Group, USA) according to the advanced 3D scanning method developed in the previous studies (Psikuta et al. 2015; Frackiewicz-Kaczmarek et al. 2012). The repeatability of 3D scans was determined using the experimental method from previous studies (Psikuta et al. 2015) and has been found to be 0.6 mm. The manikin was re-dressed and scanned six times for each garment to demonstrate the random changes in draping and to assess the reliability of 3D scans. The 3D scans of garments were done when the manikin was stable in the fixed standing straight position with arms slightly extended to the front and fixed with the additional locks.

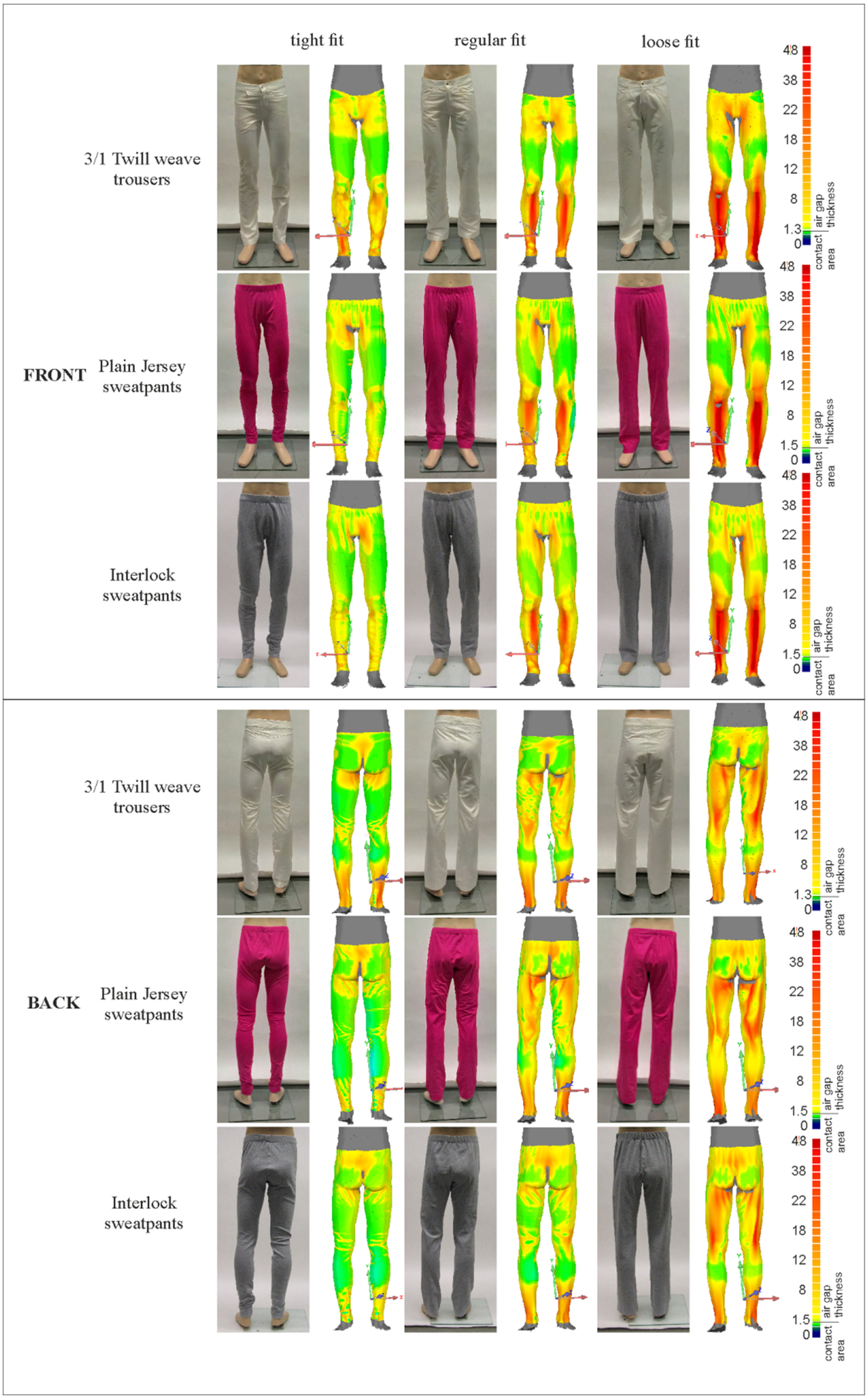

Fig. 1 Photos of sample garments and colour maps of post-processed exemplary single 3D scan of trousers and sweatpants in tight, regular and loose fits for front and back views

The post-processing method was also based on the procedures developed in a previous study using Geomagic Control 2014 (3D systems, USA) (Psikuta et al. 2012b). The average air gap thickness for the area of the particular body part was calculated individually for the body regions. It was calculated by deriving the average distance between points on the superimposed surfaces of the scans of the nude manikin body and the clothed manikin body. The division of the manikin's lower body into individual body parts corresponds to boundaries of the body coverage trousers. Additional divisions were done when the body shape changes and affects the draping behaviour of the garment (under the hip and at the knee). In this way, the division of the manikin's lower body included pelvis, thighs and lower legs (calf and shin) considered individually for anterior and posterior. Moreover, a linear model was applied between the calculated air gap thickness and the ease allowances of garments individually for each body regions.

Simulation of the physiological effect of garments

The Fiala thermal Physiology and Comfort model (FPCm 5.3) (ErgonSim, Germany), which is a mathematical model of human thermoregulation developed by Fiala et al. (1999, 2001, 2003) was used in this study. This system was validated in various environmental conditions and for a wide range of activities and clothing by Psikuta et al. (2012a). This physiological model represents an average person which has 71.4 kg of body mass and the similar body surface of 1.83 m^2 as our motionless manikin used in the presented study. Moreover, the physiological model is coupled with a clothing model which considers the garment as a simple thermal and evaporative barrier between the body and the environment. The required clothing input data to simulate the physiological response of the human body are the thermal and evaporative resistance of the garments as well as the clothing area factor (ISO 9920: 2007). These values were obtained using a steady-state clothing model described by Mert et al. (2015) based on fabric parameters and the air gap thickness measured using 3D scanning technique (Table 2) (Fig. 2). Besides, the ambient conditions (the ambient temperature, the relative humidity, and the air velocity), the metabolic rate of the body, the exposition time need to be set. In the presented study, the person wearing the selected sample garments, such as single jersey sweatpants and trousers in tight and loose fits, was exposed to three different ambient conditions of 40, 20 and 0 °C, 50 % of relative humidity, 0.15 m/s of air velocity to simulate hot, thermo-neutral and cold conditions for various working situations. Upper body garments were chosen according to the ambient temperature, i.e., in the neutral and hot environment, only a t-shirt was put on the body with sweatpants and trousers and in the low (cold) ambient temperature, the sweater was used only with the trousers to have realistic results. The simulated body dressed with these different garment combinations was exposed for 4 h, which is a normal working time between longer breaks. Furthermore, the metabolic rate of the simulated body was determined as 1.5 met, which represents light activity, such as a normal office work, light industry work, assembly work, and driving (ISO 8996: 2004). At the end of the simulation, the core temperature, total water loss of lower body, local skin temperature, local thermal sensation and local thermal comfort of different garment combinations were obtained from the model and analysed. The differences in the core and skin temperature between the beginning and end of 4 h of exposure were calculated. Furthermore, the dehydration of the simulated body was calculated using the following equation:

$$\text{Dehydration}\,(\%) = \frac{\text{Total water loss(kg)}}{\text{Body mass(kg)}} \times 100 \tag{1}$$

Table 2 The thermal and water vapour resistance of garments used as the input to the physiology model and differences in the core temperature, total skin temperatures for the lower body and total water loss at the end of exposure for two different garment styles (sweatpants and trousers) in the tight and loose fit at 0, 20 and 40 °C of ambient temperatures

Ambient temperature (°C)	Lower body garments	Upper body garments	Thermal resistance (R_{ct}) (m^{2}K/W)	Water vapour resistance (R_{et}) (m^{2}Pa/W)	Differences in core temperature (ΔT)(°C) [a]	Differences in skin temperature (ΔT)(°C) [a]	Total water loss (g)	Dehydration (%)
40	Tight sweatpants	Short-sleeved t-shirt (R_{ct}: 0.263, R_{et}: 53.42m^{2}Pa/W)	0.203	23.20	1.41	3.09	614.7	0.86
	Loose sweatpants		0.245	43.48	1.65	3.60	799.8	1.12
	Tight trousers		0.206	25.97	1.47	3.22	660.2	0.92
	Loose trousers		0.244	44.60	1.64	3.60	798.7	1.11
20	Tight sweatpants		0.203	23.20	0.43	−1.46	42.3	0.06
	Loose sweatpants		0.245	43.48	0.44	−1.07	47.84	0.07
	Tight trousers		0.206	25.97	0.44	−1.39	43.7	0.06
	Loose trousers		0.244	44.60	0.44	−1.08	47.2	0.07
0	Tight trousers	Long-sleeved sweater (R_{ct}: 0.270, R_{et}: 52.08 m^{2}Pa/W)	0.206	25.97	−0.72	−7.29	–	–
	Loose trousers		0.244	44.60	−0.72	−6.73	–	–

[a] Differences in the core and skin temperature between the beginning and the end of 4 h of exposure.

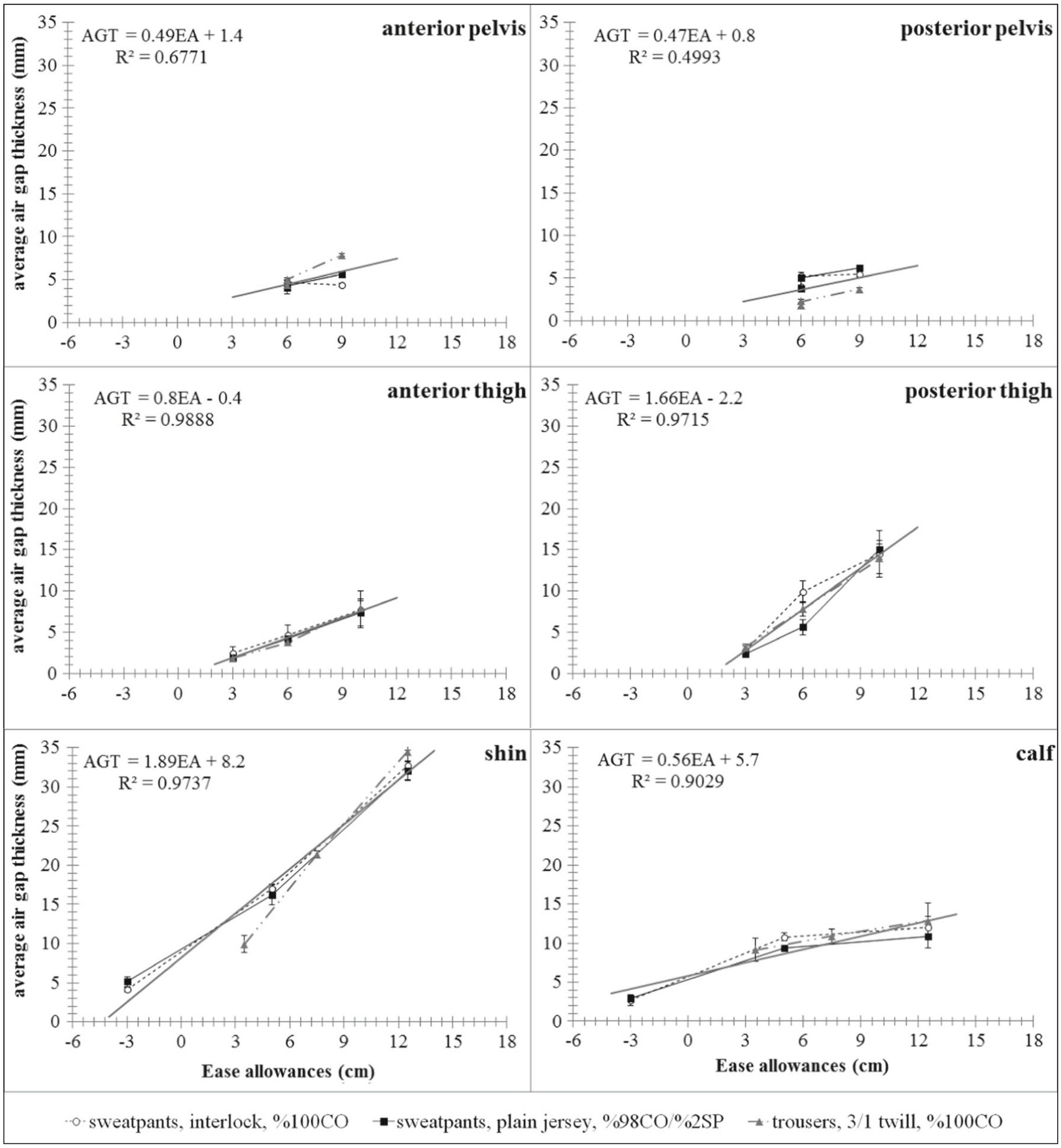

Fig. 2 Average air gap thickness and its standard deviation plotted against ease allowances in the trousers and both sweatpants presented for individual body regions and the linear model between ease allowances (EA) of the garments and the air gap thickness (AGT) individually for body regions (grey straight thick lines)

Statistical analysis

In order to evaluate the homogeneity in groups of data, such as the average air gap thickness and the contact area for different fits and styles of the garment, two-way analysis of variance (ANOVA) with Levene's test were performed using statistical software PASW® Statistic Version 22.0 (IBM, SPSS Inc., USA). However, the assumption of the homogeneity of variance was violated for the most cases, and therefore, the outcome of the statistical analysis is not reported in the paper, and trends in the data have been evaluated with regard to the effect of garment fit and style on the air gap thickness and the contact area.

Results

Figure 1 presents the exemplary colour maps of post-processed 3D scans and photos of trousers and both sweatpants confectioned in tight, regular and loose fits, where the air gap is indicated in *red* and *yellow* and contact area in *blue* and *green*.

Figure 2 shows the mean air gap thickness of six scans and their standard deviations for both sweatpants and trousers. The air gap thickness was plotted against the ease allowances of the tight, regular and loose-fitted garments. For legs, the air gap thickness and the contact area of right and left anterior and posterior thigh, both calves and both shins were averaged over body sides. Moreover, linear regressions were presented on Fig. 2 for the air gap thickness and the ease allowances individually for each body region.

Table 2 shows the differences in the core temperature and in the total skin temperature of lower body from the beginning to the end of exposure to evaluate the effect of garment style and fit on the health and thermal comfort of the human body. Moreover, Table 2 presents the total water loss within 4 h of exposure to observe the possible dehydration of the body in the different garment fits and styles. Furthermore, the thermal resistance and the water vapour resistance of garment samples used in the physiological model were presented in the table. Additionally, thermal resistance and water vapour resistance values of trousers, the sweatpants and the upper body garments (long-sleeved sweater and short-sleeved t-shirt) used as the input to the physiological model were given in Table 2.

Figure 3 shows the local skin temperature, local thermal comfort and local thermal sensation of the simulated human being wearing sweatpants and trousers in the tight and loose fit for lower body regions at various ambient temperatures (0, 20 and 40 °C) as calculated by the model. Since the sweatpants made out of single jersey knitted fabric with a t-shirt is not a realistic outfit for cold ambient conditions, only the trousers with a sweater was used and plotted in the graphs. The scale for thermal comfort is from 4 to −4 (4: very comfortable, 2: comfortable, 0: just comfortable, −0: just uncomfortable, −2: uncomfortable, −4: very uncomfortable) (Zhang et al. 2010), whilst the scale for the thermal sensation is from 4 to −4 (4: very hot, 3: hot, 2: warm, 1: slightly warm, 0: neutral, 1: slightly cool, 2: cool, 3: cold, 4: very cold) (Zhang 2003).

Discussion

The results of the present study showed that the change in the air gap thickness and the contact area due to the garment fit are

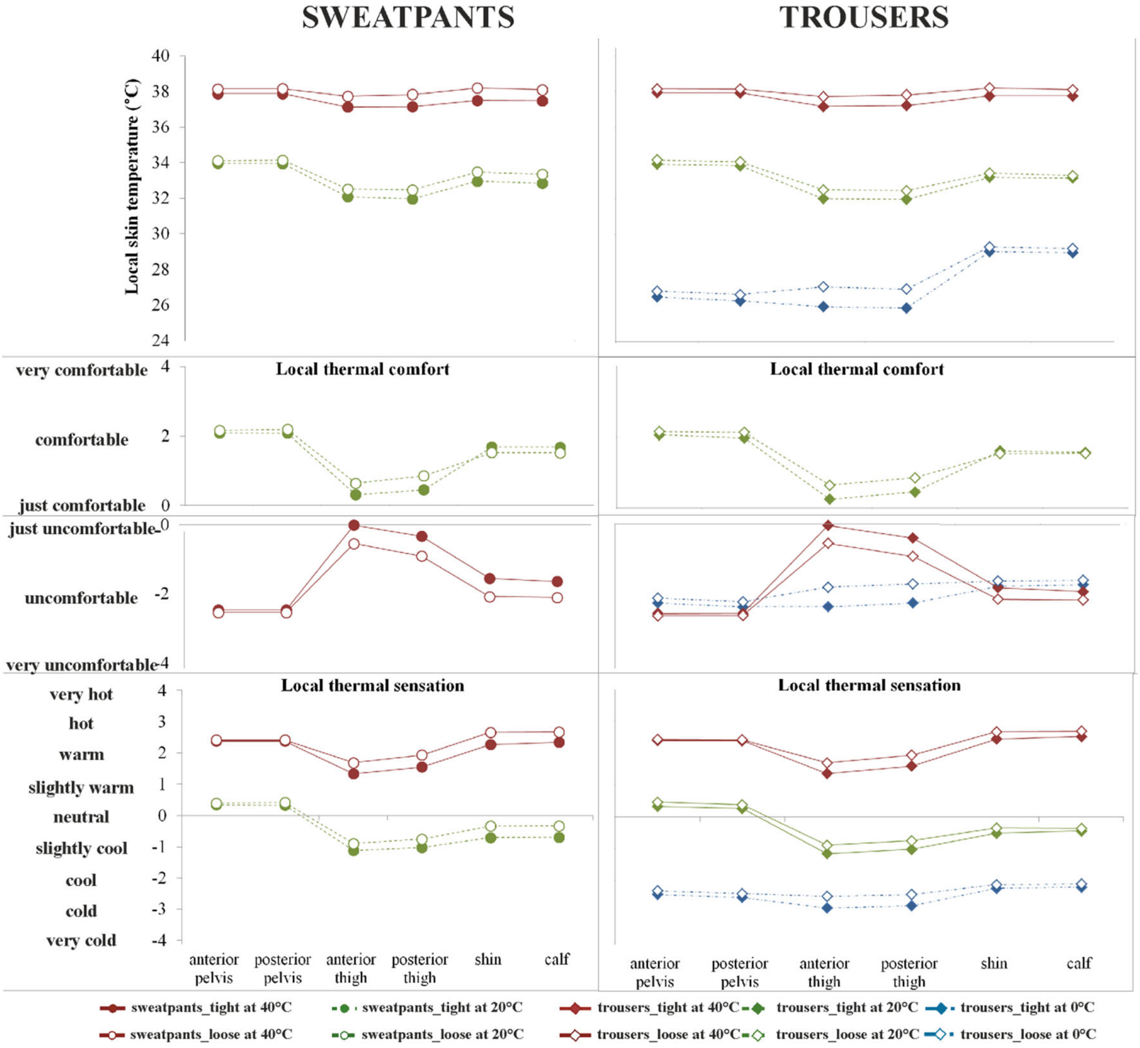

Fig. 3 Local skin temperature, local thermal sensation and local thermal comfort of simulated human being wearing single jersey sweatpants and trousers in tight and loose fits for individual body regions at 0 °C (*blue-dotted dashed line*), 20 °C (*green dashed line*) and 40 °C (*red straight line*) of ambient temperatures

highly dependent on the body geometry (Figs. 1 and 2). The change in the air gap thickness and the contact area due to garment fit was greater for legs than the pelvis area. At the pelvis area, the garment fell on the buttocks with its own weight and conformed to this body region due to the flexibility of the textile material (green areas on the buttocks in Fig. 1). Below the protruding buttocks, the garment hung downwards with a certain distance to the posterior thigh and created relatively large air layers. Similar effect was observed at the shin with knee being the protruding body part (Fig. 2). The effect of fit was clearer at the back of the thigh than at its anterior counterpart. The distance between the posterior thigh and the garment accommodated nearly the entire ease allowance at this landmark since anterior thigh was majorly in the contact with the garment for all fit cases. Similar effect was observed at the lower leg, where the change in the air gap thickness due to the garment fit was greater at the shin than the calf due to the concave shape of the shin below the knee. This result suggests that modelling the air gap thickness at the legs and pelvis is possible, because the observed trends are unambiguous. The air gap thickness results for three different garment styles (single jersey sweatpants, interlock sweatpants and trousers) and three different garment fits (tight, regular and loose) showed a good linear correlation between the ease allowances and the increase in the air gap thickness for legs. The estimation of the air gap thickness for the relevant body region can be done using the linear equations in Fig. 2 and used in clothing mathematical models. The derived ease allowances, which are calculated by subtracting the girth of the body from the girth of the garment at the relevant body landmarks (ISO 8559: 1989), can be used in the linear equations to get the average air gap thickness. Since the linear equations include different garment styles with different fabric types and various garment fits, the formulae for estimation of the air gap thickness are universal and can be used for different garment types. Furthermore, these findings for the lower body are consistent with other studies, which demonstrated that the air gap distribution depended mainly on the body geometry and the garment fit as the second most influential factor at the whole or upper body (Psikuta et al. 2012b; Frackiewicz-Kaczmarek et al. 2014a; Mah and Song 2010).

The garment style had a scarce effect on the air gap thickness in the sample garments used in the presented study, even though the trousers were designed to have larger ease allowances at some landmarks than the sweatpants. The garment style had a slight effect on the air gap thickness at the calf. The increment of the air gap thickness between regular and loose fit of sweatpants at calf was lower than that between tight and regular fit (Fig. 2). On the one hand, the reason for that phenomenon on the calf could be either the pattern construction of sample garments or the fabric type. The sweatpants were designed with one side seam at the inner leg and made of one pattern piece, whereas the trousers were designed with two side seams. The seam on the garment gives stiffness to the fabric and affects the form of the folds on the garment (Hu et al. 2005). Therefore, having more seams on the trousers could still allow the garment forming more air gap thickness with the higher ease allowances. On the other hand, limper sweatpants fell closer to the body and hindered the effect of increasing ease allowances on the air gap thickness, when the ease allowances exceed a certain distance (as it was between regular and loose fit). Secondly, the trousers showed lower air gap thickness at the posterior pelvis than the sweatpants. This finding probably resulted from the elastic band that was used for the sweatpants to adjust the size of the waistband to the hip of the manikin, whereby the trousers were confectioned with a button, a zipper and a yoke to conform to the pelvis area. In the case of sweatpants, the garment design for the waist was done bigger than the manikin's waist girth which caused more folds in the pelvis area. Furthermore, the effect of the drapability of the fabrics on the contact area was found (Fig. 1). The larger contact area occurred in the heavier and limper interlock sweatpants (DC 23 % see in Table 1), which was higher than that of the single jersey fabric (DC 41 %) (Table 1 and Fig. 1). Presumably, the interlock fabric sagged due to its own weight and remained in contact with the skin as in the case of buttocks and calves. This means that the effect of fabric properties can be probably neglected for the prediction of air gap thickness for lower body garments, whereas it should be considered for the contact area.

The findings of this study indicated that the air gap thickness and contact area could have an effect on the heat and moisture transfer in the garment. In the case of tight-fitted garments with large contact area between body and clothing, the lower air gap thickness below the threshold of natural convection (8–14 mm) was observed, which could contribute to the insulation properties of the garment. Due to the large contact area at the thighs and posterior pelvis, the moisture of the skin can be easily transferred to the surface of the clothing, where it can evaporate to the environment. In these regions, the benefit of using functional fabrics, such as with extra cooling properties or keeping the body dry, would be maximally exploited as compared to regions where the skin-fabric contact is not ensured. Moreover, the air gap at the shin for regular and loose-fitted garments, and at the posterior thigh for loose-fitted garment was above the threshold of natural convection (Mert et al. 2015 ; Spencer-Smith 1977). In this case, the heat loss may increase due to the contribution of the natural convection in these regions. At the concave body parts and for loose-fitted garments, and consequently, the garment insulation may decrease. These findings demonstrate that the thermal effect of the garment can be manipulated by the garment fit with regard to the body shape.

A correlation between the garment fit and physiological responses of the body, such as change in the core temperature and water loss for various environmental conditions, has been found (Table 2). For the ambient temperature of 40 °C, the effect of garment fit on the core temperature was observed to be up to 0.2 °C higher for the loose-fitted garments (both sweatpants and trousers) than for the tight-fitted ones (Table 2). Even though the dehydration level of the simulated body at the end of 4 h of working time did not reach the threshold of 2 % of body mass for the substantial cognitive effect (Gopinathan et al. 1988), it was essentially around 0.3 % greater for the loose-fitted garment than the tight-fitted ones (Table 2). In the case of the higher metabolic rate than that used in this study (1.5 met), the difference in core temperature and dehydration level between tight- and loose- fitted garments could plausibly increase, which could lead to a higher health risk ratio, such as heat strain or stroke, deterioration in mental functions, such as concentration and logical thinking, and premature fatigue relating to the high accident risk. The garment fit had no influence on the core temperature and dehydration level at the ambient temperature of 20 and 0 °C (the core temperature difference between fit levels below 0.01 °C). Therefore, to reduce the health risk and heat burden on the body at the higher ambient temperatures and/or metabolic rates, the tight-fitted garments should be chosen over loose-fitting ones.

The garment fit had no effect on the local skin temperature at the pelvis area, whereas it induced the local skin temperature difference at the legs for both garments (sweatpants and trousers) between 0.1 and 1.1 °C for all cases (Fig. 3). The local skin temperature of legs for loose-fitted sweatpants was 0.45–0.6 °C higher than the tight-fitted sweatpants. The only differences between loose- and tight-fitted trousers for the thermo-neutral condition were observed at the thigh (0.4–0.6 °C) but not at the calf and shin, which was related to only small difference in air gap thickness for both trousers fit levels. Moreover, 0.3–0.4 °C differences were observed at the calf and the shin of trousers in hot conditions due to increased temperature differences between the skin temperature and the ambient temperature. At 0 °C of ambient temperature, the effect of garment fit on the local skin temperature increased to 1 °C. Such temperature variation corresponds to the magnitude of the inter-subject variation in human subject trials. It is possible that the different fit levels of sample garments used in these studies might cause artificially the increase of this inter-subject variability. Thus, it is recommended to control carefully the fit level of the ensembles in such studies for better precision of the outcome.

The loose-fitted garments resulted in the body thermo-neutral sensation and more comfortable feeling in 20 and 0 °C of ambient temperatures, whereas the tight-fitted garments were more comfortable in 40 °C of ambient temperature. The differences in the scores of thermal sensation and thermal comfort of tight- and loose-fitted garments are 0.1–0.35 and 0.1–0.55 in cold condition, 0.05–0.35 and 0.03–0.4 in thermo-neutral condition and 0.03–0.4 and 0.05–0.5 in the hot condition, respectively. It can be derived from the comfort related results that when the ambient temperature is lower than the skin temperature, the loose-fitted garments with larger air layers help the body to keep its local skin temperature at the desired level. When the ambient temperature is higher than the mean skin temperature, the tight-fitted garments with higher contact area and lower air layers help the body to loose excessive heat for well-being and comfort. Consequently, the results of this study indicated that the comfort level of the human body for a given purpose can be adjusted by selection of fabric type and the design of ease allowances in the garment.

Conclusion

In the presented study, the distribution of the air gap thickness in relation to the garment fit (tight, regular and loose), the garment style (sweatpants and trousers) and the fabric properties (3/1 twill woven, interlock and jersey knitted fabrics) were evaluated. Moreover, the interaction between the air gap thickness and the physiological response of the human body was also investigated. Furthermore, the linear regression was derived between ease allowances and the air gap thickness individually for each body part. The results showed that regardless the garment fit, the air gap thickness stayed unaffected at the pelvis area, whilst the pronounced effect of ease allowance was observed at the legs. The air gap thickness results for two different garment styles (sweatpants and trousers) and three different garment fits (tight, regular and loose) showed a good linear correlation between the ease allowances and the air gap thickness for legs. The effect of fabric type on the contact area was found due to the different drapability of garments. The larger contact area occurred in the heavier and limper interlock sweatpants (DC 23 %), which was higher than that of the single jersey fabric (DC 41 %). The garment fit and style had no effect on the core temperature and the dehydration in the thermo-neutral and cold conditions. However, the core temperature and the dehydration were affected by the garment fit for trousers in the hot condition (0.2 °C and 0.3% differences, respectively). Additionally, the effect of garment fit on the local skin temperature was observed especially for the thigh, whereas the effect of garment style on the physiological responses was observed at the lower legs (shin and calf). Furthermore, the loose-fitted garments resulted in body thermo-neutral sensation and more comfortable feeling in thermo-neutral and cold conditions, whereas the tight-fitted garments were more comfortable in hot condition.

The outcome of the study showed that the comfort level of the human body for a given purpose can be adjusted by the selection of fabric type and design of ease allowances in the garment individually for body regions. Moreover, the air gap thickness derived in this study can be used in the clothing mathematical models to estimate the heat and mass transfer through the lower body garments, and hence, the outcome of simulations will be improved for different garment fits and styles. Furthermore, the linear regressions between ease allowances and the air gap thickness for individual body regions can be used to estimate the air gap thickness using the ease allowances of the garment at the relevant body part. Since the linear equations include different garment style with different fabric types and various garment fits, the formulae for estimation of the air gap thickness are universal and can be used for different garment types.

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