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Abstract

The methods to determine air gap thickness and contact area are limited for stationary position of the manikin. In this study, 3D garment simulation software was quantitatively validated by comparing these parameters obtained from this tool with the ones obtained from accurate 3D scanning method to assess the capability of 3D garment simulation software. Moreover, for the first time, these parameters were calculated for garments on walking male avatar wearing t-shirt and sweatpants. The agreement between two methods were within a range of 23 mm and 65%, and 10 mm and 45% for the air gap thickness and contact area of upper and lower body garments, respectively. Furthermore, the adapted post-processing method could discriminate the differences in the observed parameters over the body regions and among the phases of the movement. The introduced post-processing method can be used to improve 3D garment software for the determination of the regional parameters.

Key words

Air gap thickness; contact area; movement; 3D garment simulation software; heat and mass transfer in clothing

1. Introduction

The basic function of clothing is to protect the human body from excessive heat gain or loss and keep it in a state of well-being. As the clothing technology advanced in the last decades, the demand of the consumers for the clothing increased regarding its protective and comfort characteristics. In parallel, the researchers have been working on the fabrics used in the garments to improve their functionality for better protection and wearing comfort. The thermal comfort of human body is a complex issue and is affected by the physical (e.g. heat and mass transfer, mechanical behaviour of the textile), physiological (e.g. sensory and thermoregulatory responses), psychological (e.g. wearing comfort, perception of the various sensations) processes which occur in the environment-human-clothing system [1]. In this system, the insulation of the clothing is not only affected by the isolative properties of the fabric used in the garment, but also, to a great extent by the trapped air layer underneath the garment and the adjacent air layer above the garment[2-4]. Moreover, the fabric which is in direct contact with the body will contribute to dry heat transfer by conduction [5] and to moisture transfer by taking up the sweat from the skin and spread it to a larger area on the fabric, where the body heat loss may increase due to evaporation [6]. The determination of the volume and the thickness of air layer beneath the garment and the heat and mass transfer processes in this layer are important aspects to determine the thermal properties of the garment and its possible effect on the human body [7-14].

The distribution of the air layer and the contact area will obviously change constantly during the movement [15]. On the ergonomic side, the garment should give enough freedom of movements. If the garment reduces the mobility of the body due to the stiffness of the fabric or the garment design, it may increase the risk of falls or getting caught by machinery in the working environments [16-18]. On the protection side, the garment should optimally keep body in a state of well-being also during movement of the body. However, the insulation of the garment is highly dependent on the compression of clothing due to the relative air movement resulting from the walking speed and on the change of the air layer shape and volume due to posture change during the movement (i.e. pumping effect) [11-13, 19]. Therefore, the effect of body movement on the garment distortion in case of the determination of air layer thickness and the contact area should be analysed to enhance our understanding of the interaction between the human body and the garment during various movements.

To date, the determination of air gap thickness and contact area were done on manikins which were in stationary postures using advanced 3D scanning and post-processing methods [7-9, 14, 15, 20], however, there is no data available for the distribution of air layers and contact area during movement. Theoretically, it is possible to evaluate the distribution of the air gap thickness and the contact area on garments during movement, since some of the 3D scanners on the market (i.e. ArtecMT MHT, Artec Eva (Artec Group, USA) [21, 22] and temporal-3dMD systems (3dMD, USA)[23]) capture up to 15 frames per second and enable to capture 3D data in motion. Subsequently, the captured frames in motion can be transferred for post-processing to get the 3D animation. However, the high quality of the 3D data in real-time motion requires the use of several scanners capturing all sides of the moving object, and hence, high costs of the scanning system. Even though such a system could be theoretically used to scan humans in motion, the derivation of the air gap thickness and the contact area between the skin and the garment would be impossible due to the poor posture and movement control. The nude and dressed body need to be of exactly same shape for super-imposition and calculation of the parameters and this is not possible with the living subjects. Using 3D garment simulation software allows the repetitive simulation of the nude body and the garment in desired and exactly the same posture and movement.

The use of 3D simulation software in fashion industry for visual fit analysis accelerated the improvement of this technology in the last decades, and hence, different 3D garment simulation software are on the market [24]. The early attempt to simulate the deformable objects, such as rubber, paper and cloth, in virtual environment has been done by Terzopoulos et al., which offered a simple virtual environment for the further development of the method [25, 26]. The complete application to simulate the garment in 3D space has been done only in 1990s [27-29]. Despite increased efforts in the development of the 3D garment simulation software for garment designers, the question remained whether garment simulation algorithms realistically represent the garment for fit assessment. And hence, the validation of some 3D simulation software for visualizing the fit of the garments was done only by qualitative comparison of photos and movies to the simulation of draped fabric or garment [30-34]. This validation attempt was successful in the qualitative point of view except for placement of waist, front crotch and back of the upper leg, since, it is not possible to pin the garment at the desired place in the 3D simulation software. The prompt results of the designed garment and simulation on a walking avatar are the key features to use such a 3D garment simulation software, to determine the distribution of air gap thickness and the contact area over the garment and their change during movement. However, in this case the quantitative validation of the simulation output is indispensable [7, 20].

The aim of this study was to quantitatively validate the 3D garment simulation software, Fashionizer (MIRALab, Switzerland) and to elaborate a post-processing method for the determination of the air gap thickness and the contact area during walking of a male avatar. The air gap thickness and contact area obtained using 3D scan on a motionless male manikin wearing long sleeved t-shirts from the study by Frackiewicz-Kaczmarek et al. [8] and sweatpants from the study by Mert et al. [14] in three different fits (tight, regular and loose) were compared with the air gap thickness and contact area obtained from the 3D simulations of the same garments. Moreover, a male human body wearing long sleeved t-shirt and sweatpants was simulated during walking movement and the change of the air gap thickness and the contact area due to movement was determined using enhanced post-processing method based on principles presented by Psikuta et al. [7, 20], and the results were further analysed according to the movement.

2. Methods

2.1. Avatars

In this study, a motionless male manikin with a height of 189 cm, a girth of 100 cm at the chest, 74 cm at the waist, 94 cm at the hip, 53 cm at the thighs and 35.5 cm at the calves (measured according to ISO 7250-1:2008) was used in the validation phase. For the evaluation of the walking simulation, an avatar representing a scanned male human body with height of 170 cm, a girth of 87 cm at the chest, 82 cm at the waist and 88 cm at the hip was adopted. The 3D shape of the male human body in standing posture was scanned using a photogrammetric scanner consisting 96 synchronized cameras developed by Artanim (Artanim Foundation, Switzerland). All photos were acquired in a single shot in order to reduce the artefacts resulting from movement or respiration of the subject during the scanning procedure. The photos were analysed and a 3D point cloud was generated and triangulated using Agisoft PhotoScan software (Agisoft, Russia). As a second step, a template fitting technique was used to fit a template mesh with a clean topology to the 3D body scan [35] and the walking movement trajectory was applied to the meshed object.

Both bodies were divided into body regions for which the air gap thickness and the contact area were calculated (Fig. 1). Since, the draping behaviour of the garment changes for the right and left side of the garment during walking, the divisions were done separately for the left and the right side of the trunk and pelvis for the walking study.

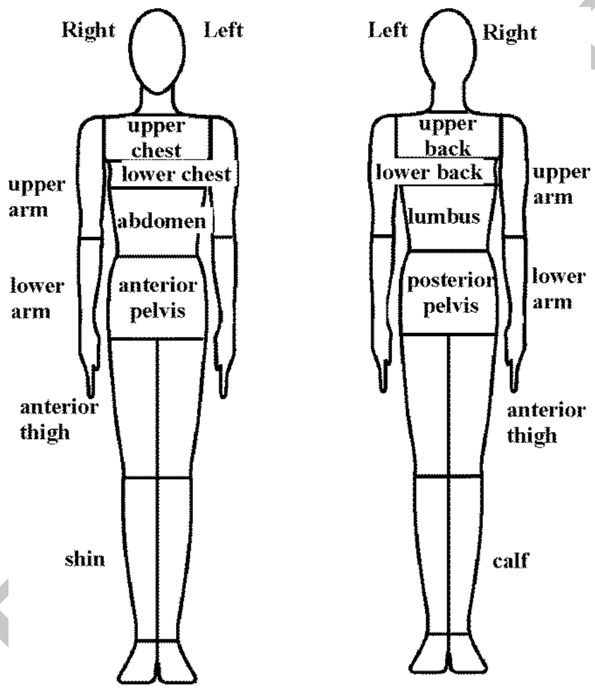

Fig. 1. Division of the body into individual body parts, for which the air gap thickness and contact area were measured in both validation and walking studies.

2.2. Fabrics and garments

The fabrics used in this study represent a range of typical textile fabrics, which are mostly used to make casual garments. Knitted single jersey (98% cotton (CO) and 2% Spandex (SP)) was used for the T-shirts and sweatpants in three different fits (tight, regular and loose) used in the validation process. Moreover, single jersey knitted fabric (100% Polyester) and a 3/1 twill woven fabric (100% CO) were used to simulate the T-shirt and sweatpants of the walking avatar, respectively.

The physical properties of all fabrics, such as weight, thickness, friction (fabric to fabric and fabric to skin), bending property and tensile strength were characterized and summarized in Table 1. The measurement of the weight and the thickness of the fabrics were done using a precision scale (according to ISO 9073-1:1989 [36]) and Frank thickness tester (according to ISO 5084:1996 [37]), respectively. The friction coefficients of the fabrics were obtained using the "tilted plane" method [30]. The bending properties of the fabrics were analysed using the hanging (pear) loop length test [38]. For the tensile strength of the fabrics, the measurements were carried out using TIRAtest 2703 (TIRA GmbH, Germany) in warp, weft and shear directions, separately. The fabric sample was tested using a series of steps with various force loads (the combination of the low and high forces) in warp, weft and shear directions.

Table 1

Properties of the fabrics used in the presented study.

Measured parameters of the sampled fabrics	**Validation study**	**Simulation study of a walking person**	
Fabrics (fibre content)	Single jersey (98% CO and 2% SP)	Single Jersey (100% Polyester)	3/1 twill woven (100% CO)
Weight (g/m^2)	225	187	380
Thickness (mm)	0.7	0.6	1.6
Friction coefficient to skin	0.53	0.47	0.44
Bending weft direction (N.m10^{-6})	0.6	7.3	17.1
Bending warp direction (N.m10^{-6})	1.2	2.4	39.5
Tensile strength weft direction (N/m)	200	180	1500, 0.02 -> 95000, 0.054 -> 290000
Tensile strength warp direction (N/m)	120	150	900, 0.03 -> 18000, 0.09 -> 22000, 0.13 -> 52000

Tensile strength shear direction (N/m)	100	130	90, 0.05 -> 600

To construct the garment in the 3D simulation software, it was necessary to digitalize the 2D paper patterns of the sample garments used in the validation study. The 2D paper patterns of the sample garments were fixed on the digitalization board of Lectra (Lectra, France) and traced to obtain the virtual pattern in the CAD software.

Table 2

Ease allowances of the garments used in the presented study during validation stage (standing) and during feasibility study with walking movement (walking).

			Ease allowances of the garments (cm)			
Garment style	**Used study**	**Garment fit**	**Chest**	**Waist**	**Hip**	**Bicep**
T-shirt	Standing	Tight	1	12	1	9
T-shirt	Standing	Regular	10	24	11	11
T-shirt	Standing	Loose	18	39	21	14
T-shirt	Walking	Loose	17	18.5	5.5	15
Garment style	**Study**	**Garment fit**	**Hip**	**Thigh**	**Lower leg**	
Sweatpants	Standing	Tight	6	3	-3	
Sweatpants	Standing	Regular	6	6	5	
Sweatpants	Standing	Loose	9	10	12.5	
Sweatpants	Walking	Loose	3.5	8	12.5	

2.3. 3D simulation software

The 3D garment simulation software Fashionizer (MIRAlab, University of Geneva, Switzerland), which was developed for modelling of the body and the garment in virtual environments, was used in this study [39-41] .This system was qualitatively validated by Luible [30] using 42 different fabrics with different raw materials (natural or man-made fibres), yarn structures (yarn twist, mono- or multi-filament), fabric structures (woven or knitted) and finishing treatments (chemical or mechanical finishing treatments). The simulated motionless and moving fabrics were compared with the photos and videos of the same actual fabric. The qualitative evaluation showed that the simulation of the fabric was successful in terms of the fabric drape and deformation during movement.

To simulate the clothed human body with a certain motion using Fashionizer, it is necessary to obtain the virtual documentation of the real input parameters, such as avatar of the human body with movement trajectory, fabric properties, and digitalized garment patterns. All of these parameters were imported to the Fashionizer and combined in the software for the simulation of the mechanical interaction between the body and the garment in the virtual environment.

2.4. Validation procedure

To demonstrate the reliability of the 3D garment simulation software for the determination of the air gap thickness and the contact area, its quantitative validation was done by comparing these parameters determined for the simulated avatar wearing virtual clothing with these obtained for the actual garments using 3D scanning and post-processing method in previous studies [8, 14]. In these studies, the manikin was scanned nude and clothed with the selected garments using Artec MHT 3D body scanner (Artec Group, USA) according to the advanced and accurate 3D scanning and post-processing method with six repetitions [7, 20]. For the 3D simulation of the avatar and the virtual garments, the imported virtual pattern pieces were placed around the avatar body in standing posture and assembled to make the complete garment. The garment was allowed to drape on the avatar and was exported for further post-processing using Geomagic Control 2014 (3D systems, USA) [7, 20]. For the adapted post-processing method of the 3D simulations, the nude and the clothed avatar were already super-imposed, since the garment was virtually tailored on the avatar and the garment stayed in a distance of

2 mm above the skin (assumption specific to the Fashionizer software) . For the calculation of the contact area of the 3D simulations, the minimal value to determine the direct contact between the body and the garment has different origin in comparison to the 3D scanning procedure. In 3D scanning this value is the sum of the fabric thickness and accuracy of the method, whereas in the Fashionizer there was a defined distance of 2 mm between two surfaces (fabric-skin or fabric-fabric). Since the thickness of the fabric was not simulated in the Fasionizer, the minimal value to determine the contact area was assumed to be 2 mm.

2.5. Simulation procedure for walking movement

The walking movement was captured with male human subject using a Vicon motion capture system (Vicon motion Systems Ltd., UK). The gait cycle lasted for 2 seconds with 1.25 m/s of walking speed. The motion was then applied to the animation skeleton of the virtual body using standard retargeting techniques. The cyclic movement pattern included the stance and swing phases of the right and left legs, such as foot clearance, tibia vertical, foot strike and toe-off positions captured in 13 frames (Fig.2). Once the garment on the virtual body was applied, the posture of the avatar was set to the starting position, the entire motion trajectory was applied to the skeleton of the virtual human body and the continuous walking animation of the clothed avatar was acquired in Fashionizer.

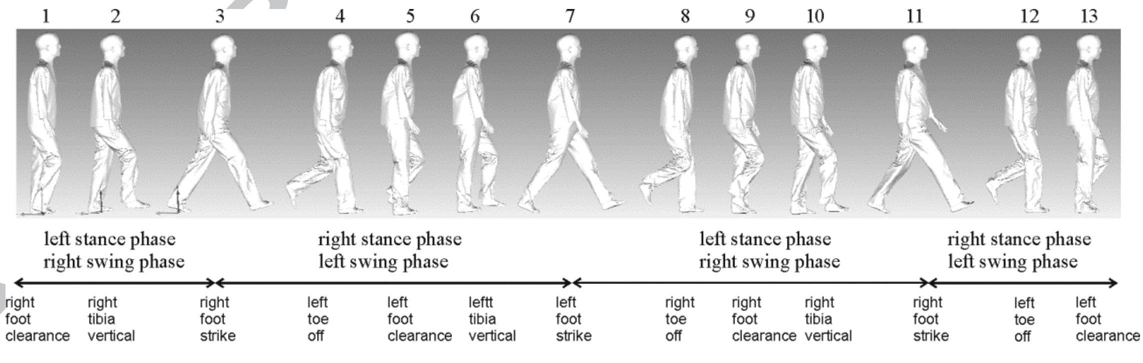

Fig. 2. The selected walking frames of simulated avatar and the phases of the walking movement

2.6. Post-processing procedure of 3D animation

In 3D animation of a simulated body, 13 frames corresponding to the phases of the gait cycle were chosen (Figure 2) to analyse whether the distribution of air gap thickness and the contact area shared also a cyclic change according to the movement of the body. The walking animation of the clothed avatar was imported from Fashionizer to the FashionViewer (Artanim, Switzerland) to select and export the 3D data for further post-processing in Geomagic Control 2014 (3D systems, USA) [7-9, 20]. The main difference in post-processing method of walking avatar was that the body posture in individual frames was changing from frame to frame that needed individual adjustment of planes cutting the body into body regions to calculate the air gap thickness and the contact area.

In the animation of the simulated avatar, the t-shirt and the sweatpants were simulated together on the avatar. Therefore, interaction between these two layers at the pelvis area was considered during the determination of the air gap thickness and the contact area. These parameters were determined individually for air gaps between the t-shirt and sweatpants, and between the sweatpants and the avatar surface.

Moreover, for the adapted post-processing method of the 3D simulations, the garment stayed in a distance of 2 mm above the skin (assumption specific to the Fashionizer software) as in the validation phase. Therefore, the minimal value to determine the direct contact between the body and the garment has different origin in comparison to the 3D scanning procedure.

2.7. Statistical analysis

In order to assess the relationship between the air gap thickness and contact area obtained using 3D scanning method and 3D simulation software, Pearson coefficients were computed separately for upper and lower body garments. The statistical software PASW® Statistic Version 22.0 (IBM, SPSS Inc. USA) was used. The results of the statistical analysis were used to evaluate whether there is an association between 3D scan and 3D simulation data and how significant is this association. The confidence interval was chosen to be 0.99.

3. Results

Fig. 3 and Fig. 4 present the pictures, the screenshots of simulations and the colour maps of the post-processed 3D scans and the 3D simulations of the t-shirts and sweatpants used in the validation phase in front and back view, respectively. These colour maps show the differences in the air gap thickness (red and yellow area) and contact area (blue and green area) distribution over the body. Fig. 5 presents the average air gap thickness and the contact area in the scanned and simulated t-shirts and the sweatpants for individual body regions. Additionally, the standard deviations of the air gap thickness of 3D scans are presented in the graphs.

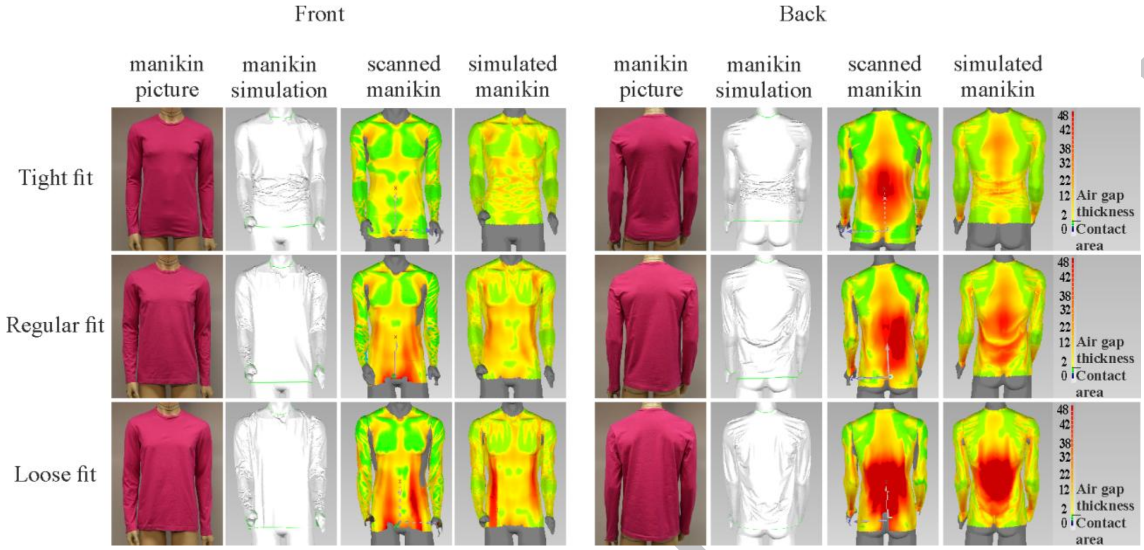

Fig. 3. Pictures, screenshots of simulations for the upper body garments on the manikin and their corresponding colour maps in front and back view, respectively.

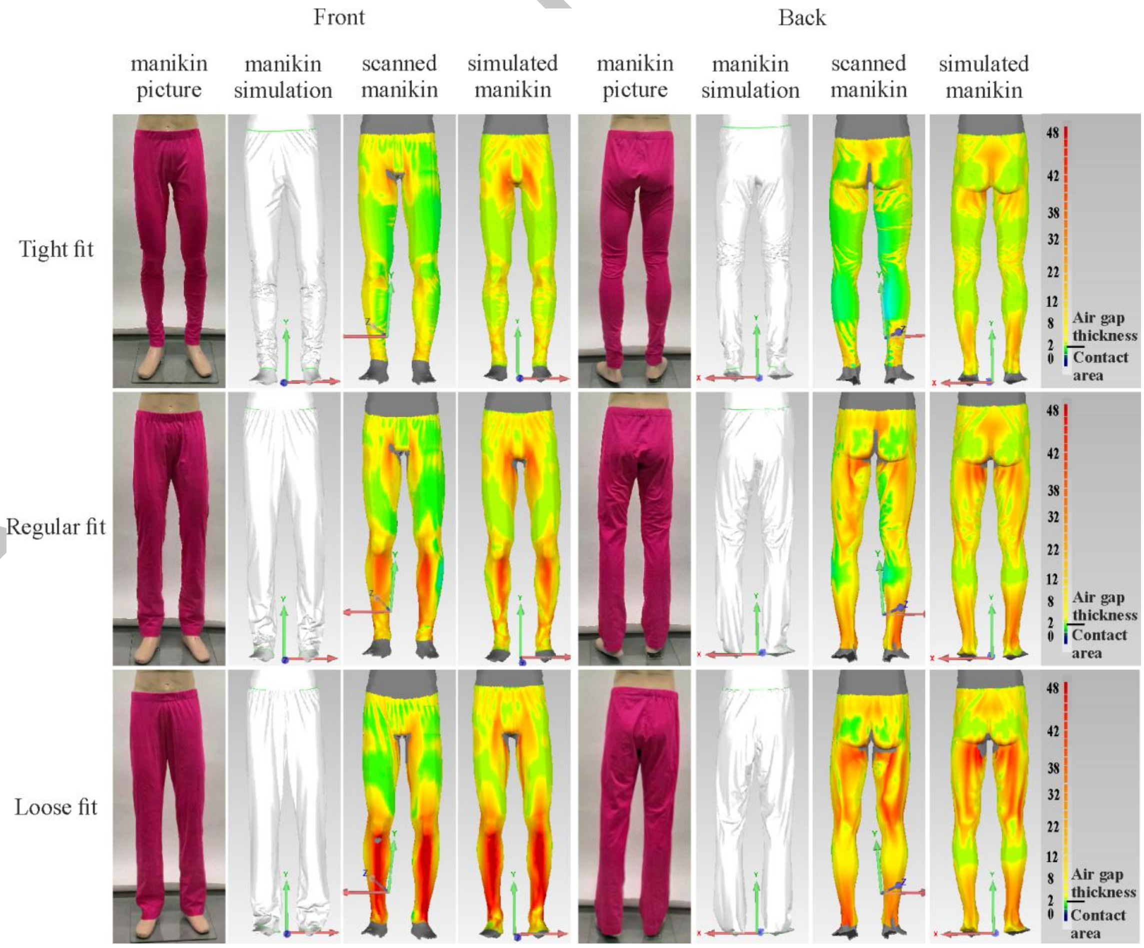

Fig. 4. Pictures, screenshots of simulations for the lower body garments on the manikin and their corresponding colour maps in front and back view, respectively.

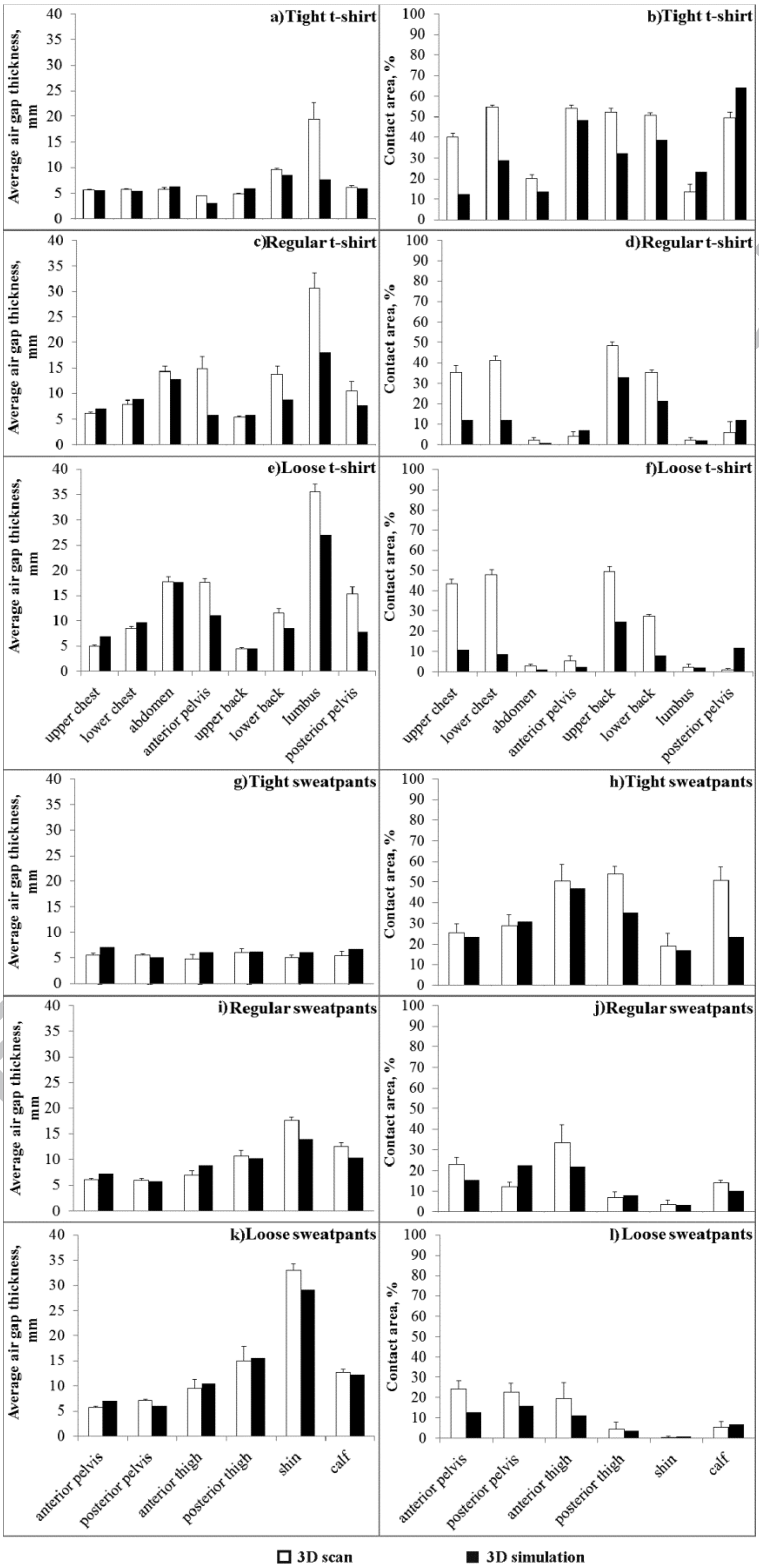

Fig. 5. Average air gap thickness and the contact area of the scanned and simulated garments presented for individual body regions

Fig. 6 presents the screenshots of the selected 13 frames of the walking animation (a), the colour maps of the post-processed simulated upper (b) and lower body garments (c). Fig. 7 and Fig. 8 show the average air gap thickness and the contact area in the simulated t-shirt and sweatpants for individual body regions.

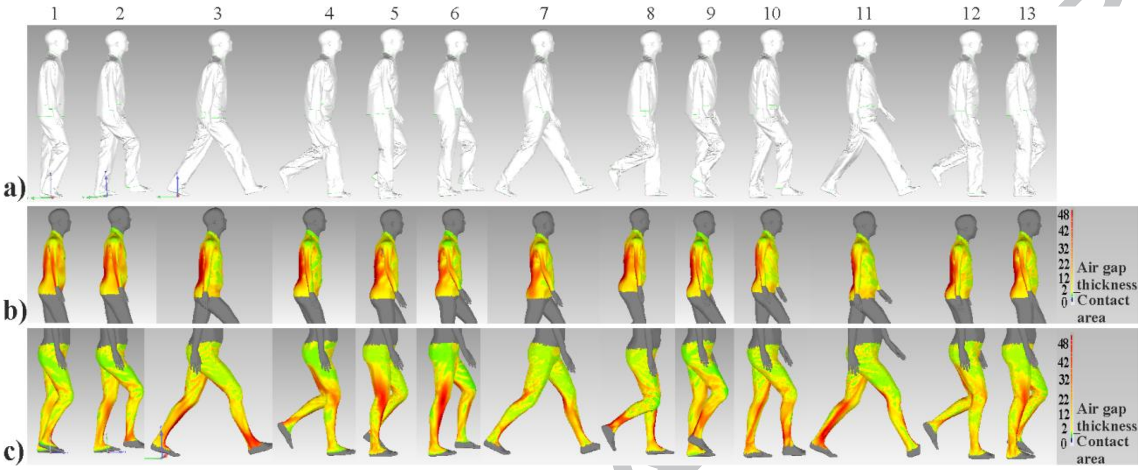

Fig. 6 The screenshots of walking frames (a) and the colour maps of the upper (b) and lower body (c) for t-shirt and sweatpants.

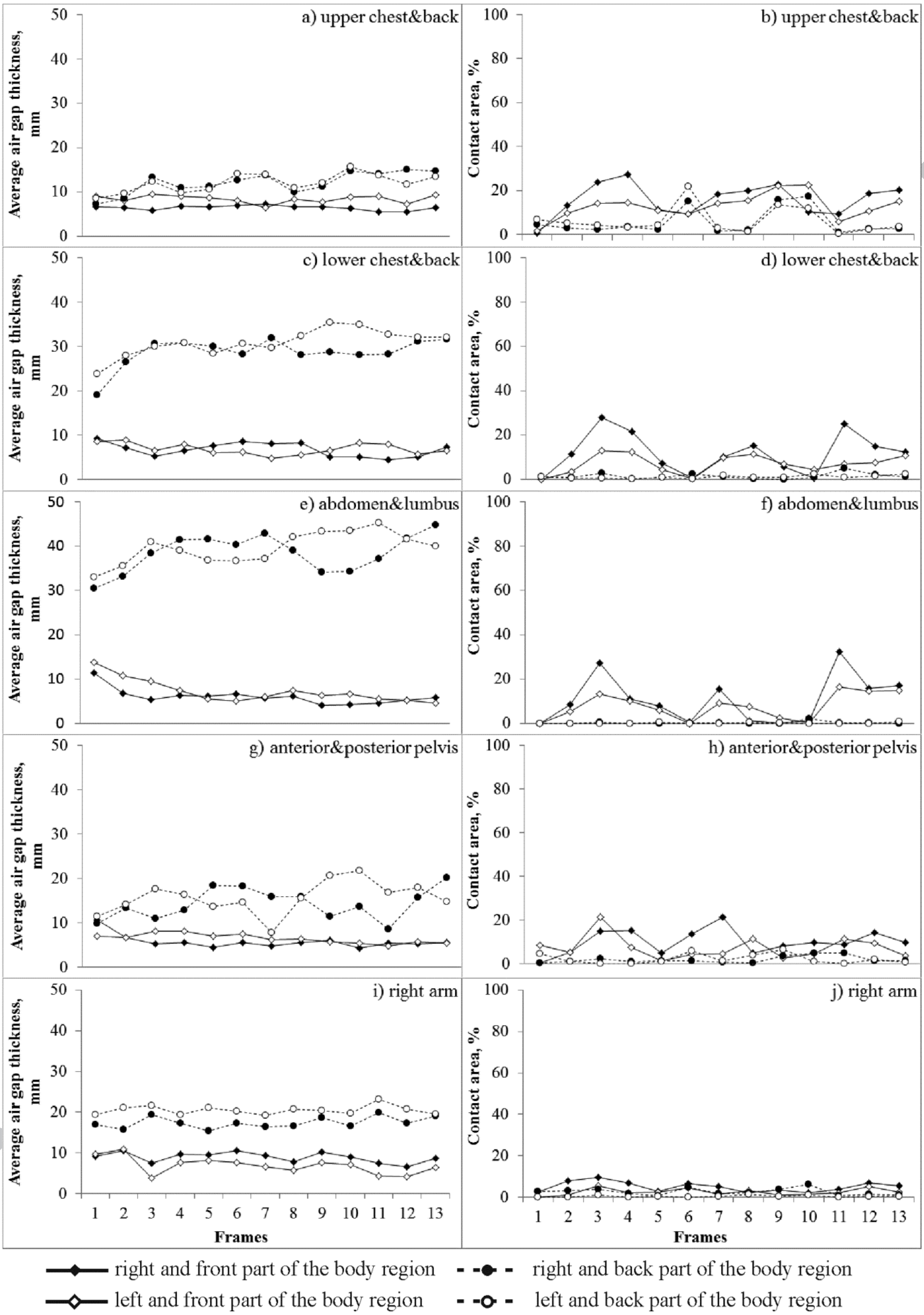

Fig. 7. Average air gap thickness and the contact area for the upper body regions of the simulated walking avatar

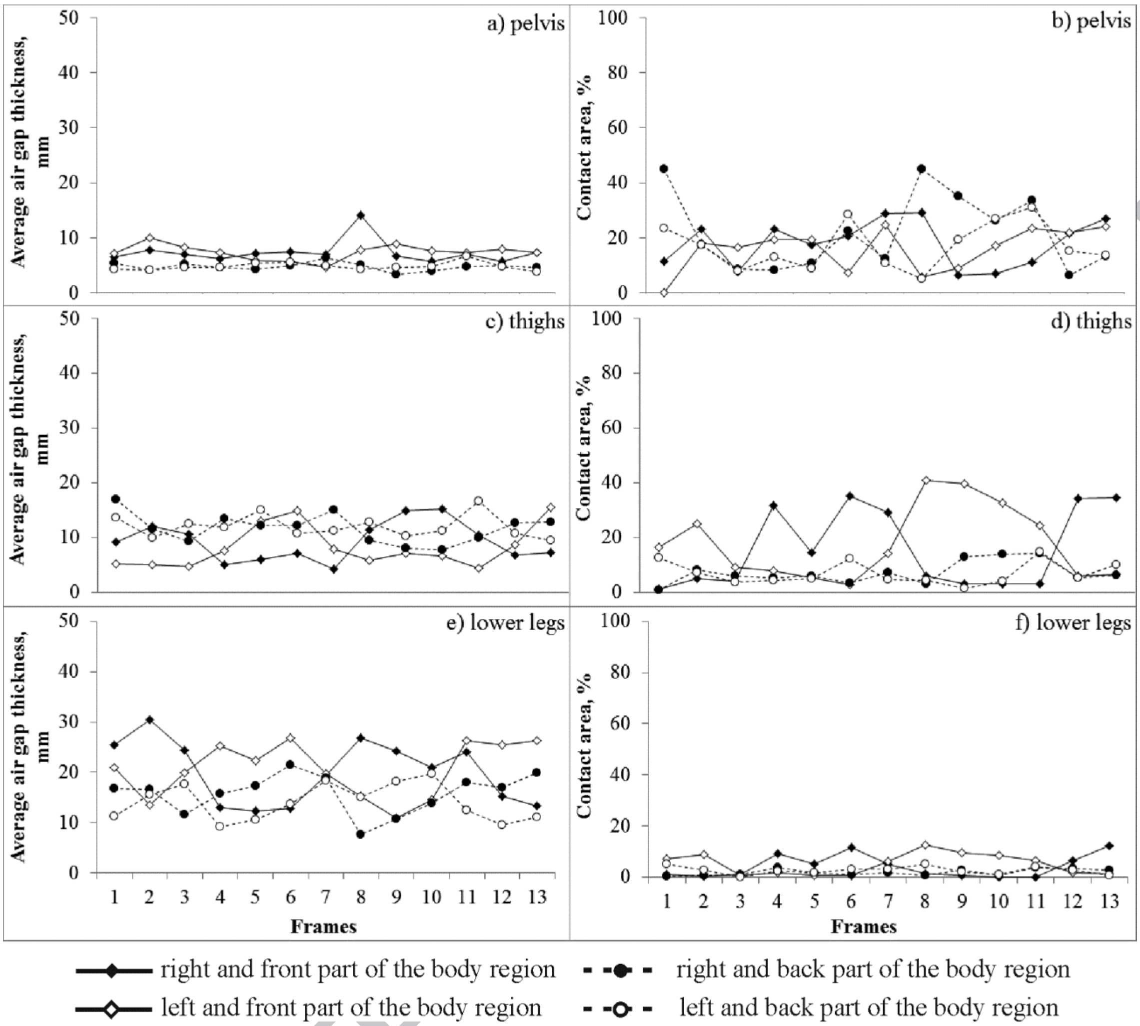

Fig. 8. Average air gap thickness and the contact area for the lower body regions of the simulated walking avatar

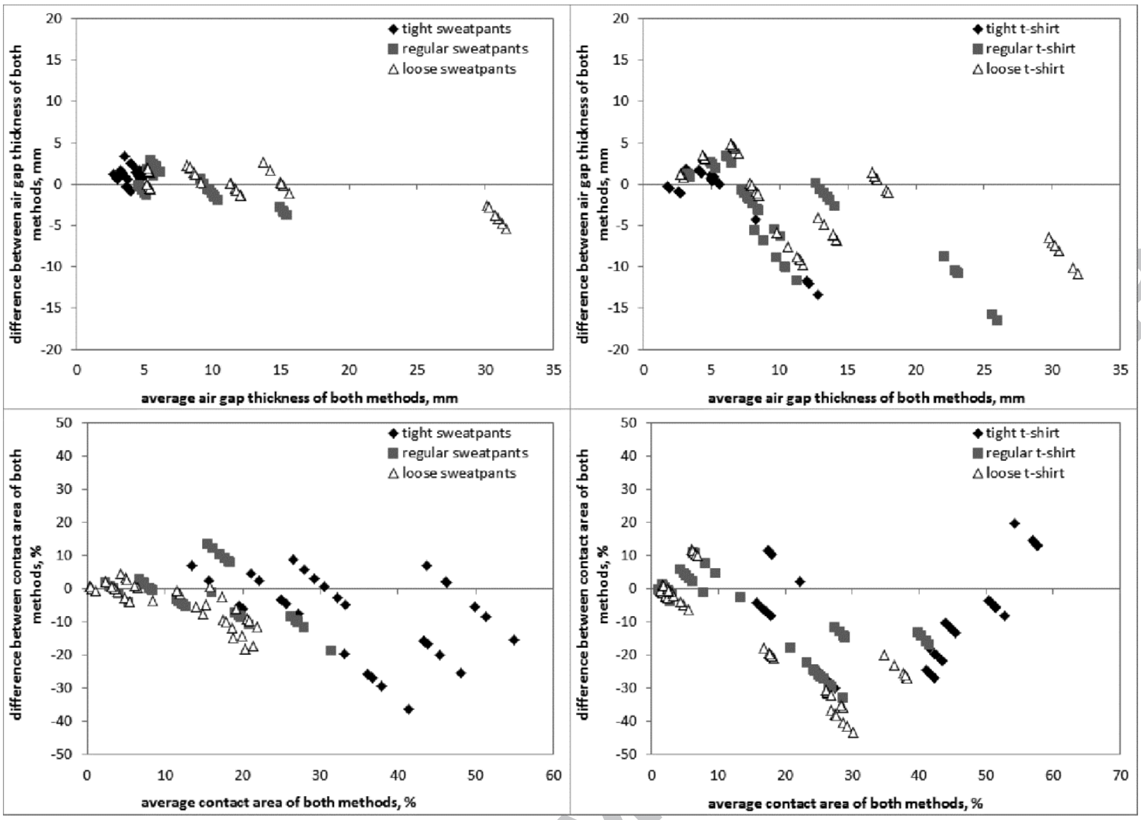

Fig.9. Tukey mean-difference plot for the air gap thickness and contact ratios of t-shirts and sweatpants in three fit (tight, regular and loose) evaluated using 3D garment simulation software (Fashionizer) and 3D scanning technique (Artec MHT).

4. Discussion

4.1. Validation results

During last decades, the 3D garment and body simulation software were used in clothing research area and fashion industry. The quantitative accuracy of 3D garment and body simulation software was unknown, although, there were some studies on the qualitative accuracy of this software. In this study, the quantitative validation method for 3D garment simulation software was addressed for the first time. . Moreover, the distribution of the air gap thickness and the contact area during movement was calculated for the first time using 3D garment simulation software. This information is necessary for realistic calculation of the heat and mass transfer through the garment. Furthermore, the prediction of the thermal properties of garment using the mathematical models of heat and mass transfer in the clothing can be done accurately using the accurate air gap thickness and contact area results during movement of the body obtained using the method from this study.

The air gap thickness on the upper body garments obtained from simulated data were generally deviated from the ones obtained from the 3D scans with the difference of up to 1 mm for tight fitted t-shirt (except for lumbus), of up to 3.5 mm for regular fitted t-shirt (except for anterior pelvis and lumbus) and of up to 2.2 mm for loose fitted t-shirt (except for anterior and posterior pelvis and lumbus) (Fig 5). The largest differences of the air gap thickness were observed for the lumbus and were found to be between 7-9.5 mm for all fit levels and for pelvis region between 5-6 mm for regular and loose fitted t-shirts. The different draping behaviour of the real and simulated garments at the lumbus and pelvis is the main reason for these differences. The real garments in the picture and in their scans hanged straightened with a certain distance to the body below the shoulder blades, whereas the same virtual garments showed horizontal folds at the lumbus. As a result, these horizontal folds decreased the air gap thickness and increased the contact area at the lumbus and posterior pelvis in comparison to the results of 3D scans (Fig. 5 a, b, c, d, e and f). This phenomenon is clearly observable in the colour maps of the scanned and simulated garments, where the lumbus region showed a higher air gap thickness (in red) in scanned garments in comparison to the virtual garments with horizontal folds (in yellow) (Fig. 3). The reason for this difference between the orientation of folds in 3D scans and simulation is that the real garments were put on the manikin by pulling the garment from the bottom of the t-shirt as a normal person would do. However, in the 3D simulation software, the garment fall on the body with its own weight and it is not possible to pull it from the bottom of the t-shirt to adjust the t-shirt comfortably on the hip.

Secondly, the validation results for the lower body garments showed more consistent correlation with 3D scans as compared to the upper body garments. The difference between the air gap thickness of actual and virtual garments was up to 1 mm for tight fitted and up to 3 mm for regular and loose fitted sweatpants. Since the upper body of the manikin is geometrically more complex in particular at the lower back, the simulation of the garment draping at this region was more complicated than at the less undulating body regions (chest and legs). Moreover, the Pearson coefficient analysis showed that there was a correlation between the data from 3D scans and the data from 3D simulation for both upper and lower body garments and clearly this correlation was higher for the air gap thickness and the contact area at the lower body garments than the air gap thickness and the contact area at the upper body garments (for air gap thickness of upper body garments: $r=0.88$, $n=21$, $p<0.01$; for contact area of upper body garments: $r=0.755$, $n=21$, $p<0.01$; for air gap thickness of lower body garments; $r=0.985$, $n=18$, $p=0.000$; for contact area of lower body garments: $r=0.868$, $n=18$, $p<0.01$).

The contact area differed by up to 27% for tight and regular fitted t-shirts and up to 37% for loose fitted t-shirt. The difference between the contact area results of actual and virtual garments was greater at the body regions with inherently larger contact area, such as chest and back. The probable reason of these differences was the position of the neckline in the virtual garment that did not correspond to its position on the body in the actual t-shirts. The neckline of the simulated t-shirts stayed at a higher point due to random resultant drape of the virtual garment according to Fashionizer algorithms and lack of control over exact placement of certain garments landmarks (Fig. 3). As a result, horizontal folds occurred on the chest and back due to the tension between neckline and sleeves. For the lower body garments, the difference of up to 5% for tight and regular fitted sweatpants (except for posterior thigh and calf) and the difference of up to 7% for all body regions of the loose fitted sweatpants were observed. For posterior thigh, posterior pelvis and calf in tight and regular fitted sweatpants, the difference of up to 21% was observed due to the more complex (undulating) body shape at these regions. Nevertheless, based on the colour maps for the actual and virtual garments, the patterns in the distribution of the air gap thickness (red and yellow area) and the contact area (green and blue area) were generally consistent (Fig. 3 and Fig. 4) for lower body garments and upper body garments except for the abdomen and lumbus regions of the tight t-shirt and.

In summary, as shown in Figure 9, the agreement between two methods were within a range of 5 mm to -17 mm and 4 mm to -6 mm for the air gap thickness of upper and lower body garments, respectively. Moreover, the contact area was within a range of 20% to -45% and 15% to -35 for the upper and lower body garments, respectively. The contact area on the virtual tight garments was generally lower than that real tight garment as indicated by mainly negative differences between contact areas. It was also observed that lower contact area at the tight garments and at the chest and back gave more potential for inaccurate calculation as shown by greater differences between methods for greater contact area. The majority of these differences between two measurements (355 out of 504 data) fell between the range of the standard error in the air gap thickness prediction, in which the effect of this difference on the thermo-physiological response is lower than the differences between healthy humans as speculated by Psikuta et al.[42]. Moreover, at larger air gap thickness the heat transfer is only little influenced by increase of air gap so large error also does not have a great effect as described in the study of Mert et al [3]. The only differences, which is out of these ranges, are lumbar and pelvis area for the air gap thickness and chest and back for the contact area on the t-shirt, whilst anterior pelvis and thigh for the contact area at the loose sweatpants and posterior thigh and calf for the contact area at the tight sweatpants. The contact area of the garments used in the validation section was not higher than 64%, which is the threshold of about 42-67%[3]. The heat loss is insensitive to the contact area change below this threshold. Consequently, the air gap thickness and the contact area results from this study which are in the range of standard error in the air gap thickness prediction from the study of Psikuta et al.[42], can be use in the clothing mathematical models for realistically determine the heat and mass transfer through the garment.

4.2. Effect of movement on the distribution of air gap thickness and the contact area

For the first time, the determination of the air gap thickness and the contact area for individual body regions of the walking avatar and garments was successfully achieved using advanced and adapted post-processing method. The method was sensible enough to observe the variability of the air gap thickness and the contact area over the body regions for the same frame and among the selected frames during the movement (Fig 6, Fig 7 and Fig 8). As expected, the observed change of the air gap thickness and the contact area in the t-shirt and sweatpants among the selected frames was showing cyclic trend correlated with the gait cycle. Since the legs changed their positions more than the trunk during the walking, the effect of movement was clearly stronger for the lower body (Fig. 8) than for the upper body garments (Fig 7). The results also showed that the effect of movement on the distribution of the air gap thickness and the contact area varied along the individual body regions according to the ease allowance of the garment that allowed a larger range of the garment displacement (Fig 7 and Fig 8). For example, the body movement at the upper body affected mainly the lumbus and upper back regions (Fig 7 c, e and g) with variation of 5-9.5 mm between selected frames. For the lower body, the influence of movement on the air gap thickness was stronger at the legs than at the pelvis area (Fig 8). The resultant contact area variation related to movement varied up to 45% for both t-shirt and sweatpants all body regions except for the lumbus and lower back (which shown generally low contact area of up to 2% and 5% for all frames, respectively, Fig 7 d and f). As the figure 9 shows that the contact area of the virtual garment was lower than the real one by approximately 27-37%, especially at the body regions with largest differences such as chest and back.

A walking movement is a cyclic activity with a certain interval. Fig 2 shows that the walking of the animated avatar had a gait cycle starting at frame 3 and finishing at frame 11. After the change in the air gap thickness and the contact area in between frames 3 and 11 due to the movement, these values came to the similar value at the frame 11 as at the frame 3 (Fig 7 and Fig 8). For example, the air gap thickness decreased till frame 7 at the right anterior thigh and right shin during extension of the leg to the front (left swing phase). The reason of this phenomena is that the anterior thigh changed from vertical position (right foot clearance at frame 1) to inclined position by bending at the hip causing elongation on the garment (right foot strike at frame 3) (Fig 5). In the case of contact area, the similar trend was observed. This result indicates that the cycles of the movement were reflected in the cyclic and regular change in the air gap thickness and the contact area. Furthermore, the difference of the air gap thickness and the contact area between the front and the back of the t-shirt was observed during walking of the avatar due to the mechanical inertia of the garment. The air gap thickness decreased at the end of the movement (frame 13, around 5 mm) for the front trunk in comparison to the beginning of the movement (frame 1, 12-14 mm) (Fig 7 c) due to the movement of the body at speed of 1.2 m/s.

4.3. Effect of movement on insulation of the garment

Since the thickness of the air layers between the garment and the body plays an important role for the thermal and evaporative resistance of the garment [2, 3, 42], the resultant heat transfer through air layers using the results from actual and virtual garments is expected to be different for certain body regions according to the validation results. In the study of Mert at al. (2015), the effect of different sizes of homogeneous air layers, different fold sizes, and various magnitude of the contact area on the heat transfer through a combination of a simple fabric and air layer has been evaluated. They found that the heat loss through homogeneous air gap decreases with the increase of the air gap thickness. The largest increment in the heat loss was seen below 5 mm of air gap thickness due to prevailing conductive heat exchange and above 30 mm due to the development of natural convection. In the validation phase of the present study, the results fell majorly between this 5 mm and 30 mm range (Fig.5), in which the heat flux can be potentially linearized due to its flat linear course. And hence, the differences between air gap thickness of 3D scans and 3D simulation in this range is expected to be small. Only at the lumbus of the loose t-shirt and at the shin of the loose sweatpants the air gap thickness obtained from 3D simulation was above the 30 mm, whereas the air gap thickness at the same body regions of 3D scans was below this limit, which may lead the mathematical models to obtain overestimated heat loss due to the small contribution of the free convection to the heat transfer. When the contact area exceeded the threshold of about 42-67%, a steep increase in the heat loss, probably in exponential manner would be observed as reported by Mert et al (2015). In the validation phase of the present study, the majority of the contact area results obtained from real and virtual garments fell below this 42-67% of the threshold except for some body regions, such as lower chest, upper and lower back of the tight t-shirt, at the upper back of regular and loose t-shirt and at the posterior thigh and calf of tight sweatpants. In these body regions and garments the heat loss due to the increased contact area in 3D simulation is expected to be higher. It is of great importance to account for the realistic distribution of air layers in the clothing when using clothing models for prediction of the human thermal response and comfort.

The insulation of the garment is highly dependent on the air velocity resulted from walking [11-13]. Two phenomena have influence on the decreased insulation of the garment during walking, namely, the effective forced convective heat transfer due to the air velocity resulting from walking and the relocated air gap volume and the contact area observed in this study. In Fig 6, the red and yellow area (larger air gap thickness) at the front trunk turned to be green (contact area), whilst the red area turned to be darker red at the back trunk among the walking frames. These changes in the air gap thickness distribution were due to the pumping effect resulting from walking movement. The same phenomenon can be seen at the shin and calf of the pants. Since the thickness of air layer decreased due to the air flow, the insulation of the worn garment will effectively decrease. The reason for this decrease in the insulation of garment is the air velocity due to compression of air layer (pumping effect) [43]. Havenith and Nilson [44] evaluated the correction coefficient for the effect of walking on the total thermal insulation of the garment and their study was also used in the international standard ISO 9920:2007 [45]. This approach is only limited for the walking movement and provides the global correction coefficient instead of local values. In the present study, the local values of air layers for each frame can be used to estimate the local effect of walking movement, physiological response, thermal sensation and comfort in more detailed in comparison to the method described in ISO 9920 [45]. Since, the change in the air layer during movement can affect the insulation of garment, it is also possible to optimize the garment design locally according to the information provided in the presented study. For instance, for the walking case in this study, the spacer fabrics can be used at the front of upper body garment to achieve stable air layer for insulation and still obtain a good moisture management [46, 47]. Moreover, the direct contact between the human body and the garment is particularly important for the transfer of the sweat from the skin to the clothing and the environment. To ensure a moisture management at the back of the body where higher air gap thickness was observed in this study, the pattern could be adjusted using patched pattern pieces following the curvatures of the lumbus and spine. Consequently, the insulation of the garment can be adjusted using functional fabrics and different design individually for the relevant body regions based on the information provided by this study.

Mathematical clothing models assume even air layers between the body and the garment or its full contact [48, 49]. On one hand, such a simplification of air layers and contact area can be used for the lumbus, which showed an air gap thickness between 30-45 mm and contact area between 0-5% for the entire walking cycle. On the other hand, for the other body regions such simplification could result in the over- or under-estimation of the heat transfer. For example, the air layers formed as folds (combination of the uneven shaped air layers and different magnitude of contact areas) at the lower chest, abdomen, upper arm and thigh (Fig 7 and Fig 8). Moreover, the number of folds increases during movement, since the garment patterns are designed based on standing straight posture and changes due to the movement of body part during movement. Furthermore, the air gap volume displacement occurs due to folds and relative movement of garment in relation to the body which contributes to forced convection and excessive air exchange with ambient environment. Therefore, the modelling of spatial geometry of air layers in relation to the heat and mass transfer and the physiological response of the human body should be considered individually for body regions and state of the body, such as static body posture or movement.

5. Conclusions

In this study, for the first time the validation of the 3D simulation software, Fashionizer, was done with a comparison of the air gap thickness and contact area results obtained from 3D scans of the same garments. Moreover, for the first time the distribution of the air gap thickness and the contact area was calculated for the garments on the walking male avatar using elaborated post-processing method. The presented study showed that the agreement between two methods were within a range of 5 mm to -17 mm and 4 mm to – 6 mm for the air gap thickness of upper and lower body garments, respectively. Moreover, the contact area was within a range of 20% to -45% and 15% to -35 for the upper and lower body garments, respectively. According to these ranges, the air gap thickness and the contact area obtained from 3D simulations of the lower body garments had more consistent results with 3D scans in comparison to the upper body garments. Furthermore, the contact area on the scanned garments and their simulations were not consistent at the body regions where higher contact area occurs, such as chest and back (up to 37 %).

The adapted post-processing method was sensitive enough to observe the difference in the air gap thickness and the contact area over the body regions and among the phases of the movement (frames). Moreover, these differences over body regions resulted from the interaction between the complex geometry of the body and the garment, whilst the variance among the selected frames (movement phases) resulted from the elongation and compression of the bending joints during walking. The post-processing method introduced in this study could be used to improve the use of 3D garment software on the market for the determination of the air gap thickness and the contact area. Moreover, the reported air gap thickness and the contact area during movements can be used in mathematical clothing models to realistically determine the heat and mass transfer in clothing for various postures. Nevertheless, further studies are required for the determination of the air gap thickness and contact area for more complex movement cycles.

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Highlights

- Agreement between air gap of 3D scanning and simulation dependent on body region.
- The movement of the body has an effect on the air gap thickness and contact area.
- Cycles of movement were reflected in cyclic change in air gap thickness.