Quantitative Analysis of the Air Gap Between the Skin and the Clothing

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Abstract

Thickness of the air gap between the clothing and the human body is a crucial factor for the heat flow and the water vapor and liquid transport occurring in garments. Nowadays, the 3D body scanning technique is commonly used to evaluate the thickness of the air gap. However current methods focus only on either the investigation of the air layers in clothing at discrete number of points or evaluation of the total air volume underneath an ensemble. Therefore, the main aim of this study was to obtain a surface overview of the air gap distribution for modern casual menswear. Detailed mapping of the distribution of the air gap thickness, which is responsible for thermal properties of garments, was done using 3D body scanner and dedicated post-processing software. Moreover, the contact area between the skin and the garment, which is one of the key factors for wicking properties of clothing, was evaluated. This study also analyses the impact of clothing fit on the distribution of the air layer thickness and the contact area.

Keywords: air gap, clothing contact area, 3D body scanning

1. Introduction

Nowadays, the apparel market offers a large variety of garment types ranging from casual clothes to highly specialized functional clothing. All of them are expected to protect human body against harsh environmental conditions. One of the most important properties of garment is sufficient physiological comfort. It can be provided by balanced heat and moisture transfer between human body, the clothing ensemble and the environment. In this case, physical processes such as dry heat exchange, evaporation and condensation, as well as sorption and water vapor and liquid transfer must be taken into account [1]. The size and shape of the air layers enclosed in the clothing ensemble are major contributors to the magnitude of heat and water vapor exchange. Thus, these processes are influenced significantly by garment displacement caused by clothing design and fit, body posture and movement as well as garment compression induced by wind [2,3,4,5]. The effect of the air gap thickness and its change on thermal and evaporative resistances according to the model presented by Wissler [6] is shown on Fig.1. It indicates that both resistances increase meaningfully with an air gap thickness change of 5 mm.

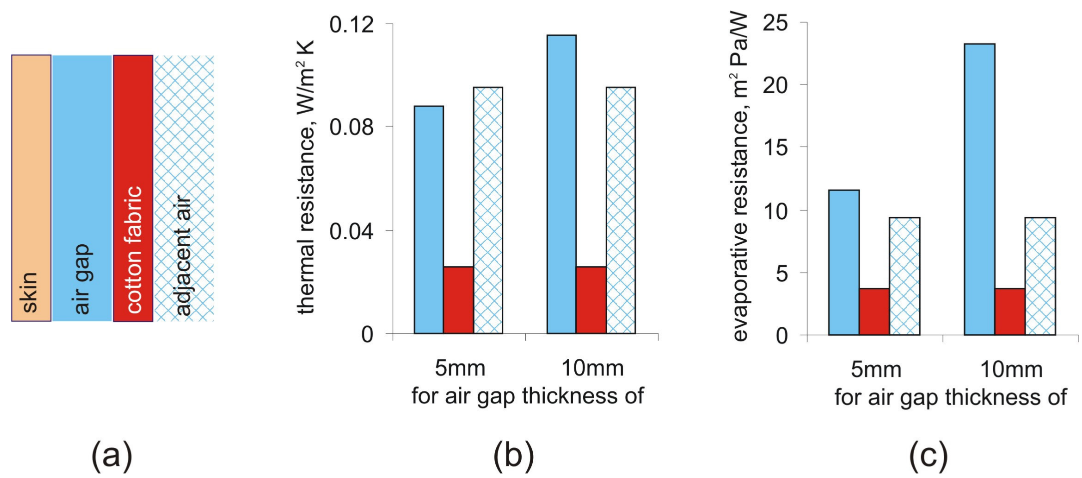

Fig. 1. Thermal (b) and evaporative (c) resistances of the layers in a clothing system consisting of a cotton fabric (227g/m2, 1mm thick) separated by an air gap as in scheme (a) for environmental conditions as follows: T_{skin}= 34˚C, RH_{skin}= 99%, $T_{ambient}$= 10˚C, $RH_{ambient}$= 81%.

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The absence of the air void between body and garment facilitates the transport of liquid into fibrous assembly first by wetting and later on by wicking processes. Thus, immediate exchange of the liquid water results from the direct contact between fabrics and/or skin surface [7,8].
The need to quantify the air gap in clothing ensembles resulted in several studies to try to determine the air layers. Generally, the volume of the air trapped underneath and within clothing was investigated. Main measurement techniques included gas trace method [9,10,11], cylindrical method [12], so-called silhouette method [13] and three-dimensional body scanning [14]. They were effective for global evaluation of the air volume in garments but did not provide any direct indication of the thickness of the air layer. Therefore, 3D body scanning was further developed to evaluate the distance between body and garment. The air gap thickness was then measured either for a selected number of points [15, 16, 17] or estimated from a discrete number of cross-sections through the dressed body [18, 19]. Nevertheless, no comprehensive local distribution of the air gap thickness could be obtained by these measurement techniques. Therefore, none of the derived methods allowed extensive and detailed evaluation of the air gap thickness nor did they address the issue of contact area in ensembles.
Current clothing models assume either homogenous air gap between body and garment or its lack. This approach simplifies the computational process but lacks in precision and poorly relates to realistic conditions. Therefore, available mathematical clothing models are not adequate to simulate non-uniform heat, water vapor and liquid transport occurring in textile ensembles. In this case, detailed mapping of the air gap distribution should be investigated and included in clothing models.
Therefore, the aim of this study was to establish an accurate method to obtain an overview on local distribution of the air gap thickness in casual clothing. Additionally, stress was put on the precise determination of contact area between body and garments. Exact mapping of both parameters is expected to allow more realistic predictions of heat and mass transfer occurring in clothing ensembles.

2. Methods

2.1 3D body scanning

3D body scanner Vitus XXL (Human Solutions GmbH, Germany) was used in this research as currently one of the most precise tools for immediate capturing the dimensions of the human body. This is a four-column laser system working with eight scanning heads. It offers a 360 degree image of the scanned person in a 3D space within about 12 seconds. Measurement principle is based on optical triangulation which provides high degree of accuracy during scanning process with maximum circumference error of less than 1 mm (DIN EN ISO 20685) [20]. The density of obtained data is 27 points per square centimetre. Scanning process was done in the recommended range of temperature conditions to avoid mechanical failure of the scanning system. Thus, the room temperature ranged from 20ºC to 30ºC during individual scanning events. Additionally, the scanner was calibrated each time in the beginning of the scanning day and after every 2-3 hours of scanning using scanning reference tube (0.11 m in diameter and 2.1 m in height).

A motionless male manikin with locks against turning of the body parts was provided for this study. To enable the scanner to cover as large body area as possible and still keep normal body posture, the manikin was standing fully erect, with feet apart and arms slightly extended forward. Special construction supporting arms and feet ensured identical body position during repetitive scanning. Manikin was scanned nude and dressed in sample garments. Each clothing piece was scanned six times with prior re-dressing to obtain random drape of the garment.

Casual garments chosen for this study were of appropriate size for the manikin. The shirt represented typical loose-fitting garment sewn from woven fabric and a T-shirt made of knitted fabric represented tight-fitting clothing.

2.2 Scans post-processing

The air gap thickness is defined in the three-dimensional space as the average distance between points on surface of the nude and dressed manikins whereas contact area is the ratio coefficient of the skin in the direct contact with the garment and the total skin area covered by the garment. Theoretically, direct contact of the body and a garment occurs when the distance between these surfaces is equal to the thickness of the fabric. Thus, the fabric thickness was used in calculation process.

Post-processing of 3D scans was carried out in the inspection software Geomagic Qualify 11 (Geomagic, U.S.A). Basic stages of scan post-processing regarded scan improvement and, hence, included:

- cleaning up and setting up orientation of point data;
- creating polygon mesh from point cloud data;
- refinement of the scan surface by removing redundant scanning artefacts and closing surfaces with deficiencies.

Further analysis of improved scans aimed at the evaluation of the air gap thickness and contact area. Therefore, the scans of nude and dressed manikins were super-imposed in the three-dimensional space. Uncovered body parts, such as head or legs, were used as reference areas in the alignment process. Results of the super-imposition were accepted only if accuracy of the alignment was less than 1 mm. Otherwise the scan was either subjected to a renewed alignment or excluded from further investigation. Then, super-imposed scans were divided into body sections which corresponded to the boundaries of body coverage for casual clothing (Fig. 2) [21]. Additionally, selection followed observed variability of the garment fit due to the relative changes of the body girth and width of the clothing pattern. Finally, for each body part, the geometrical comparison between aligned scans was done and resulted in the determination of the shortest distance between points on the surface of the nude and dressed manikins. A graphical output of the analysis included detailed color-coded mapping of the distribution of the contact area and the air gap thickness. Additionally, all data was gathered into a report presenting the percentage distribution of sought parameters.

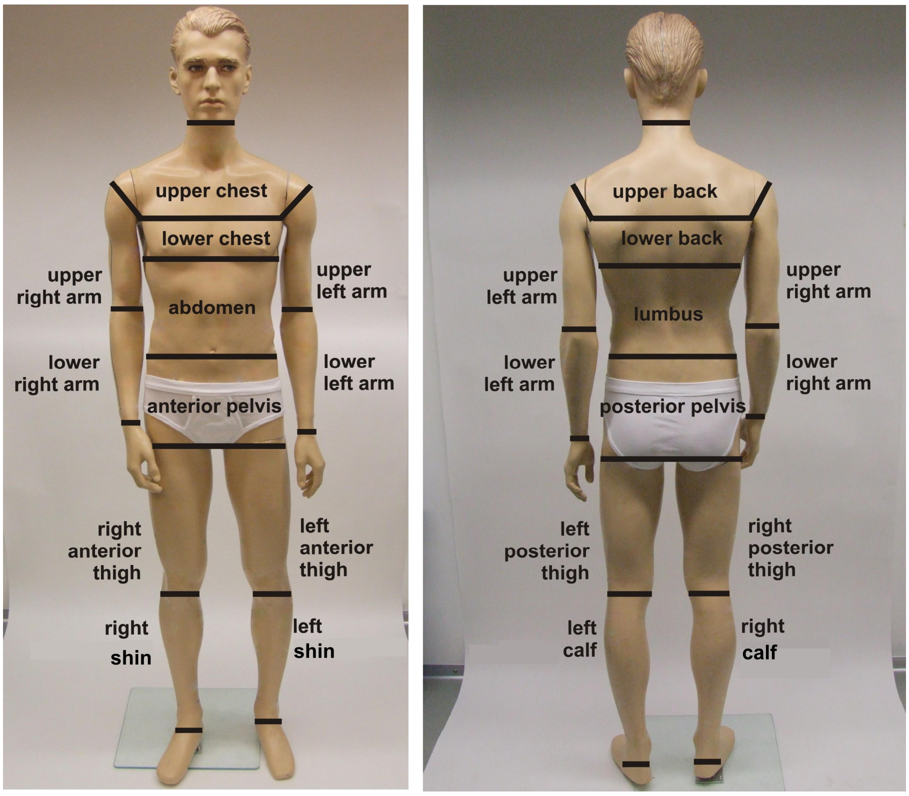

Fig. 2. Division of the manikin body into the body parts for which the air gap thickness and the contact area were measured.

3. Results

3D body scanning and scan post-processing resulted in a comprehensive analysis of the air layer enclosed in clothing ensembles. The results were not only presented as a statistical report but also as a coloured map displaying distribution of the air gap and contact area in selected garments. The views of resulting post-processed three-dimensional scans representing tight- and loose-fitting garments (T-shirt and shirt, respectively) are shown in Figure 3. The color scale depicts the distinction between the contact area and the air gap.

Apart from the graphical output, obtained data set was gathered in a detailed report comprising percentage distribution of sought parameters. Fig. 4a shows the average air gap thickness and its standard deviation whereas Fig. 4b presents average contact area and its standard deviation. In both cases the statistical summary was derived separately for each selected body part.

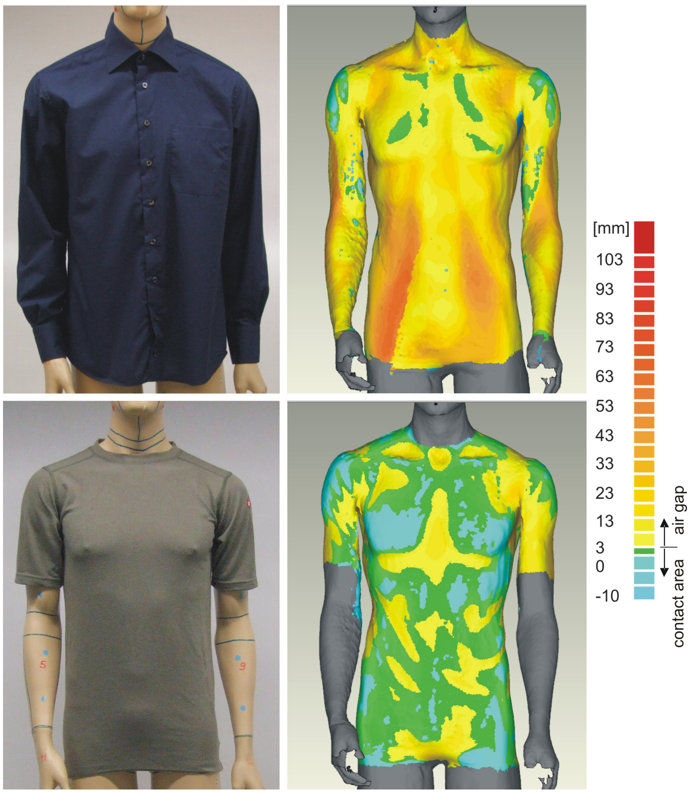

Fig. 3. Photographs and the view of post-processed 3D scans indicating the contact area (blue and green) and the air gap thickness (colour scale from yellow to red) of the shirt and the T-shirt.

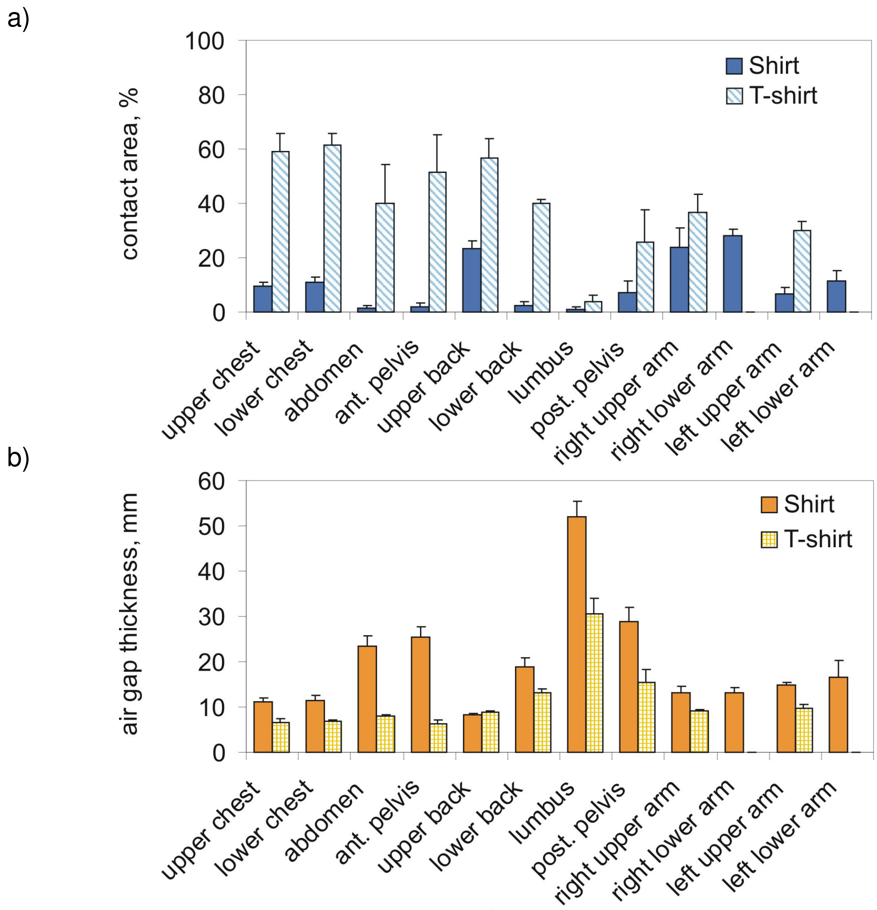

Fig. 4. Mean air gap thickness (a) and contact area (b) of the studied garments covering upper body determined for each body part.

The developed method provided measurements in 5mm intervals to show distinct changes of the air gap thickness within one garment as well as between clothing of tight and loose fit. Fig. 4a indicates that the average air gap thickness in loose-fitting garments was on average 40% larger than in the tight-fitting garments. As expected, the largest differences were noticed for sections around waist and hips where elastic, snug clothing followed the body silhouette in contrast to loose clothing which was widened up. Interestingly, derived method disclosed characteristic distribution of the air gap thickness in tight-fitting clothing that was almost constant for all body parts considered and was included in the range between 6-9mm. Exceptionally high values exceeding 30mm were only found in the lumbus and lower back regions. This exception was attributed to the clearly concaved form of the mentioned body parts (Fig. 4a). On the contrary, the air gap in the shirt showed a larger variability over body parts, however, with the same trend of higher values in the lower back and lumbus region.
The distribution of the contact area (Fig. 4b) showed high variability regardless body part and type of garment. According to the results, the contact area in the tight T-shirt generally did not exceed 60%. The limited contact between the body and the tight garment undoubtedly must have resulted from non-uniform body shape. In contrast, loose garments were characterized by much smaller contact area between skin and clothing which seldom exceeded 10%. Exceptions were found only in upper back and arm region and oscillated around 30%.

3. Discussion

Three-dimensional scanning technique allowed a thorough investigation of the garment displacement relatively to the body and, hence, the distribution of the air gap and the contact area were determined. Moreover, distinct differences between clothing of tight and loose fit were ascertained with the established method. Due to division of the body into preferred number of parts, selective and comprehensive evaluation of the air gap thickness and contact area was possible.
Reliability and accuracy of the measurement was verified in the post-processing phase. The nude manikin was scanned five times. Each scan was successively super-imposed with others and errors of alignment were recorded. Alignment error indicates the average deviation of all points of comparison. The scan of the nude manikin with the lowest average alignment error when compared to remaining four scans was used for further research.
Another validation test was provided for accuracy of mapping of the air gap and contact area distribution. Results were verified based on values determined for a tight-fitting garment such as T-shirt. Photos of the dressed manikin were visually compared with corresponding colored images obtained by 3D scanning. Characteristic folds as well as similar locations and shapes of contact area were observed on both pictures. Additionally, the contact area was traced manually with the soft pencil on the dressed manikin, again showing qualitatively the reliability of the method.
Summarizing, the proposed post-processing method providing a precise and accurate coloured map displaying distribution of the air gap and contact area is a reliable method for visual investigation of the displacement of air layers in casual garments. Also acquired percentage distribution of air gap thickness and contact area ensured accurate quantitative analysis. Consequently, this method could be used for fast determination of areas prone to loss of the heat as well as recognition of places of enhanced liquid transport in garments.

4. Conclusions

This study describes the method for measurement of the air gap thickness and the contact area based on the 3D scanning and advanced post-processing of the scans. Thanks to this method the distribution of the air gap thickness and the contact area could be investigated in details over body parts as well as for tight- and loose-fitting garments. This knowledge applied in the models of the heat and mass transfer in the clothing and/or in the garment design process will contribute to fast and precise prototyping and better performance of individual clothing.

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