A Novel Approach for Fit Analysis of Protective Clothing Using Three-Dimensional Body Scanning

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Abstract

The purpose of this study is to explore a proposed approach to quantitatively characterize a three-dimensional (3-D) fit. A 3-D body scanning technique was applied to capture the contour of nude and clothed manikin. The mesh model formed from nude and clothed scan by Rapidform software was aligned, superimposed and sectioned. From the neck to cuff, total 72 horizontal sections with equal interval of 2 cm were developed. The air gap size and distribution of overall and local body surface were analyzed. The total air volume was also calculated. Fit analysis was conducted on several protective clothing. The effect of fabric properties on air gap distribution was explored. The results indicated that average air gap of the fit clothing is around 25~30 mm and the overall air gap distribution is similar. The air gap showed uneven distribution over the body and it related to the body geometry and fabric properties. Larger size of air gap in legs and abdomen was observed. The air gap in chest, pelvis and arms, however, is minimal. The air gap over convex area is smaller than that of concave area. Coverall made of stiff fabric provided large air gap size. The research finding provides a technical base for clothing engineer to understand the overall fit associated with protection, thermal and movement comfort.

Keywords: Air gap, Fit analysis, Three-dimensional body scanning, Protective clothing

1. Introduction

Clothing covers over the three-dimensional (3-D) human body, the unique space developed between these two surfaces and the overall contour formed along the body represents the garment fit. As the fit depends on many factors, such as individual perceptions of fit, fashion style, function, it is hard to define it. [1]. Garment fit is crucial for the performance of protective clothing. In thermal protective clothing, the air gap developed between clothing layers and the body affected the thermal damage to the skin [2]. Garment style and fit influenced thermal protection, as the inappropriate fit of the women's style compared to the men's made some areas of the female easily burned [3]. Protective clothing often required a stringent conformity to end users' body dimensions, as garments that were out of proportion to the wearer might result in accidents and impair efficient and safe work performance [4]. The garment fit had great influence on the air gap size and distribution [5, 6], which greatly affected the heat and mass transfer in the microclimate under clothing and range of mobility. To design well-fitted protective clothing and give suggestions on the selection of protective clothing, fit analysis of protective clothing is necessary.

Normally, the garment fit is determined visually, and only the qualitative analysis can be made. Fit analysis of clothing, namely the evaluation of relationship between the human body and clothing, was a procedure to judge how well the clothing conforms to a set of requirements [7]. Current methods of analyzing garment fit compared linear garment measurements to linear body measurements. Although these were useful for evaluating simple garment fit issues, they were not adequate to investigate the multifaceted relationship between the body and clothing. The 3-D body scanner captured 3-D data of the surface of human body and provided valuable information to analyze the garment fit [8]. Kim et al. have quantified wearing ease, the distance between the body and the garment at critical locations, using merged cross-section slices between the body scan and clothed scan [9]. Loker et al. quantified and visualized fit by superimposing scans made with and without clothing [10]. Two-dimensional and three-dimensional data such as circumference slices, surface areas, and volumes between the body scan and the clothed scan can be used to provide comprehensive and objective analyses of fit. The 3-D body scanning was introduced to measure the air volume of clothing microclimate quantitatively [11]. The air volume was an integrated index to represent the overall garment fit, which was not sufficient to provide information in particular locations. The quantitative analysis performed by 3D body scanning technology provides a better way to characterize complicated 3-D garment fit.

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The air gap distribution in US army apparel was investigated using 3-D body scanning [5]. It was noted that the arm was removed forward or backward to decrease shadow region at torso, which has effect on the air gap distribution at adjacent positions. Song has investigated the average air gap size at the locations where a burn prediction occurred in single layer protective clothing exposed to flash fire [6]. The less drapable Kevlar®/PBI coveralls presents larger mean air gap sizes than more pendulous Nomex® IIIA coveralls with the same style and size. A procedure using a 3D body scanner to measure the size and distribution of air gaps between a female mannequin and a garment was developed to investigate the garment style and fit on thermal protection [3, 12]. The findings demonstrated that air gap sizes were not evenly distributed over the manikin, and depended on garment style and fit, as well as body contour. There were a great number of smaller air gaps over the manikin than larger ones. The principle of air gap measurement was the same with previous study [5], i.e. the magnitude difference of two vectors with the same direction originated from the centroid of nude body scan. Due to the irregular profile of human body, this principle might cause significant error in concave or convex area such as chest and pelvis regions. Recently, Psikuta et al. quantitatively measured the air gap distribution and contact area of daily wear clothing by Geomagic software [13]. However, the method of air gap determination was not provided.

The purpose of this study was to conduct systematic fit analysis of thermal protective clothing using 3D body scanning technology. It was also the intention of this study to develop a new approach to comprehensively characterize the 3-D fit relationship between protective clothing and human body. In this study, a proposed approach using 3-D body scanning to characterize fit of protective clothing was developed. The air gap size and distribution of overall and local body surface were statistically analyzed. The effect of garment design features on fit of protective clothing was investigated.

2. Experimental

2.1. Testing garment and manikin

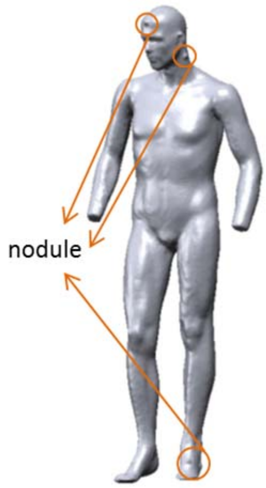
Several thermal protective coveralls in size 42 with different styles were provided by manufacturers. The specifications about these garments are shown in Table 1. All the garments consist of a double layer fold-over collar and a top fly in the front center as well as a horizontal segment line at the waist, as shown in Fig. 1(b). The fabric thickness used in these garments was measured in accordance with ASTM D1777-96 under pressure of 1kPa. The flexural rigidity of the fabrics was measured using cantilever method according to ASTM D1388-08.

Table 1. Specifications of experimental garments.

Garment	Configuration	Weight (g/m^2)	Thickness (mm)	Stiffness (μjoule/m)	
				warp	weft
C1	100% Nomex®	169	0.60	11.46	9.89
C2	88% cotton/12% nylon with polymer finishing	412	0.67	207.64	45.75
C3	88% cotton/12% nylon	237	0.62	98.79	9.26
C4	88% cotton/12% nylon	305	0.65	151.38	30.61
C5	88% cotton/12% nylon with polymer finishing	322	0.66	177.23	52.48
C6	88% cotton/12% nylon	305	0.69	49.56	19.5
C7	100% cotton	360	0.67	102.72	106.39

"---" indicates the stiffness is not measured due to double layer combination.

In this study, a duplicate manikin used in flash fire manikin system (40 regular male) was employed for the 3-D body scanning as shown in Fig. 1 (a). The manikin head and legs are not movable and only the arms can be rotated forward and backward. A number of nodules at forehead, side neck and instep were mounted on the manikin surface for the alignment of nude and clothed scan.



(a) nude manikin *(b) clothed manikin*

Fig. 1. Nude manikin and clothed manikin for 3-D scan.

2.2. 3-D body scanning

To capture the 3-D body shape and clothing profile, a VITUS Smart 3-D whole body laser scanner by Human Solutions was used. This scanner was a non-contact optical measuring system capable of rapidly generating a 360° representation of the surface geometry of an object. A horizontal line of laser was projected onto the object to be scanned, and the light was reflected back into cameras located in a series of scan heads that moved vertically along the length of the scanning volume. The lasers moved from the bottom to top with a constant velocity. Computer software used the displacement of the light pattern to calculate the distance from the object to the camera, from which the data were inverted to produce a 3-D form. The different camera views were then patched together to create a single image. The scanned object, formed by point cloud data and x, y, z coordinates, can be rotated, resized, and sliced. The VITUS scanner was connected to a computer equipped with the ScanWorX (version 2.9), which was used to visualize, process, and evaluate scan information. The ".stl" file format was used to output the raw scan data for fit analysis.

To analyze the garment fit, nude and clothed scans were required to be overlapped and aligned as accurate as possible. Successful alignment required minimal changes in the position of the nude and clothed mannequins between scans. The nude manikin was scanned first, and then the dressed manikin was scanned with the same positions and status. Each garment was scanned for three times by dressing and undressing to determine the reproducibility of the measurements. Because the size and distribution of air gaps were variable between scans and depended on how the manikin was dressed, changes in air gaps were minimized by following a specific dressing protocol, which involved gently pulling downwards on the waist, sleeve and leg cuffs of the garments. Pictures of the dressed manikin were taken and compared among garments of the same style to ensure consistency of fit.

3. Method for fit analysis

3.1. Scan data processing

The raw data of nude and clothed scan were imported in the software of Rapidform XOR. There were some missing areas in the scans where the cameras could not capture data. These missing areas included horizontal surfaces such as the top of the shoulder and head, and regions that are hidden by the body such as the area under the arms and the crotch. In addition, there were also some missing holes on the deep wrinkle locations. To well measure the air gap between the clothing and human skin, integral and smooth body surface was necessary. Firstly, the scan data was meshed. Then it was rewrapped and the holes were filled. Subsequently, healing wizard was applied and optimized mesh was made to smooth the mesh model. Finally, the model was exported for air gap measurement.

3.2. Air gap and volume measurement

Both the processed nude and clothed scans were imported in Rapidform XOV for measurement. The nude scan was defined as nominal data, the clothed scan was considered as scan data. The two scans were aligned by several points of nodules and then slightly shifted x, y, z coordinate of clothed scan to refine alignment of the two scans. The horizontal slices were carried out at different positions. In this study, the cross-section of neck, chest, abdomen, arm, pelvis, thigh, knee and calf were made. From the neck to cuff, there were total 72 sections with equal interval of 2 cm. Fig. 2 presented the body separation according to the slices. As the horizontal sections at abdomen and pelvis included parts of arms, the analysis of air gap in these areas should narrow the range of sections to exclude the arms. Likewise, the air gap at each arm was determined respectively via the selection of slice range. It should be noted that the garment contour at armhole was difficult to separate, and thus the air gap at upper chest and upper arm was integrated.

The cross-section displayed two contours that alternately coincided or were separated by some distance, shown in Fig. 3. The distance between the contour lines was the air gap. In previous studies [5, 12], the air gap was measured by the difference of two vectors originated from the centroid of base scan with the same direction. However, it would result in big error for the convex or concave regions. In this study, the principle of minimum distance was applied to determine the air gap at each point. The statistical analysis of the whole contour of the sliced cross-section was carried out. The minimum, maximum and average air gap was determined respectively, and the distribution of air gap for each slice was plotted. The overall air gap distribution over the body surface was presented with different color bars. In addition, the air volume entrapped in the protective clothing was calculated.

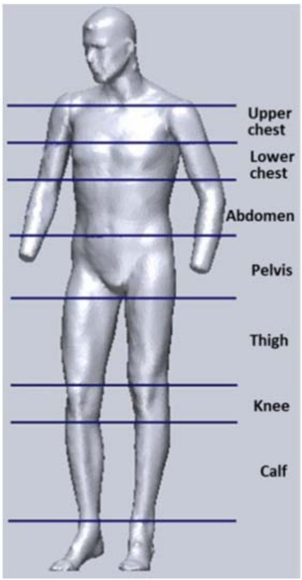


Fig. 2. Schematic of body separation.

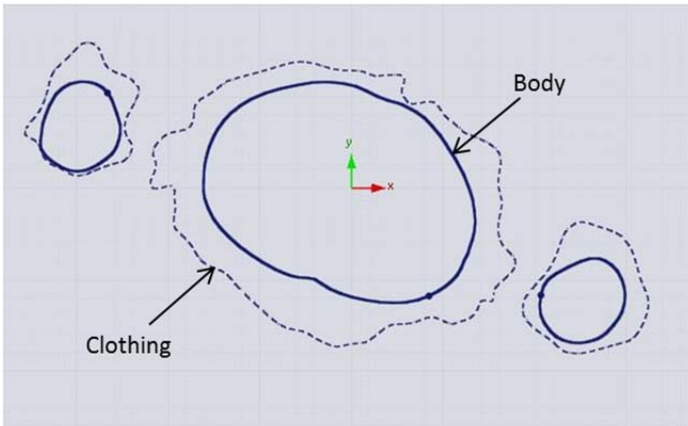


Fig. 3. Contour of body and clothing.

4. Results and Discussion

4.1. Average air gap and air volume

Fig. 4 showed the average air gap size of scanned coveralls. Coverall C1 presented smallest average air gap, and coverall C7 showed biggest average air gap among all selected coveralls. The overall air gap of selected single layer thermal protective coveralls was in the range of 25~35mm.

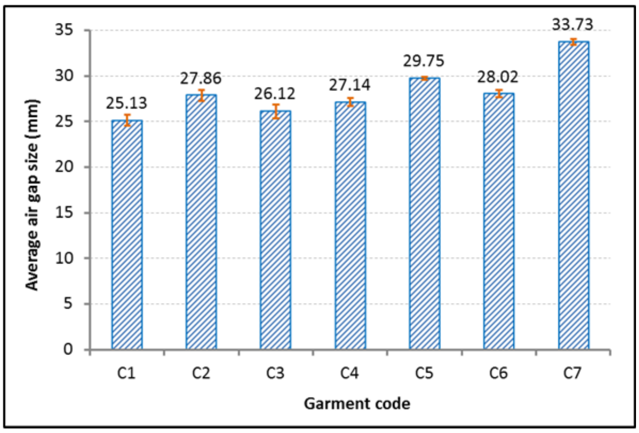


Fig. 4. Average air gap sizes of different coveralls.

The relationship between rigidity of fabric and average air gap size of the coverall was shown in Fig. 5. The warp stiffness was bigger than the weft stiffness, showing anisotropy, except the fabric for garment C7. The weft stiffness showed a significant linear correlation with average air gap size (R^2 = 0.92). However, the correlation between warp stiffness and air gap size was low. If the garment C7 was removed, then the correlation coefficient R^2 turned to be 0.41, showing a moderate correlation. C1 was made of Nomex® IIIA, which was soft, resulting in small space between garment and body. Coveralls C2~C7 were made of pure FR cotton or blended with nylon, which was stiffer than C1, therefore the air gap in these coveralls was larger than that of C1. In previous studies, it was found that Kevlar®/PBI coveralls had larger mean air gap sizes than more drapable Nomex® IIIA coveralls with the same style and size [6]. Based on the analysis, the weft stiffness could be applied to predict the average air gap size.

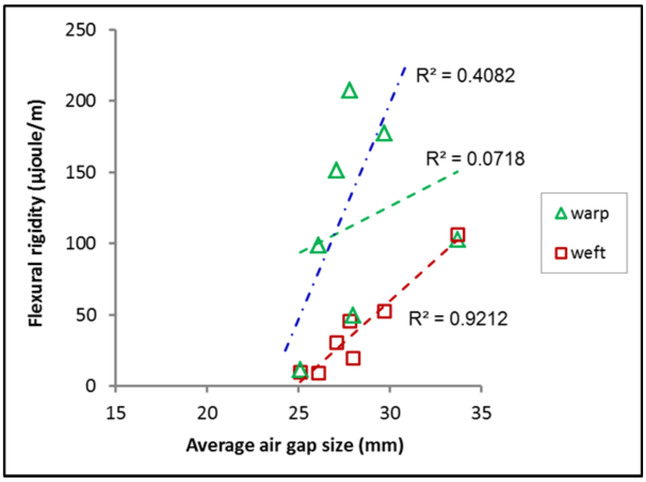


Fig. 5. Relationship between fabric stiffness and air gap size.

Hu and Chan found that fabric weight had positive effect on drape coefficient [14]. Mah and Song investigated the relationship between fabric drape coefficient and average air gap size and found these two parameters positively correlated well [15]. As shown in Fig. 4, the coverall C4 with higher fabric weight showed bigger average air gap size than C3 with the same style, which confirmed the positive effect of fabric weight on the entrapped air layer. The C5 was treated by polymer finishing on C4, resulting in higher flexural rigidity, and thus the air gap size was bigger. This indicated that the surface finishing affected the air gap size entrapped in clothing.

Total air volume was another parameter to characterize the space between body geometry and garment contour. Fig. 6 showed the relationship between air volume and average air gap size. The air volume of selected single layer thermal protective coveralls was in the range of 3.5~6 × 10^7 mm^3. It was found that the air volume linearly increased with the average air gap size. In Lee's study, the air volume was well correlated with thermal insulation [11]. However, only the vest was investigated. For thermal protective coveralls, the air volume showed good relationship with average air gap size based on the results in this study. The air volume could provide useful information to assess the garment fit.

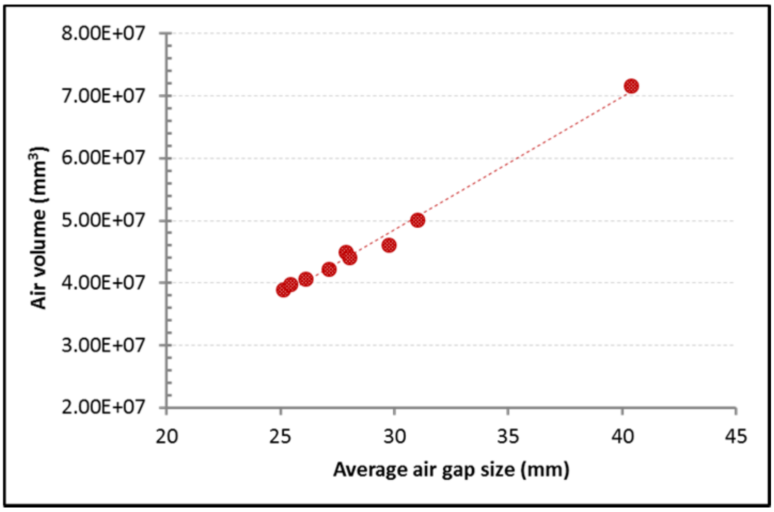


Fig. 6. Relationship between average air gap and air volume.

4.2. Air gap distribution

4.2.1. Air gap at different areas

The average air gaps at different body parts were compared in Fig. 7. All the coveralls showed similar change trend. The air gap formed in leg including thigh, knee and calf was much bigger than any other regions, and the air gap in upper chest and neck area was smaller than other areas. Lower air gap in chest and pelvis might be related to the convex body geometry. The contour of abdomen was concave, showing large space between body and clothing. The bigger air gap at lower chest than that at upper chest also demonstrated that concave locations showed higher air gap than convex areas. The small air gap in arm might be caused by the posture of arm, as shown in Fig. 1(a). The bent arms resulted in many folds and wrinkles around sleeves. This might lower the air gap.

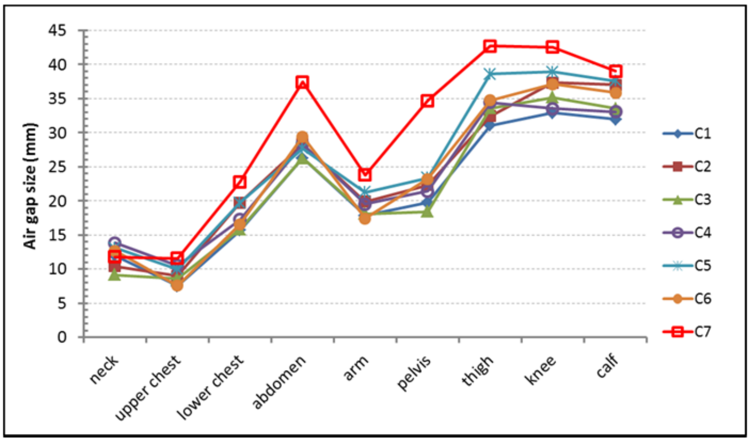
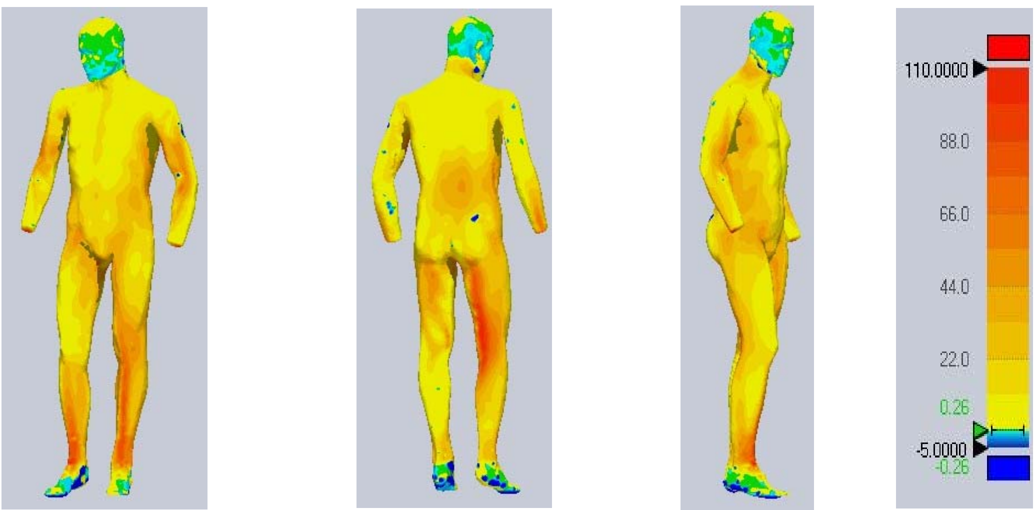


Fig. 7. Air gaps in different body parts.

4.2.2. Overall air gap distribution

The overall air gap distribution of C2 on human body was shown in Fig. 8 presented by color bar. The air gap between body and clothing unevenly distributed over the whole body. The air gaps on right posterior thigh and both anterior calves were obviously higher than other parts. However, the air gaps on right anterior thigh and posterior calves were small. This might be caused by forward flex of right knee. In addition, the air gap of forearm was bigger than that of rear arm. It was also related to the flex of elbow. The air gaps at two sides were relatively higher than the front and back. There was larger air gap at waist than abdomen, and there was smaller air gap in buttock. It demonstrated that the air gap in concave areas was higher than that in convex positions. The air gap at chest and upper back showed relatively uniform distribution. Based on the results obtained in this study, it was indicated that the air gap distribution of a specific coverall depended on body geometry and posture. Some areas at head and feet showed negative air gap, which might be due to the processing of scan data (void filling and alignment) and scan errors [5, 13]. This was considered as contact area in previous study [13].



Front view *Back view* *Side view* *Color bar*

Fig. 8. Overall air gap distribution of C2.

The average air gap of C2 determined by the whole air gap distribution was 24.23 mm, which was smaller than that shown in Fig. 4. The air gap estimated by the whole deviation method included the head and feet. They were not covered by clothing, and thus the air gap was around zero. Therefore, the average air gap was lower than that calculated by multiple sections which only took areas covered by clothing.

Fig. 9 showed the accumulative percentage of average air gap of sections for selected coveralls. The statistic generated from the average air gap of total 72 sections. Coveralls of C1~C6 showed similar trend and the overall air gap size was similar. The maximum average air gap of all the sections was around 50 mm. The percentage of the average air gap of section increased sharply between the size of 12 and 40 mm. Among the air gap distribution, the air gap less than 12 mm was 10% and higher than 40 mm was 10%. It indicated that about 80% air gap size was in the range of 12~40 mm. There showed no significant difference between C7 and the other single layer coveralls (C1~C6) when the percentage of air gap was less than 15%. The range of air gap size for C7 less than 28 mm only took 20% of all the sections, while the air gap between 28 and 40 mm took 40% of all the sections. The air gap of 80% of the all sections was in the range of 28~50 mm. It was observed that C3 took more percentage than C4 as the air gap was between 6 and 26 mm and they occupied the same percentage at the other air gap sizes. This might be because the lower fabric weight and softer of C3 resulted in lower air gap in body parts (shown in Fig. 7).

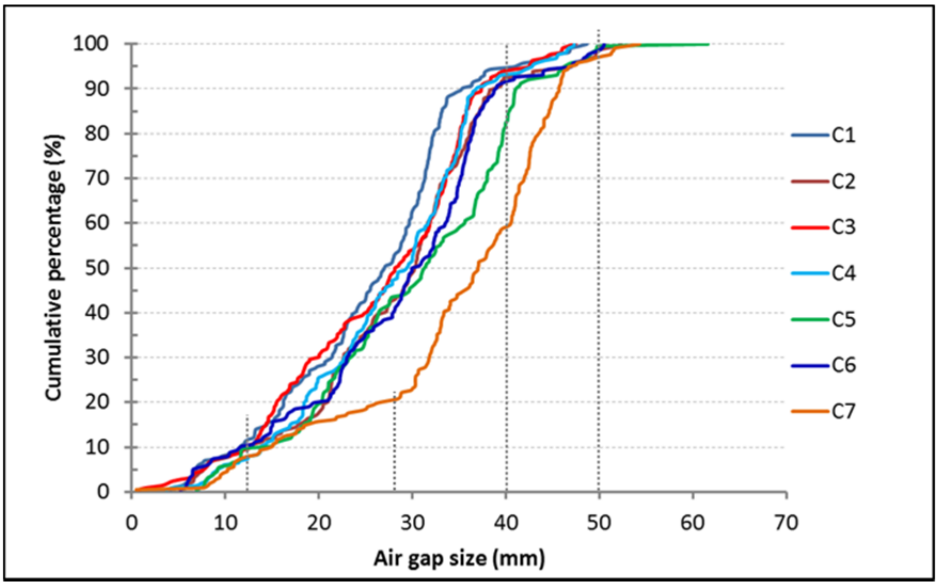


Fig. 9. Cumulative percentage of average air gap of section for different coveralls.

Conclusions

A comprehensive 3D body scanning data was developed to characterize the air gap size and distribution of selected protective clothing. It was found that air gap developed between human body and clothing depended on body geometry, fabric properties, and garment size and design. The air gap showed unevenly distributed over the body. Larger size of air gap was observed in legs and abdomen. The air gap in chest, pelvis and arms was small. The air gap of convex area was smaller than that of concave area. Coverall made of stiffer fabric provided larger air gap size. The proposed approach could provide both information on overall air gap distribution and the air gap of localized body areas. The data obtained could be correlated to thermal protective performance and dexterity performance, and thus provided information on the design of protective clothing to improve thermal performance and reduce physical burden.

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