Investigation into Fit, Distribution and Size of Air Gaps in Fire-Fighter Jackets to Female Body Form

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Abstract

The fit of the garment and the resultant air gap distribution and size between the human skin and the inner surface of clothing is one of key factors in the physiological comfort level of firefighters' protective clothing since the heat loss efficiency through protective clothing is in part affected by the size of air gaps. The size and distribution of air gaps between the body and the garment worn not only depend on the construction and style of the garment but also on body shape of the wearer. Often the same construction and style of garments are worn by male and female workers where the choice of the protective clothing for females is limited to a smaller size of man's garments only. Thus the air gap between the clothing and the body of a female wearer will therefore have a substantially different size and distribution to that between the clothing and the body of a male wearer. This would not only impact the physiological comfort of the garment ensemble worn but most importantly and most likely its protective and safety attributes as well. For the objective laboratory testing of physiological and protective properties of firefighters' ensembles thermal manikins are often used. In this study 3D body scanning technology was used to evaluate the fit of the selected fire-fighter's jackets to both male and female thermal manikin form. The size and distribution of air gaps between the manikin's male and female body form and the protective jacket were determined, analysed and compared. Thermal manikin "Newton" in male and female form was used in this study where the manikin was scanned nude in male and female form and then scanned wearing the fire-fighters' protective jacket in two different sizes in both forms. The 3D body scanning data generated in the form of 3D point clouds was analysed to investigate the fit of fire-fighters' protective jackets to male and female forms and to quantify the air gap size and distribution. It was concluded that the female body geometry leads to more trapped air between the body and the garment worn than the male form, resulting in larger trapped air volume while using the same size, design and construction for both.

Keywords: 3D body scanning, air gaps, thermal comfort, protective clothing

1. Introduction

One of the important aspects of thermo physiological comfort of clothing refers to the thermal balance between the human body and the environment. In hot environments, the proper balance between body heat production and heat loss is most important, so that the body does not undergo the heat stress. This balance is achieved by transportation of heat and moisture, both sensible and insensible, through the human-clothing-environment system [1]. Modern protective clothing should be able to protect the wearer from environmental hazards such as thermal, chemical and biological, and also provide adequate comfort. Its impact on thermal comfort of the wearer depends on the extent to which the clothing and the microclimate next to skin influence heat and moisture transport between the human body and the surrounding environment [2]. Fire-fighters' protective garments consist of a layered material assembly which typically include a flame-resistant outer shell and inner layers. The inner layers are generally composed of a moisture barrier and a thermal barrier or liner. When firefighter is performing a task in a fire, the heat and perspiration generated from the body become trapped inside the protective clothing which may cause heat stress [3]. Therefore the challenge is to produce comfortable protective clothing with adequate protection against the specific hazard whilst achieving thermal comfort to the wearer [4-5]. To achieve this, the selection of appropriate materials for thermal comfort and hazard protection is very important. The initial evaluation and comparison of textile materials used for firefighters has been carried out [6-8] where the textile components used in two different Australian firefighter's protective garments (Generation I and Generation IV) were examined as relevant to human physiological comfort. At material assemblies level the study revealed that Generation IV garment was more capable to transfer body heat and moisture in vapour form to outer atmosphere as compared to Generation I providing better thermal comfort [9-10]. However it is not sufficient to evaluate thermal comfort and protection offered by protective clothing at the level of material assemblies and physiological modelling alone. Garment style, fit and construction

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are also important factors to consider. The reason behind this is that the fit of the garment is directly linked to the size of the air gaps between human skin and inner surface of clothing, and thus is a key factor not only in protective efficiency of the garment but also in a process of heat loss from a human body [11].

Heat transfer between clothing and environment is a complex process. Air is entrapped between clothing ensemble and the human skin, and also between the material layers of their assembly. It is also trapped inside the fabric itself, e.g. within the fibres, yarns and other structural elements. This entrapped air plays a major role in heat and moisture flow through layers of protective ensemble. Air is one the best thermal insulators due to its low thermal conductivity, and is a barrier for the energy transfer between the skin and the environment [12]. The size and distribution of air layers between the wearer's skin and the garment surface depend on garments' style, size, fit, ease and fabric drape as well as on features such as collar folds, pockets and openings at the cuffs and neck, and pockets. Loose fitting garments tend to trap more air and have larger openings at places like the neck, waist, wrist, and ankles; as a result their thermal insulation and moisture vapor resistance during windy conditions and body movement is reduced [13]. Material properties such as fabric stiffness, bending rigidity and drapability affect the fit of the clothing construction of the garments. For example, Song investigated thermal protective performance of Kevlar®/PBI Matrix® (polybenzimidazole) and Nomex® IIIA coveralls of the same size and style and found that less drapable coveralls of Kevlar®/PBI had the larger mean air gaps than more drapable coveralls of Nomex®IIIA [14].

Currently there are three common methods to quantify the volume of air under clothing as briefly explained by Daanen H. et al.: vacuum suite method, cylinder model and 3D body scanning technology. He summarized that vacuum suite method is accurate but complex and time consuming, cylinder method is easy but it utilizes results that are too approximate and 3D body scanning technology is the most reproducible and accurate method [15]. In recent years 3D body scanning is the most widely used technology suitable for determination of the air gap size between body and the garment. Kim et. al used a 3D body digitizer to quantify the size of the air gaps in a single- and multi-layer clothing systems consisting of five different clothing configurations of existing military protective clothing The method for measuring the air trapped between clothing and skin was based on the observation that when clothing is put on, the surface of the clothing is displaced away from the underlying surface. After taking the thickness of the material into account, the displacement of the clothing surface was due to air trapped in the clothing layer. The displacement of the new surface relative to the original surface was measured in the following manner. Initially the scan of the nude manikin was taken as a base surface then the clothing was put on. The two scans were then superimposed using a region unchanged in both scans. The two scans were aligned and cross – section of the scan pair was taken along the vertical axis. The cross-section displayed two contours that alternately coincide or are separated by some distance. The distance between contour lines was measured as the air gap distance between clothing and the body. In this study full-scale manikin fire tests were also carried out to investigate the relationship between air gaps distributions and burn patterns. This study demonstrated that the size and distribution of air gaps depend on the drape of the composing fabrics in protective garment, as well as the geometry of the human body. Further to that it was observed that burn severity increases as the air gap between body and clothing decreases [16]. Later on it was noted that the air gap size between body and garment is not distributed evenly due to size and geometry of human body and that the garment may be in direct contact with skin in some areas whereas hanging loosely in others [17-18]. Tannie et al. investigated the effect of garment style and fit on thermal protection by determination of air gap size between body and garment using 3D body scanning technology, however there is not enough information available on how the air gap between clothing and the body was measured in the study. Researchers concluded that to achieve better thermal protection and fit for women, their body geometry is the most important factor to consider while designing their protective work wear. In this study different styles for male and female body forms were used which cannot provide sufficient information on how different human body geometry affects the air gap distribution [19]. Later Z. Zhang measured the air gap volume entrapped between body and garment on thirty experimental garments using 3D body scanner. The air gap volume was calculated by calculating the volume of the naked body and clothed body using Reverse Engineering software Geomagic. In this study the total air volume entrapped in thirty different experimental garments were calculated and analysed and relationship between fabric mechanical properties and thermal resistance was determined. This study did not demonstrate which areas of the body entrap most of the air and thus where the garments need potential modification [20].

In another study [21] 3D body scanning technology was used to scan the human leg in three different postures while nude and also when dressed in firefighters' protective trouser to determine resultant air gaps between leg and the trouser in different leg postures. The size and distribution of air gaps between clothing and skin was based on the 3D point cloud scanning data by superimposing nude and dressed surfaces in the same 3D axis using Rapidform software. After superimposing the two scans the surface of the scanned leg was sliced evenly from crotch to ankle in transverse plane. Then some common points were marked on nude leg scan. The distance between these points and the fabric was the measure of air gap between clothing and the body. During leg-lifting posture the air gaps on the front positions became smaller than the leg-upright posture, especially at the knee area where there was no air gaps because the fabric tightly pressed the body skin. Also the size of air gaps gradually decreased as the knee joint bent more under unchanging conditions of subject, garment size and material. Therefore the different body postures change the air gap between body and clothing [21].

Different methods have been employed to measure the air gap between clothing and the body in previous research as discussed. However there is no study into; the influence of male and female body forms on how air volume is determined at different body zones. This is necessary to demonstrate the influence of different body geometries on local air volume distribution across different body sections.

In Australia, there are no specific firefighting garment designs and styles available for female firefighters. The female firefighters are using the same firefighter protective ensemble as male fire-fighters do. Therefore the present study intends to determine the need for female firefighters to use a different style or design of the protective jacket compare to current jacket. For this reason, the air volume between body and the selected protective jacket were evaluated and compared at different body zones for male and female body forms using the same designs, styles and sizes for both forms.

2. Materials and methods

2.1 Materials

The Firefighters' protective jacket used in this study is a three-layered garment having a structural fire coat with removable inner liner as shown in Fig. 1. The inner layer and the middle layer are stitched together while the outer layer is a removable fire coat. The outer layer is made from protective material A, the middle layer is made from material B and the inner layer is made from material C. The selected jacket is available in eight different sizes ranging from XS to 4XL. The Small and Medium sizes were selected for the present study. The measurements of selected sizes of protective jacket are given in Table 2.

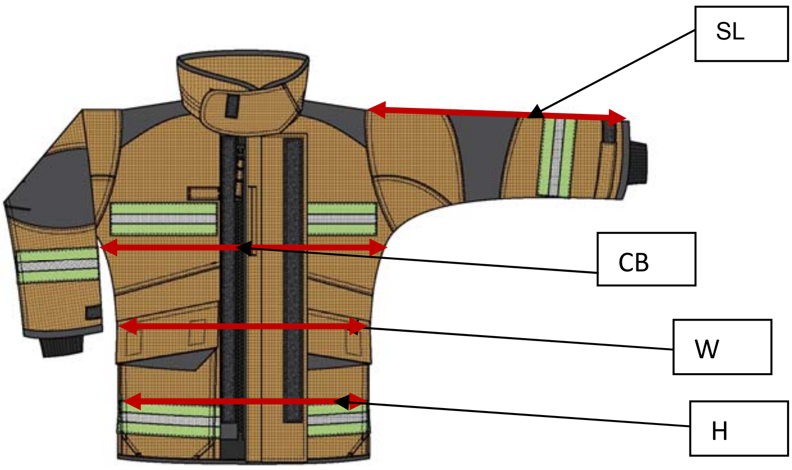
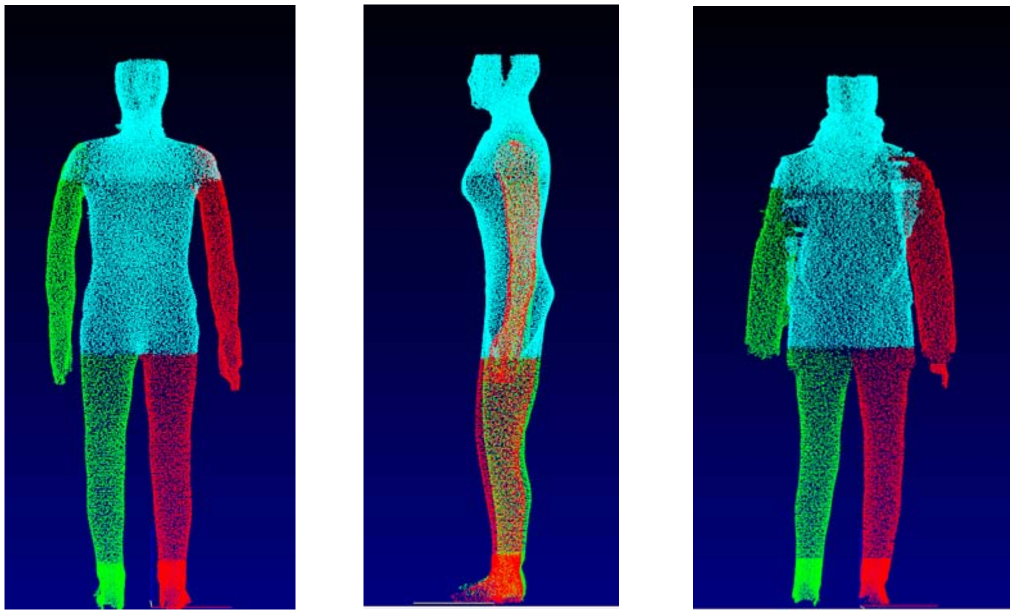


Fig. 1. Firefighters' protective jacket.

2.2 3D Body scanner

NX-16 TC^2 3-Dimensional white light body Scanner was used for scanning. The resulting data was generated in the form of 3D point cloud (Fig. 2) [22].



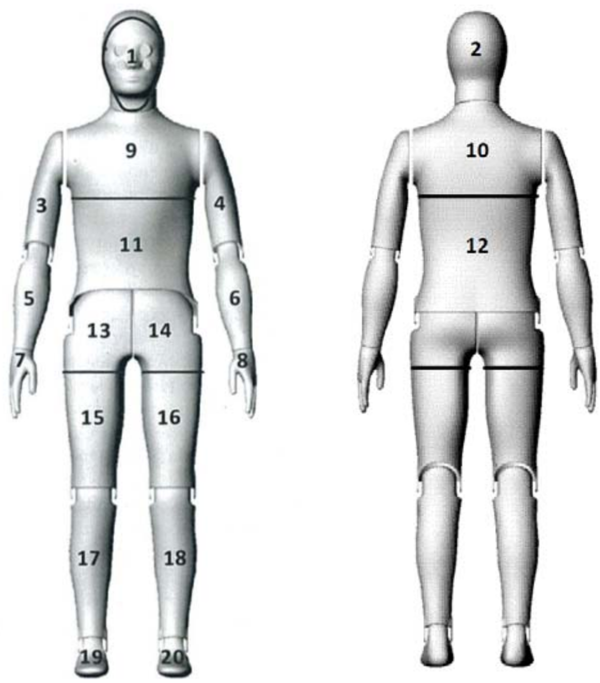
(a) (b) (c)

Figure 2. 3D point cloud data a) Manikin in male form, b) Manikin in female form, c) Dressed manikin.

2.3 Thermal manikin

The Newton Thermal manikin (supplied by Measurement Technology Northwest Seattle, WA, USA) was used in this study for scanning. The manikin has 20 segments for which the surface temperature is controlled independently, and the total heat input required to achieve set surface temperature is accurately measured (Fig. 4). The manikin can be modified to either male or a female form. This is achieved by adding breast segment at the chest of the manikin to simulate the most critical female form as shown in Fig. 5 (a,b). Each zone of the manikin corresponds to a theoretical human body zone e.g. for example zone 9 at front refers to chest of the manikin, zone 10 refers to the shoulders etc.(Table 1).

Scans were made with the nude manikin and while dressed in protective jackets in both its male and female forms.



(a) (b)

Fig. 4. Thermal manikin Newton in male form: a) Front b) Back.

Table 1. Manikin zones and corresponding body segments.

Manikin zone	Body segment	Manikin zone	Body segment
1	Face	11	Stomach
2	Head	12	Back
3	R Upper Arm	13	R Hip
4	L Upper Arm	14	L Hip
5	R Forearm	15	R Thigh
6	L Forearm	16	L Thigh
7	R Hand	17	R Calf
8	L Hand	18	L Calf
9	Chest	19	R Foot
10	Shoulders	20	L Foot

2.4 Test protocol

The thermal manikin Newton was scanned in both its male and female forms (Fig. 5). Scans were taken with each form of the manikin in nude and dressed form with jacket in Small (S) and Medium (M) size (Fig. 6). Each scan was taken five times and mean values of air volume calculated for five scans were reported.

(a) (b)

Fig. 5. a) Female manikin, b) Male manikin.

Fig. 6. Dressed manikin.

The volume of each zone (cm^{3}) covered by the jacket was calculated and the volume of the same zone in nude manikin subtracted from the corresponding volume of dressed zone using Rapidform software. The result of this calculation was the volume of entrapped air (cm^3) (Fig. 7). The resulting data for each zone of the manikin covered with jacket were presented in bar charts as shown in Fig. 8 and 9 where the error bars representing the standard deviations in the measurements.

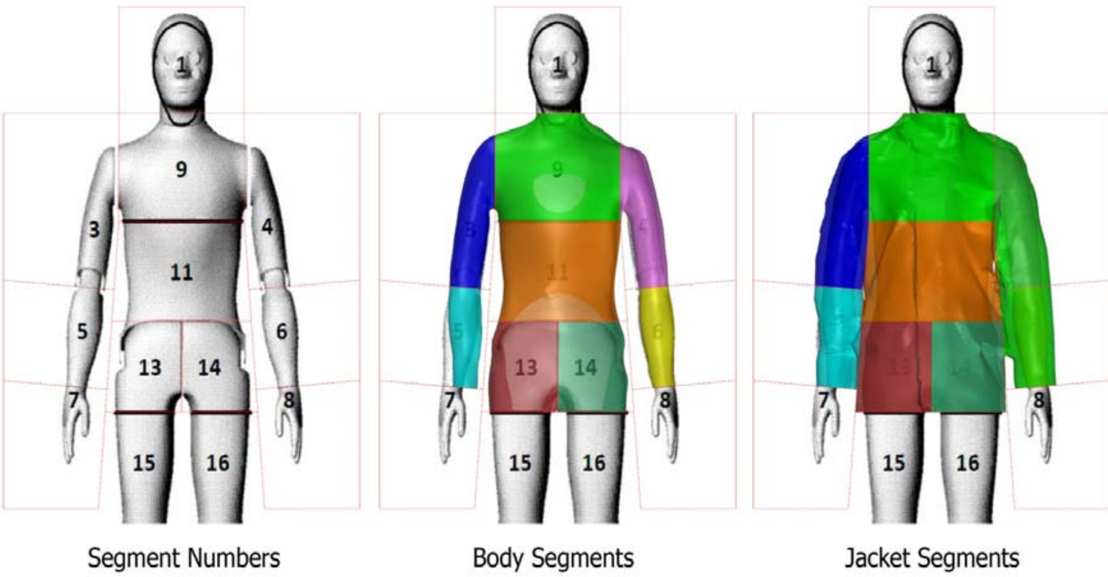


Fig. 7 Manikin segments (zones) for volume calculations.

In addition the measurements of the nude manikin, both in male and female form, and also of the jacket were obtained manually (Table 1). Each measurement was also carried out 5 times.
Standard deviation is a statistical value used to determine how spread out the data in a sample is, and how close individual data points are to the mean value of the sample. A standard deviation of a data set equal to zero indicates that all values in the set are the same. A larger value implies that the individual data points are farther from the mean value [23].

3. Results and discussions

Manual measurements of the manikin and jackets are shown in Table 2.

Table 2. Measurements of the manikin and the protective jackets

Mean Measurements	Thermal Manikin (Male) cm	Thermal Manikin (Female) cm	Protective jacket (Small) cm	Protective jacket (Medium) cm
Cross Shoulder, CS	42	42	54	56
Chest/Bust, CB	89	100.5	122	127
Waist, W	73.5	73.5	116	122
Hips, H	92	92	116	122
Sleeve Length, SL	56	56	60	64
Back Length, BL	68	68	81	81.5

3.1 Air gap volume resulting from Small and Medium size jackets

The volume of air under the Small and Medium size jackets on manikin in male and female form is presented in Figures 8 and 9.

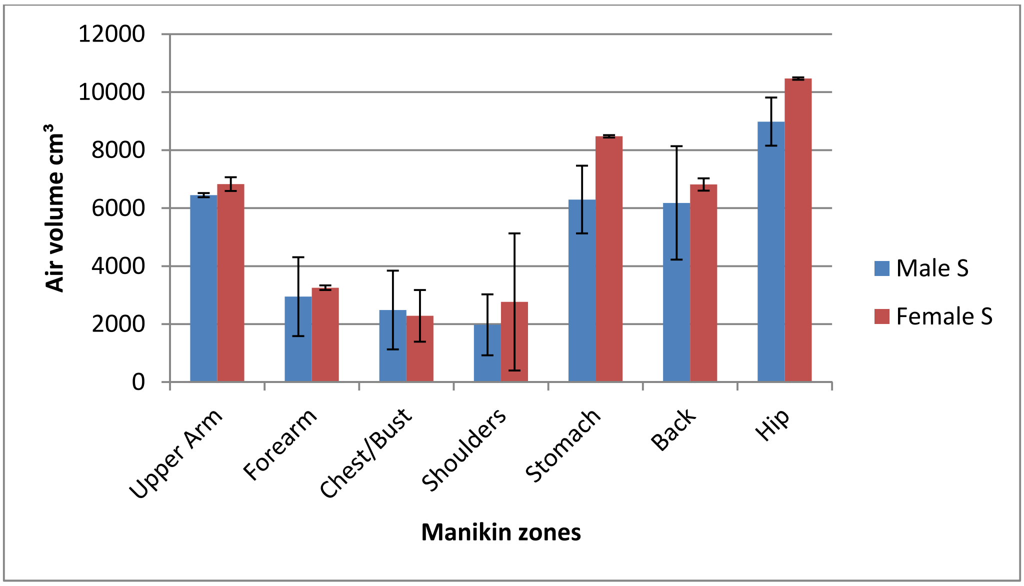


Fig. 8. Air volume for jacket size Small in each zone.

Fig. 8 shows that air gap volume in each zone is greater while the manikin is in its female form than the male body form while wearing the Small size jacket except across the bust. It is interesting to note that the volume of air gap increases by 34% at the stomach and by 10% at the back for the same size of the jacket when changing male form to female form. At chest/bust the volume of the air gap is 8% lower in female form than in male form. This is due to having breasts in female form which reduces entrapped air at bust level, However the entrapped air gap increases at stomach level in female form just under the bust for the same reason. At the shoulders the air gap volume is 37% larger in female form than in male form for the same size of the jacket. Men typically have broader shoulders than women; therefore the entrapped air at shoulders level would be smaller in males than in females while wearing the garment of the same size. However the thermal manikin used in this study has the same size shoulders in both the male and female body form, as only breast segments where added to create the female shape. It is evident that the addition of breasts changed the distribution of entrapped air gaps across different body zones, especially at the stomach and at the back. The volume of air also increases in all other zones in female manikin form as compared to male manikin but not to the same extent as for stomach and back. The standard deviations represented in the charts by the error bars are high at all zones except the shoulders when the manikin is in the male form. When the Small jacket is worn by the male form of the manikin the distance between the body and the jacket is small but the variation between measurements is high. The geometry of the manikin is such that when dressed in smaller jackets there are more folds in the clothing surface which in turn leads to additional occlusions and more variation in the point clouds recorded by the 3D surface scanner. In case of the female wearing the small jacket the distance is even smaller but the variation is less as the garment surface is smoother due to the tighter fit of the garment on the larger volumed form of the manikin.

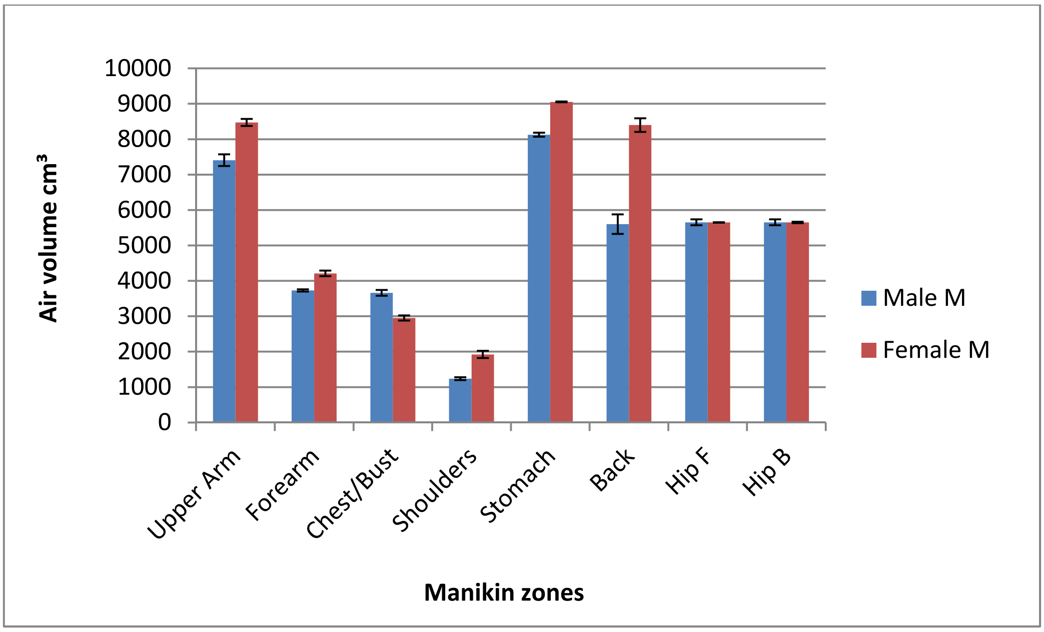


Fig. 9. Air volume for jacket in size Medium in each zone.

When the jacket size was changed from Small to Medium the volume of entrapped air in each zone was found to follow the similar pattern as for the small size jacket (Fig. 9) with most of the air being entrapped at the stomach zone in both body forms and for both jacket sizes. Each zone of female manikin had larger entrapped air volume when compared to the male manikin (Fig. 9). The back zone of the manikin in female form entrapped 33% more air volume than the manikin in male form. In female form the jacket is hanging backward with support of shoulders and bust so there is more air volume entrapped across back as compared to male form.

The standard deviation in both forms is very low when wearing the Medium sized jacket. With the Medium size jacket, the garment surface is smoother since the larger jacket entraps more air and shape of the garment surface is less influenced by the shape of the manikin wearing it. This leads to less variation in the point clouds data captured by the scanner.

3.2 Total air volume in male and female form of manikin using small and medium size jacket

Form Fig. 10, it can be seen that the total air volume entrapped between the jacket and the manikin surface in female form is larger when compared to the total air volume for manikin in male form for both small and medium size jackets. For the Small size on both manikin forms the total air volume entrapped increased by 15% in female form. With Medium size there was an increase of 13%. Further to that, the Medium size jacket entrapped a larger volume of air compared to the Small size jacket in both male and female forms. The reason behind this is that when bigger size was used for the same manikin size the gap between body and the jacket increased which led to increase of the entrapped air volume.

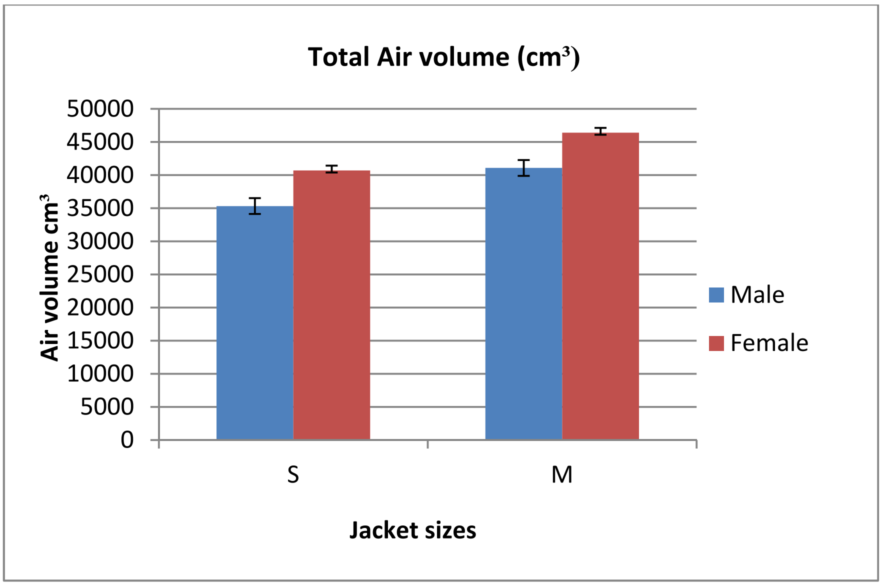


Fig. 10 Total air volume using Small and Medium size jacket.

When the manikin was changed from male to female form by the addition of the breasts section, the increase in total volume of the manikin was about 1%. The total air volume reported here was calculated by subtracting the total volume of the naked manikin form total volume of the dressed manikin. Therefore when the manikin is wearing the same size of the jacket in female form it would be first assumed that it should have lower total entrapped air volume as the volume of manikin is larger in female form. However experimental data for both jacket sizes demonstrates that the air volume for female form increases by 13-15% as discussed earlier. The reason behind this is that when breasts sections are added to the manikin it leads to capturing more air under the breasts (at stomach and back), thus increasing the overall volume of entrapped air by the dressed manikin and resultant total air volume between the jacket and the manikin's body.

4. Conclusion

In conclusion, when comparing a garment of the same size and construction on both a female and male body, the female body shape forms a greater air gap between the body and the garment than on the male body shape. The results also show that a looser garment of larger size entraps larger air volume. In present study the same manikin was used in male and female form which changed the air volume entrapped only by addition of the breast segments with the rest of the manikin remaining of the same size/configuration. The results are valuable for the objective thermal garment testing, especially in understanding the influence of the size and distribution of air gaps on garment thermal characteristics. However for actual human subjects the male geometry is different from the female body shape in all body sections, not just at the chest area. Therefore the total air volume and volumes across different body sections could be larger than the ones reported in this study for the females wearing the same size jacket as compared to males. Consequently the results of present study clearly indicate that there is a need for modification of the existing firefighters' jacket design to better suit the female human body geometry where the air volume can be optimized through garment design and engineering.

It would be necessary to investigate further how the present results relate to the thermal performance of the protective jackets. Large volumes of entrapped hot air could adversely affect the thermophysiological comfort attributes of the protective jacket. Alternatively large air gaps could allow convection which could also affect comfort of the wearer. Conversely small air gaps may not provide enough insulation and put the wearer at risk of skin burns as proven in previous research studies [19, 24]. Further research is needed in this direction to clarify these issues.

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