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Improving garment thermal insulation property by combining two non-contact measuring tools

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To investigate the effect of air gaps on the heat transfer performance of clothing, the method using the combination of two non-contact measuring tools (infrared thermal camera and 3D body scanner) has been developed considering the quantification of the air gap thickness and clothing surface temperature of different body parts without contacting clothing surface directly. The results show that the air gaps over middle and lower back of upper body have the largest thickness in all body parts, while the front and back shoulders have the smallest air gap thickness. The one-way analysis of variance shows that air gap thickness under shoulder segments has no significant difference in terms of size. Furthermore, clothing surface temperatures of shoulder and chest decrease gradually along with air gap thickness; clothing surface temperatures of front abdomen, front waist, pelvis and hip segments decrease initially but begin to increase when the air gap is above 1.5cm; clothing surface temperatures of middle back and back waist continually increase with the air gap thickness. Based on the comprehensive analyzation of the distributed features of air gap thickness and clothing surface temperature of different body parts, a revised clothing pattern with lower regional temperature and higher thermal insulation is put forward.

Keywords: 3D body scanner, Air gaps, Cotton, Garment, Non-contact measuring tool, Thermal insulation

1 Introduction

The comfort and functions of garment have long been the main concerns of customers when they make a purchase. Owing to the excellent thermal insulation of static air, the air gaps entrapped between human skin and clothing can influence the clothing thermal insulation significantly[1,2]. Many researchers[3-5] have investigated the relationship between clothing fitness resulting from air gap and clothing heat transfer property. Chen *et al.*[6] found that the thermal insulation and moisture vapor resistance increase with the thickness of air gap within a comparatively small scope, yet the growth rate slows down as the air gap becomes thicker. Havenith *et al.*[7] showed that when a wearer is sitting or walking against the wind, the thermal insulation of tight clothing is lower by 6-31% than that of a loose piece. Although great progress has been achieved by studying the effect of air gaps on clothing thermal function, few researchers have mentioned the uneven air gap distribution over human skin and the relationship between local heat transfer features and local air gap thickness.

The development of three-dimensional scanning technique[8] makes it possible to measure the air gap between human skin and inner surface of clothing accurately. Some researchers[9-11] have utilized 3D scanner to investigate the influence of air gaps entrapped in protective clothing on fireproof performance. Using a 3D body scanner, Mah and Song[12,13] measured the air gaps between a female mannequin and protective coveralls, and proved that air gap size has a positive correlation to burning by employing a flash-fire instrumented female mannequin evaluation system. Based on the above researches, we should further quantify the heat transfer of different body parts and apply these findings to garment pattern design.

In this study, we propose a method to determine the air gap thickness of different body parts accurately, and relate this with the clothing surface temperature through advance analysis of 3D body scans and infrared thermography of nude and dressed human body. Additionally, a clothing pattern design to improve the thermal insulated performance of clothing is put forward, which is expected to provide a scientific instruction on clothing design of thermal protective garments.

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2 Materials and Methods

2.1 Testing Garments

Five men's shirts made from the same fabric but of different sizes were prepared as experimental garments. The fabric is made of 100% cotton [weight 282.62 g/m^2, thickness 0.56 mm, air permeability 49.78 mm/s (permeability tester, YG461E, Wenzhou China), thermal insulation 0.016 K·m^2/W (sweating guarded hotplate, Measurement Technology Northwest, U.S.A.)]. All the shirts were having the same style of long sleeves and button up at the front, but the size is gradually increased at chest, waist and hip girths. The specifications of experimental shirts are shown in Table 1. The chest circumference of the shirt is 92cm, represented as B92.

2.2 Subjects

Eight men with age 22 ± 1.5 years, height 170±2.4cm, weight 65.2±3.1 kg, bust circumference 88.3±2.3 cm, waist circumference 74.1±2.1 cm, hip circumference 90.6±1.8 cm and shoulder 41.4±1.2 cm volunteered to participate in the tests. All participants were nonsmokers and with no history of any cardiopulmonary diseases. They were provided with a participant information sheet, informing them of the aims and procedures of the experiment. After familiarizing with the laboratory and the equipments, every participant signed an informed consent document. Except for the test garments, they were dressed uniformly in full length, form-fitting pants and socks.

2.3 Test Procedures

The tests were conducted in an environmental chamber at a temperature of 25 ± 2°C, relative humidity of 50 ± 5% and air velocity of 0.4 m/s. Before the experiments, all test garments were laundered in cold, soft water and ironed. The garments were then hung in the environmental chamber for 24h before the test. During each test, subject selected one testing shirt randomly to avoid order effects. Subjects came to the laboratory at the same time of day, and each day only one subject was tested. Subjects entered the chamber and rested for 15 min to adapt to surrounding conditions. During resting period, subjects sat quietly and listened to light music or read books. The experiment was divided into two parts, viz. 3D scanning test and infrared thermal imaging test. A 3D human body scanner (BMS from TC^2) was used to detect the air gap thickness under garments. Before testing, the 3D body scanner was calibrated by a cylinder (height 152.5 cm, radius 28 cm). The scanning included two steps, namely (i) subjects wore full length, form-fitting pants as a reference garment while bared their upper body to get the surface images of their naked body, and (ii) subjects put on the experimental shirts and sat for 10 min to adapt to their ensembles, then scanned second time to obtain surface images of the clothing. During each scan, subjects were required to stand on a pair of given footprints and hold handles at both sides of the human body to fix the spreading angles of the legs and arms. Every shirt was dressed and undressed three times to improve scanning accuracy and reduce errors caused by human respiratory.

Table 1—Measurements of experimental shirts (cm) [Neckline 40cm and Length 71cm]

Shirt code	Bust	Waist	Hip	Shoulder
B92	92	90	94	41.6
B96	96	94	98	42.8
B100	100	98	102	44
B104	104	102	106	45.2
B108	108	106	110	46.4

To detect the temperature distributions of clothing outer surface, another non-contact measuring tool, infrared thermal camera (M7800, Micron Infrared, Inc.) with a resolution of 0.06°C and an applicable temperature range of -40-500°C was employed. The standing posture and opening angles of arms under the armpits were consistent with 3D scanning tests. Subjects were asked to stand on the footprints and open their arms to the preinstalled angles with the guide of the angle gauge. The locations of infrared thermal camera and body posture were kept constant during the tests. The infrared thermal tests also included two steps, viz. the subjects were photographed with bared upper body for the first time, and then every shirt was put on and photographed again. Each subject and shirt was photographed three times for the frontal and posterior to calculate the average temperature. The clothing surface temperatures were then analyzed by thermal imaging software (Micron Infrared, Inc.), which was used to analyze thermal images by point, line and area measuring methods to get the maximum, minimum and average temperatures of testing scopes.

2.4 Air Gap Measurements

Three cylindrical nodules (1.5cm diameter×1cm height) were placed on uncovered body parts, such as head, left and right calf. By using register tool (Pick 3 Ref. Points) in Rapid Form software, the nude image was aligned with the clothed image by aligning three pre-defined nodules. The space between human body and clothing is the air gaps under clothing.

To investigate the regional distributions of air gaps under human torso, thirteen cross-section pairs of aligned image (S1-S13) were taken according to the height of the human torso at an interval of 5 cm. As is shown in Fig.1, every cross-section pair contained two contour lines, the inner line represented the shape of human body and the outer line represented the shape of the garment. Furthermore, a 360° protractor[13] was superimposed on cross-section pairs to measure the air gap thickness of different angles (every 10°), with angle 0° represents the front center of upper body, angle 180° represents the back center and 90° represents the right center. Then the air gap thicknesses at thirty-six angles of thirteen cross-section pairs were obtained. To further investigate the distribution features of air gaps over upper body, the human torso was divided into fourteen segments according to the positions and angles of cross-sections pairs. Table 2 outlines the 14 body segments (front shoulder, front chest, front abdomen, front waist, pelvis, lateral chest, lateral abdomen, lateral waist, lateral hip, back shoulder, upper back, middle back, back waist and hip) and the regions each segment represents. The air gap thickness of each body segment was calculated by arithmetic means value.

2.5 Clothing Surface Temperature Measurements

To measure the temperatures of clothing surface at different torso segments, ten temperature measuring areas (front shoulder, front chest, front abdomen, front waist, pelvis, back shoulder, upper back, middle back, back waist and hip) were drawn on the frontal and rear infrared photos of upper body, corresponding to the zones of air gap measurements. Figure 2 shows the positions of ten areas and the average temperature of each body segments measured by area tool in MikroSpec software. Thus, the relationship between air gap distribution and clothing surface temperature can be further analyzed to find out the heat transfer features of different torso segments.

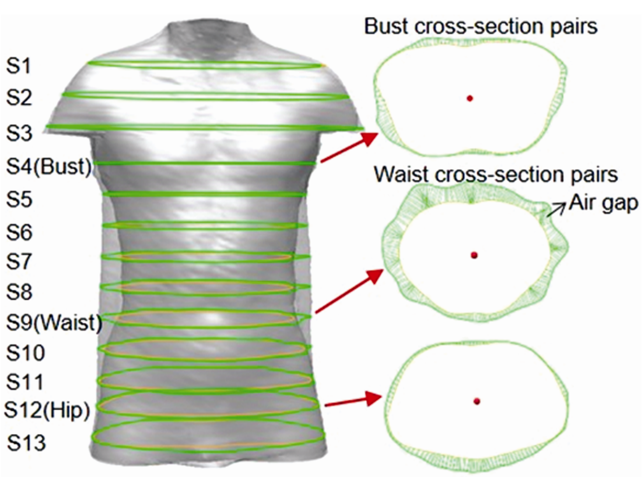

Fig. 1—Cross-section pairs on garment B96

2.6 Statistical Analysis

Data are presented as mean ± standard deviation (SD). The differences in air gap thicknesses between experimental shirts were analyzed by one-way ANOVA (analysis of variance) with SPSS 17.0 software package. The level of significance was set as $p<0.05$.

3 Results and Discussion

3.1 Distribution of Air Gaps under Clothing

Figure 3(a) shows that the thickness of air gaps at different cross-sections is not evenly distributed along the height of upper body. For all shirts, the middle back and back waist segments (Z12 and Z13) have the largest mean air gap thickness, followed by lateral abdomen and lateral waist segments (Z7 and Z8), and the front and back shoulders (Z1 and Z10) have the smallest mean air gap thickness. As a whole, the air gap thickness at frontal body is smaller than that at lateral and rear body, and the larger air gaps under pelvis is due to the garment design on the hem. The

Table 2—Distribution positions of 14 body segments

Code	Body segment	Section	Angle, deg
Z1	Front shoulder	S1-S3	-60-60
Z2	Front chest	S3-S5	-60-60
Z3	Front abdomen	S5-S8	-60-60
Z4	Front waist	S8-S10	-60-60
Z5	Pelvis	S10-S13	-60-60
Z6	Lateral chest	S3-S5	±60-±120
Z7	Lateral abdomen	S5-S8	±60-±120
Z8	Lateral waist	S8-S10	±60-±120
Z9	Lateral hip	S10-S13	±60-±120
Z10	Back shoulder	S1-S3	-120-120
Z11	Upper back	S3-S5	-120-120
Z12	Middle back	S5-S8	-120-120
Z13	Back waist	S8-S10	-120-120
Z14	Hip	S10-S13	-120-120

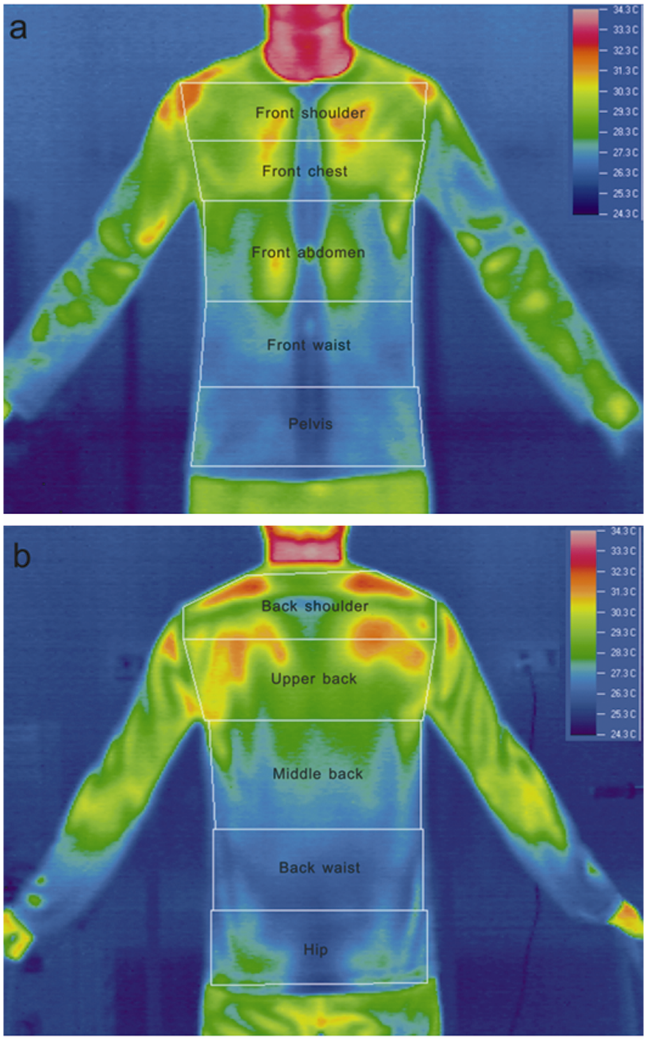

Fig. 2—Ten temperature measuring zones (a) frontal body, and (b) rear body

body shape also influences the distributions of air gaps under different segments. The air gaps usually have larger thickness at concave areas. For example, the S-type of lumbar vertebrae makes human waist bend forward and results in the largest air gap at back waist. While the convex areas formed by human skeleton and muscle, such as the shoulder and hip, tend to have smaller air gap thickness.

Although the air gap thickness increases with the garment size, the difference of air gap thickness at different segments is not significant among five experimental shirts. A one-way ANOVA analysis of air gap thickness among five experimental shirts for different body segments demonstrates no significant differences ($P \leq 0.05$) for front and back shoulder segments (Table 3). But significant differences at $P \leq 0.01$ are found in all other segments. It shows that the garment tolerance can significantly increase the air gap thickness for all body segments, except for the shoulder areas. As human shoulder plays a supporting role to garment, the garment is closest to human skin at this area. That is why, the air gap thickness over human shoulder is not significantly increased with garment size. It seems that garment tolerance has no evident effect on increasing air gap thickness of shoulder segments.

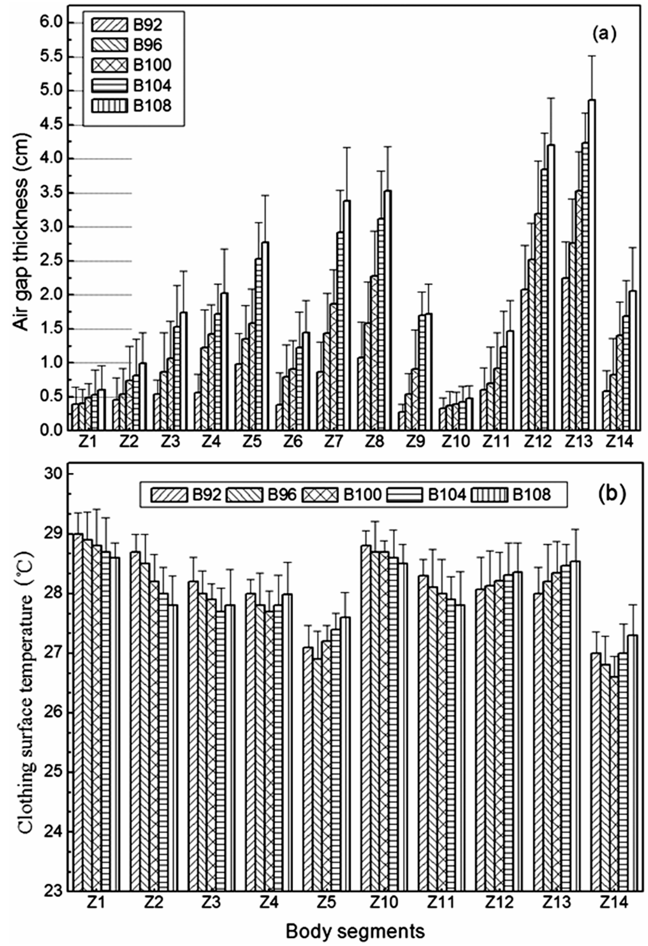

Fig. 3—Air gap thickness (a) and clothing surface temperature (b) of five shirts

3.2 Distribution of Clothing Surface Temperature

Because it is difficult to photograph the infrared photos of lateral body (Z6-Z9), only frontal and rear body parameters were analyzed. The clothing surface temperatures of ten body segments of five experimental shirts are shown in [Fig. 3(b)]. The front and back shoulder segments (Z1 and Z10) have the highest clothing surface temperatures due to the smallest air gap thickness; whereas the pelvis and hip segments have the lowest clothing surface

Table 3—Significant difference in air gap thickness between five experimental shirts

Body segment	*n*	Mean, cm	*SD*, cm	*F*	*Sigma*	*P*≤
Front shoulder	195	0.482	0.312	2.15	0.076	NS
Front chest	195	0.707	0.612	4.687	0.001	0.01
Front abdomen	260	1.148	0.791	28.266	0.000	0.01
Front waist	195	1.390	0.769	33.956	0.000	0.01
Pelvis	260	1.843	1.162	35.03	0.000	0.01
Lateral chest	210	0.951	0.818	10.856	0.000	0.01
Lateral abdomen	280	2.095	1.465	46.346	0.000	0.01
Lateral waist	210	2.318	1.564	26.606	0.000	0.01
Lateral hip	280	1.029	0.899	38.832	0.000	0.01
Back shoulder	195	0.401	0.231	2.247	0.066	NS
Upper back	195	0.987	0.834	8.540	0.000	0.01
Middle back	260	3.167	1.677	18.405	0.000	0.01
Back waist	195	3.528	1.669	22.970	0.000	0.01
Hip	260	1.309	1.173	17.617	0.000	0.01

NS–not significant.

temperatures because the overlap between these two segments and pants increases the thermal insulation. To compare quantitively between air gap thickness and heat transfer, the pelvis and hip segments will not be analyzed in following contents.

Although the static air has good thermal insulation property, the clothing surface temperatures of ten body segments are not all linearly decreased with the increase in air gap thickness. The changing features of clothing surface temperature with air gap thickness can be classified into three types: (i) the clothing surface temperature decreases gradually with the increase in air gap thickness, such as the front and back shoulder, front chest, upper back segments (Z1, Z2, Z10, Z11), which usually has smaller air gap thickness than other segments; (ii) with the increase in air gap thickness, the clothing surface temperature decreases firstly, and then increases when the air gap attains certain thickness, such as the front abdomen, front waist, pelvis and hip segments (Z3, Z4, Z5, Z14); and (iii) the clothing surface temperature increases with the air gap thickness, such as the middle back and back waist segments (Z12, Z13), which is corresponding to the largest air gap thickness in all body segments. The garment B100 shows the lowest average surface temperature in five experimental shirts.

The scatter point analysis of surface temperature and air gap thickness is shown in Fig. 4. It shows that the clothing surface temperature decreases sharply with the increase in air gap thickness, but begins to increase when the air gap is larger than the critical thickness of 1.5cm as a result of natural convection. As the air gap thickness for the first type is all below the critical thickness, the clothing surface temperature decreases with the increase in garment size. On the contrary, the air gap thickness for the third type is larger than the critical thickness even for the smallest garment (size B92), which is why the clothing surface temperature increases with ease allowance. It seems that the middle back and back waist segments are the easiest to emerge natural convection in fourteen segments.

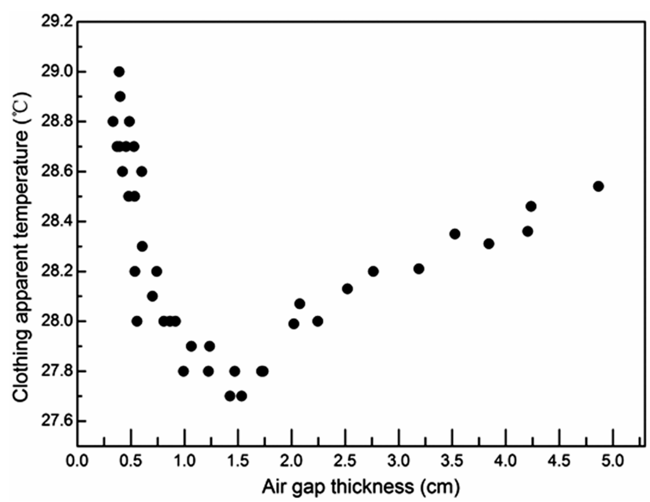

Fig. 4—Scatter plot of clothing surface temperature and air gap thickness

3.3 Improving Garment Thermal Function Design

The uneven distribution of air gaps under clothing leads to the difference in heat transfer performance from skin to environment among different body segments. Based on the measuring data of 3D human scanner and infrared thermal camera, the original pattern of men's shirt [Fig. 5(a)] is redesigned to improve the thermal insulation properties of garment. As the experimental shirt B100 has the lowest surface temperature, the chest circumference of the revised pattern is 100cm in order to achieve the best heat insulation performance of the whole clothing.

Judging from experimental data, the front and back shoulder segments have the smallest air gaps and highest clothing surface temperatures. As the increase in clothing tolerance cannot enlarge the air gap thickness significantly, the thermal insulation of shoulder segments cannot be improved by increasing ease allowance of the clothing. The revised pattern makes the shoulders cover 5cm above the chest circumference of original pattern, and by which way the thermal insulation of front and back shoulder can be improved by adding cover cloth.

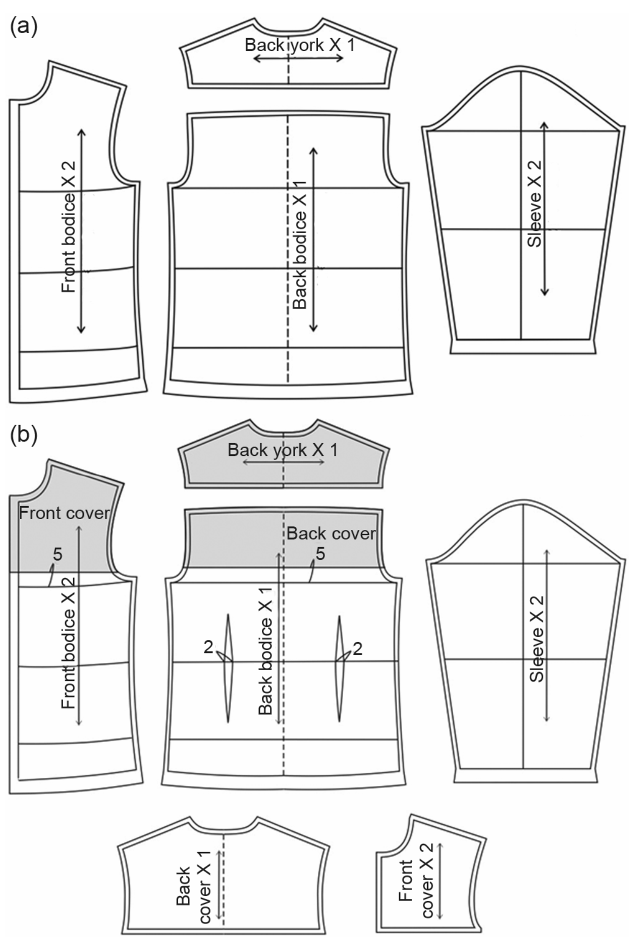

Fig. 5—Original (a) and revised (b) pattern of experimental garments

Another conclusion is that the middle back and back waist have the largest air gap thickness in fourteen segments. Even under the smallest tolerance (4cm), the natural convection will take place at these segments and this increases the heat transfer from skin to clothing surface. For these areas, the air gap thickness must be controlled within the critical thickness to avoid the onset of natural convection. The linear regression equation between the air gap thickness of back waist and waist tolerance is:

$$\hat{y} = -0.498 + 0.168x \qquad \ldots (1)$$

where $\hat{y}$ is the air gap thickness of back waist segment (cm); and x, the waist tolerance, namely the waist circumference difference between garment and upper body (cm). The regression coefficient R^2=0.997 ($P < 0.05$).

When the critical thickness of air gap is 1.5cm, the calculated waist tolerance is 12cm according to Eq.(1). As is shown in [Fig.5(b)], by adding two back waist darts (each 2cm) on the original pattern, the air gap thickness of back waist segment is controlled within 1.5cm. According to the revised pattern, a new shirt was made of the same fabric as the original shirts and the same experimental procedure was followed to test the surface temperature of the new shirt. The result shows that the surface temperatures of the revised shirt (R100) at the front shoulder, back shoulder, middle back and back waist segments are lower than original shirt (B100), which demonstrates that the local heat resistance of the new shirt is improved by the revised pattern. Furthermore, the thermal insulations of five original shirts and the new shirt was tested by a thermal manikin (ISO 15831, 2004) in a climate chamber at a temperature of 25 ± 2°C, relative humidity of 50 ± 5% and air velocity of 0.4 ± 0.1 m/s. The skin surface temperature at each of the manikin's body segments is maintained constant at 34 ± 0.2°C during the test period. The effective thermal insulation is increased when the shirt size does not exceed B100. After that, it begins to decrease due to the onset of natural convection. The original experimental shirt with chest circumference of 100cm has largest thermal resistance, but the new shirt R100 achieves larger thermal resistance by improving the detail pattern design of body parts.

It seems that the best thermal insulation property of men's shirts can be achieved by adding shoulder cover cloth and back waist darts on traditional shirts, which should have a chest tolerance of 12cm.

4 Conclusion

Air gaps entrapped between the human skin and the clothing function as an insulating material to protect human body from losing too much heat to environment. Considering the soft characteristic of textile fabric, it is difficult to measure air gaps directly without disturbing its natural distribution state. By the combination of two non-contact measuring tools (3D human body scanner and infrared thermal camera), the air gap thicknesses and surface temperatures of experimental shirts are successfully quantified. The results have proved that the uneven distributions of air gaps over body segments: the smallest air gaps lie in human shoulder as it is the supporting point to clothing, while the largest air gaps lie in back waist as human lumbar bends forward. Influenced by the uneven distribution of air gaps, the clothing surface temperatures are also unevenly distributed over different body segments. For most parts, the clothing surface temperatures decrease with the increase in air gap thickness, but begin to increase when the air gap is thicker than 1.5cm. The clothing surface temperatures at middle back and back waist increase continually with the increase in air gap thickness, which shows that these two segments tend to have natural convection even under the smallest size of clothing. According to the results of two non-contact measuring tools, a revised pattern is designed to improve the thermal insulation performance of traditional men's shirt, is put forward by adding cover cloth at the shoulder segment and waist darts at back waist segment. The experimental results show that the revised shirt has better thermal insulation than the original one. This research explores the correlation between air gap thickness and clothing surface temperature of different body segments by the combination of two non-contact measuring tools, which provides a scientific foundation to design thermal function garments and predict the possible position to make natural convection to take place under clothing.

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