COMPARISON OF THERMAL RESISTANCE BETWEEN TWO GARMENT DESIGNS DRIVEN BY MATERIAL CHARACTERISTICS USING A THERMAL HEATED MANIKIN

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INTRODUCTION

The Laboratory for Engineered Human Protection (LEHP) has developed prototype garments for the purpose of improving comfort while protecting warfighters. This paper examines the difference in thermal resistance to dry heat loss of three LEHP designed garments. The effect of garment design has been investigated previously (McCullough, et al., 1983). The garment design was driven by fabric characteristics (stretch versus non-stretch) and therefore resulted in two designs, one having a closer or tight fit to the body (Design T) and the second having a loose fit (Design L). One comparison is made between designs T and L, produced from the same stretch material referred to here as Material A. A second comparison is performed between garments made from Material A and a non-stretch material (Material B) in same garment design L. Our goal is to understand effects of fabric characteristics on thermal resistance.

METHODS

Two fabrics were selected for this study, one exhibiting a high degree of stretch (Material A) and the second a non-stretch fabric (Material B). One-piece “union suit” type garments were produced from each fabric. Since each fabric exhibited different mechanical properties, measured using the Kawabata Evaluation System (Kawabata, 1982), particularly extension under tensile load (EMT), bending rigidity (B), bending hysteresis (2HB), shear rigidity (G), and shear hysteresis (2HG and 2HG5) (Table I), the garment design was driven by the fabric properties. The Material A garment (garment 1) resulted in a close, or tight fit to the body (Design T), and the non-stretch Material B resulted in a loose fit garment (Design L, garment 2). A third garment was produced from Material A using Design L (garment 3) to investigate the thermal resistance properties of the same fabric using the loose garment design. (Table II)

Table I Mechanical Properties of Material A and B.

Property	Description	Unit	Material A	Material B
W	Weight	oz/sq. yd.	8.6	6.74
EMT	Elongation	%	90.82	3.03
G	Shear Rigidity	gf cm^{-1} $degree^{-1}$	2.2	6.18
2HG	Hysteresis of shear force at 0.5 degrees of shear angle	gf/cm	3.15	8.54
2HG5	Hysteresis of shear force at 5 degrees of shear angle	gf/cm	4.59	14.99
B	Bending rigidity	gf cm^{-1} $degree^{-1}$	0.177	0.882
2HB	Hysteresis of bending moment	gf cm cm^{-1}	0.119	0.561

Thermal insulation of each garment was determined using a male form thermal manikin having 34 independently heated zones. ('Newton", MTNW, Seattle, WA, USA). All zones were heated to 35°C. Testing was performed in an environmental chamber set to 23 $\pm$0.5°C and 50$\pm$5%RH with a wind speed of .4m/s. (ASTM F 1291 -05). 100% cotton underwear (jockey style briefs and crew neck T-shirt) and cotton athletic socks were placed under each garment for testing. Three replicate measurements were made on each garment, undressing and redressing the manikin between each test. Nude manikin tests were conducted in the same environmental conditions to determine the insulation of the boundary air layer surrounding the manikin.

The total clothing insulation, I_T, was calculated using the parallel method in m^2 °C W^{-1} as suggested by Virgilio et al. (2008) and Havenith et al. (2005):

$$I_T = \frac{1}{\sum \frac{A_i}{A} \times \left(\frac{H_i}{T_{sk,i} - T_a} \right)}, \qquad \text{Eq. (1)}$$

where T_a is the air temperature in °C, $T_{sk,i}$ is the mean skin temperature of segment i of the manikin in °C, H_i is the local heat flux of segment in W m^{-2}, A_i is the surface area segment i in m^2, and A is the total surface area of the manikin in m^2.

The intrinsic clothing insulation, I_{cl} (m^2 °C W^{-1}), is then calculated as the following:

$$I_{cl} = I_T - \frac{I_a}{f_{cl}} \qquad \text{Eq. (2)}$$

where f_{cl} is the dimensionless clothing area factor, I_a is the thermal resistance of the air layer on the surface of the nude manikin in m^2 °C W^{-1} (McCullough 2001).

Various methods have been proposed to be used in determining the clothing area factor. Most of the methods involve taking high-resolution photographs of the garment (McCullough et al., 1985) or using a 3D body scanning system (McCullough et al., 2005). An empirical expression relating f_{cl} and I_{cl} was also proposed by McCullough et al. (1985) as the following:

$$f_{cl} = 1.0 + 0.31 I_{cl} \qquad \text{Eq. (3)}$$

Note that equation (2) and (3) must be solved iteratively to obtain f_{cl}. Although this technique produces f_{cl} with a relative large error (Al-ajmi et al., 2008), it has been demonstrated that the impact of an error in f_{cl} on I_{cl} is relatively small (Al-ajmi et al., 2008; Havenith, 2005).

RESULTS

Table II Thermal insulation values of garments in units of (clo) and m^2 °C W^{-1}

Garment Code	Material	Garment Design	f_{cl}	I_a		I_{cl}		I_T	
				clo	m^2 °C W^{-1}	clo	m^2 °C W^{-1}	clo	m^2 °C W^{-1}
1	A	T	1.23	0.465	0.072	0.764	0.118	1.14	0.177
2	A	L	1.29	0.465	0.072	0.952	0.148	1.31	0.204
3	B	L	1.33	0.465	0.072	1.101	0.171	1.45	0.225

The thermal insulation values of garments are listed above in Table II. Our results indicate that the measured thermal insulation value for garment 1 is 13% lower than that of garment 2 and the intrinsic clothing insulation for garment 1 is 20% lower than that of garment 2. This finding is in agreement with the fact that the loose fit design L garment increases the surface area, thus increasing the total insulation as well as intrinsic clothing insulation. The increase in surface area is also reflected in the clothing area factor in which the f_{cl} value for garment 1 is 5% lower than for garment 2.

Further examination of the data shows that although garment 2 and 3 were constructed using the same loose fit design L, the measured thermal insulation values are quite different between the two garments. The I_T value for garment 3 is 10% higher than that of garment 2 and the intrinsic clothing insulation value for garment 3 is 15% higher than that of garment 2. In addition, the clothing area factor for garment 3 is 3% higher than that of garment 2.

It is expected that garment 2 and 3 have different measured thermal insulation values since they are made of two different materials. However, it is not surprising to see the clothing area factor of garment 2 and 3 differ. One characteristic of material A is that the fabric incorporates easy stretch with lower bending and shear rigidity as compared to material B. As a result, garment 2 lies closer to the body than garment 1, thus producing a fit that has less surface area than garment 3.

CONCLUSIONS

We have concluded from our results that the thermal resistance of a garment is determined by both the material from which it is fabricated and the design of the garment. We have found that by altering the design of the garment, one can alter the thermal resistance and vice versa.

REFERENCES

1. McCullough E A, Jones B W, Zbikowski P J. The effect of garment design on the thermal insulation values of clothing. ASHRAE Transactions 1983; 89: 327-352.

2. Kawabata S. 1982. The development of the objective measurement of fabric handle. In: Proceedings of the Japan-Australia Joint Symposium on Objective Specification of Fabric Quality, Mechanical Properties and Performance, Kyoto, Japan, pp. 31-59.

3. ASTM F 1291. Standard test method for measuring the thermal insulation of clothing using a heated manikin. West Conshohocken, PA: American Society for Testing and Materials; 2004.

4. Virgilio, A., Oliveira, M., Gaspar, A.R., Quintela, D.A., 2008. Measurements of clothing insulation with a thermal manikin operating under the thermal comfort regulation mode: comparative analysis of the calculation methods. Eur J Appl Physiol 104:679-688.

5. Havenith, G., 2005. Clothing heat exchange models for research and application. In: Proceedings of the International Conference on Environmental Ergonomics, Ystad, Sweden, pp. 66–72.

6. McCullough, E.A., 2001. The use of clothing in thermal comfort standards. Moving thermal comfort standards into the 21st Century, Cumberland Lodge, Windsor, 5–8 April, pp 292–300.

7. McCullough, E.A., Jones, B.W., Huck, J., 1985. A comprehensive database for estimating clothing insulation. ASHRAE Trans 91:29–47.

8. McCullough, E.A., Huang, J., Deaton, S., 2005. Methods for measuring the clothing area factor. In: Proceedings of the International Conference on Environmental Ergonomics, Ystad, Sweden, pp. 433–436.

9. Al-ajmi, F.F., Loveday, D.L., Bedwell, K.H., Havenith, G., 2008. Thermal insulation and clothing area factors of typical Arabian Gulf clothing ensembles for males and females: Measurements using thermal manikins. Applied Ergonomics 39:407-414.