Thermophysiological Responses to the Alternation of Exercise and Rest at 20°C when Wearing Underwear made of Cotton or Wool

Shin Jung Park*, Jee Hye Chang, Hiromi Tokura*****

Concurrent Professor, Dept. of Fashion Design, Sungkyunkwan University*

Professor, Dept. of Fashion Design, Sungkyunkwan University**

Professor, Institute of Textiles & Clothing, The Hong Kong Polytechnic University, Hong Kong, China***

Abstract : The purpose of this study was to investigate the effects of two kinds of underwear material on subjects exercising and resting in an ambient temperature of 20°C, a relative humidity of 60% and an air velocity of $0.13 m \cdot sec^{-1}$. Two kinds of underwear ensemble were tested, differing in their hygroscopic properties: 100% wool (W) with higher moisture regain and 100% cotton (C) with lower moisture regain. Five young females served as subjects. The experiments comprised two repeated periods of 15 min exercise on a treadmill with a speed of $6 km \cdot h^{-1}$ followed by 10 min rest. The main results were as follows: 1) Mean skin temperature was significantly higher in W than in C throughout the whole experimental period ($p<0.05$). 2) The temperature and humidity of the microclimate between the skin and underwear provided by the first layer of clothing was higher in W than in C ($p<0.1$ and $p<0.05$, for temperature and humidity, respectively). 3) Heart rate was significantly higher in W than in C ($p<0.05$). 4) Subjects felt warmer during the second exercise session when wearing wool rather than cotton ($p<0.05$), and they also reported more increased wetness during the second exercise and rest periods in W than in C ($p<0.05$). These results suggest that underwear made of wool with higher moisture regain might not act as effectively as cotton to transfer exercise-induced heat from the body to the surrounding air when light exercise is taken in a thermally-neutral environment.

Key Words : Cotton and Wool, Moisture Regain, Heat Transfer, Thermal Response, Subjective Sensations

I. Introduction

There are many studies dealing with the effects of different clothing material on physiological responses and subjective sensations in various conditions (Gonzales & Cena, 1985; Ha *et al.*, 1995a, 1995b, 1999; Holmér, 1985; Kwon *et al.*, 1998; Nielsen & Endrusick, 1988; Rodahl *et al.*, 1973; Tanaka *et al.*, 2001; Vokac *et al.*, 1976). Underwear made of materials with different moisture absorption and transfer properties probably changes the dynamic heat exchange between the body and environment and alters the sensation of comfort (Adler & Walsh, 1984; Tokura, 1985).

Many researchers (Ha *et al.*, 1995a, 1998; Kwon *et al.*, 1998; Park *et al.*, 2005; Tokura & Midorikawa-Tsurutani, 1985; Tokura & Natsume, 1987) have reported that hydrophilic textiles like cotton and wool seem to have beneficial influences on thermal responses and clothing comfort during exercise and during rest afterwards, when compared to hydrophobic textiles like polyester, nylon and polypropylene.

Corresponding Author: Shin-Jung Park, Dept. of Fashion Design, Sungkyunkwan University, 3-53, Myongnyun-dong Chongno-gu, Seoul 110-745, Korea Tel: +82-2-760-0515 E-mail: sjpark@skku.edu

However, these studies concentrated on comparisons between natural and synthetic fibers, with the great differences in moisture absorption, and with exercise performed in hot or cold environments.

Generally, wool is accepted as a warm material for winter clothing, due to higher heat of absorption and lower thermal conductivity, so reducing heat loss from the body (Cassie, 1962; David 1965; Stuart *et al.*, 1989). However, Rodahl (1973) and Rodwell *et al.* (1965) did not show any significant differences in physiological responses and subjective sensations when comparing wool and nylon garments during a trial in the cold. Holmér (1985) also found no differences in heat exchange and thermal insulation when garments made of wool were compared to those made of nylon during walking, running and resting activities at 8°C.

On the other hand, some studies (Kwon *et al.*, 1998; Tokura & Natsume, 1987) reported that, even in hot environments, wool was better able to reduce heat stress on the body because of its higher moisture absorption compared with polyester. This result seems to depend upon the physical properties of the fibers of the two materials and to the microclimates formed in different conditions.

More studies are needed for a systematic understanding of the role of clothing material on human thermal responses in various environments. This study attempted to compare the effects of underwear made of two natural fibers with different levels of moisture regain, cotton and wool, on the physiological responses and subjective sensations associated with exercise and rest in a neutral ambient temperature of 20°C.

II. Materials and Methods

1. Subjects

Five healthy females participated as subjects in this study. Their physical characteristics were 26.4 (SEM 1.75) years of age, 162 (SEM 1.92) cm in height and 51.4 (SEM 1.33) kg in body mass. They were college students with regular sleep-rest daily rhythms, and none had undergone exercise training. The general purpose, procedure and possible risks involved in testing were fully explained to each subject and informed consent was given. Each subject was tested at the same time of day and same phase of the menstrual cycle to avoid circadian and menstrual effects on core temperature and other physiological responses.

2. Experimental Garments

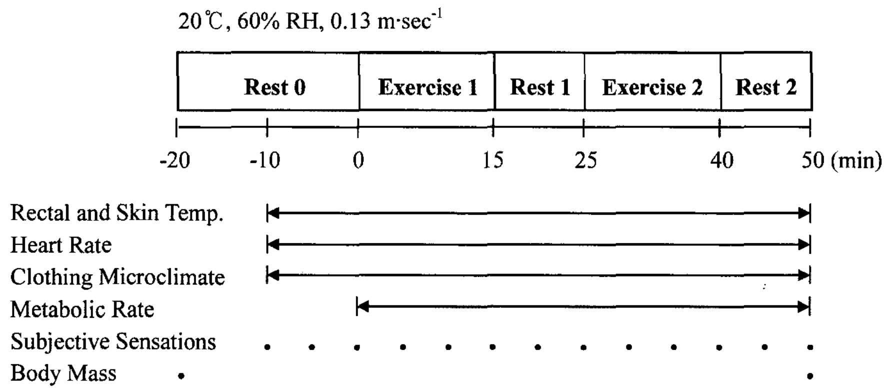
The two kinds of underwear tested were made of 100% cotton (C) and 100% wool (W). Each type consisted of long-sleeved shirts and full-length trousers in appropriate sizes to assure fit and comfort for each subject. Additionally, subjects wore outer garments consisting of long-sleeved training shirts and full-length trousers with a 50%/50% blend of cotton and polyester, and a pair of socks made of 100% cotton. The two kinds of underwear material were very similar in thickness, density and air permeability, but due to the fiber type C or W they differed in their moisture regain. To ensure that subjects could not visually distinguish between the two kinds of clothing material, both C and W underwear were the same color. The detailed physical properties of the clothing materials are listed in <Table 1>. Before being worn, the clothing was laundered without a detergent and dried naturally and stabilized in the experimental conditions of 20°C and 60% RH.

3. Experimental Protocol

The experiments were conducted in a climatic chamber controlled at 20°C and 60% RH, with an air velocity of 0.13m·sec^{-1}. The experimental schedule is shown in <Figure 1>. After taking a rest for 30 minutes in the anteroom, the subject entered the experimental chamber and measured her nude body mass. The subject then dressed in the cotton or wool underwear on briefs and a brassiere, put on her outer garments,

<Table 1> Physical properties of experimental clothing materials

	C	W
Underwear: long-sleeved shirts and full-length trousers		
Fiber contents	100% cotton	100% wool
Construction	interlock stitch	interlock stitch
Thickness (mm)	0.660	0.698
Density (picks · $inch^{-1}$) wale × course	46 × 53	40 × 44
Weight (g · m^{-2})	175.4	197.9
Moisture Regain (%) at 20˚C, 65%	8.23	17.32
Air Permeability ($cm^3 \cdot cm^{-2} \cdot sec^{-1}$)	113	114
Thermal Resistance ($m^2 \cdot K \cdot W^{-1}$)	0.042	0.049
Outerwear: long-sleeved training wear and full-length trousers		
Fiber contents	50% cotton/50% polyester	
Construction	cross tuck stitch	
Thickness (mm)	1.478	
Density (picks · $inch^{-1}$) wale × course	32 × 35	
Weight (g · m^{-2})	313.25	
Shorts and Socks	100% cotton	



<Figure 1> Experimental schedule

socks and shoes. The subject was fitted with a rectal thermistor probe, skin temperature sensors and an electrode for measuring heart rate. The temperature and humidity sensors for measuring the microclimates between the skin and the underwear (the first layer) and between the underwear and the outer garments (the second layer) were attached at the chest level.

The subject then sat on a chair for 20 minutes for stabilization of rectal temperature. While wearing a mask for the measurement of metabolic rate, the subject exercised on a treadmill at a speed of 6 km · h^{-1} (similar to brisk walking) for 15 minutes, followed by 10 minutes rest. This exercise/rest session was performed a second time. At the end of the experiment (70 minutes), nude body mass was measured again after the subject dried herself using a towel.

4. Measurements

Rectal temperature was measured by a thermistor probe every minute and recorded with a Squirrel Meter Logger (Grant Instruments Ltd., U.K., accuracy; 0.05°C). Skin temperatures were measured every minute by epoxy-coated copper thermistor probes at seven skin sites (forehead, abdomen, arm, hand, thigh, leg, and foot). Mean skin temperature was calculated by the equation of Hardy & DuBois (1938). Heart rate was measured every minute with a pulse watch (PE-3000, Sports Tester, Finland). Temperature and humidity of clothing microclimates were measured every minute by a hygrothermometer (TRH-CZ, Shinyei, Japan, accuracy; 0.1°C and 0.001 $g \cdot m^{-3}$, for temperature and humidity, respectively). Metabolic heat production was measured every minute by an open circuit method using an aeromonitor (AE-280, Minato Med. Sci., Japan). Subjective ratings of whole-body thermal sensation and comfort, and the sensation of clothing wetness, were made every 5 minutes. The scales for each sensation are summarized in <Table 2>. Body mass was measured by a platform balance (Sartorius F150S, Germany, accuracy; 1 g).

5. Statistical Analysis

The data were analyzed by a two-way ANOVA with repeated measures (for a comparison of time courses and the effects of clothing type). Dependent variables were rectal and skin temperatures, clothing microclimates, heart rate and metabolic rate. Paired Student's t-test was used for the loss of body mass. Also, the subjective ratings were analysed by Wilcoxon signed ranks tests as nonparametric tests. A p-value less than 0.05 was considered statistically significant, and a difference where $0.05<p<0.1$ was referred to as a tendency in the data. The values were expressed as mean and SEM.

<Table 2> Scales of subjective sensation

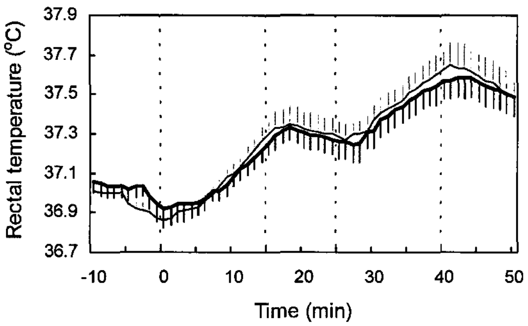
Thermal sensation	Comfort sensation	Clothing wetness
1 very cold	1 comfortable	1 dry
2 cold	2 slightly uncomfortable	2 slightly damp
3 cool	3 uncomfortable	3 damp
4 slightly cool	4 very uncomfortable	4 wet
5 neutral		
6 slightly warm		
7 warm		
8 hot		
9 very hot		

III. Results

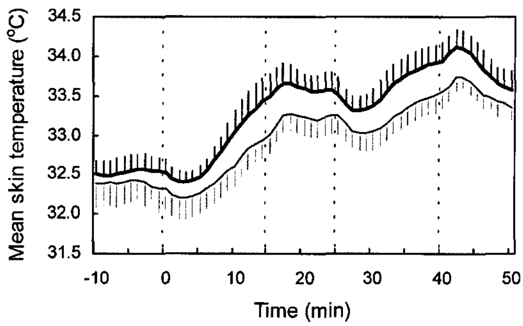
<Figure 2> shows temporal changes of rectal temperature with C and W. Rectal temperature increased gradually overall, with a clear rise during exercise and a smaller fall during rest. There was no significant difference between the two kinds of clothing.

<Figure 3> demonstrates the time course of mean skin temperature. This was significantly higher in W than in C throughout the whole experimental period ($F= 12.735, p<0.05$).

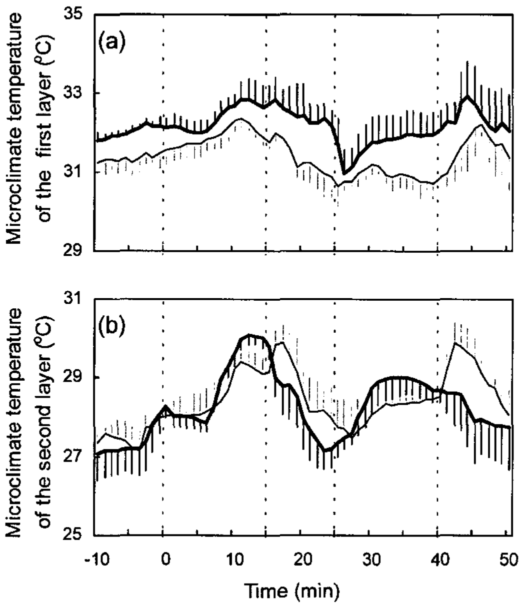
The time courses of clothing microclimates are shown in <Figure 4> and <Figure 5>. Data were obtained from only four subjects (Subject 5 was omitted due to instrument malfunction). As shown in <Figure 4-a>, the average temperature of the microclimate between the skin and the first layer tended to be higher in W than in C ($F=6.396, p<0.1$). Both layers showed a similar profile, with rises during exercise and falls during rest periods, but the changes were more marked in the second layer. There was a significant interaction between the changes in temperature of the microclimate in the second layer with time and the two kinds of clothing ($F=3.832, p<0.01$). This interaction arises because, even though there were general rises in temperature during exercise and falls during rest periods, this profile was earlier in W than in C (see Figure 4-b). The humidity of the first layer (Figure 5-a) showed similar profiles to the temperature, but the average value was significantly higher in W than in C ($F=14.688, P<0.05$). The second layer showed similar profiles but, unlike the case with



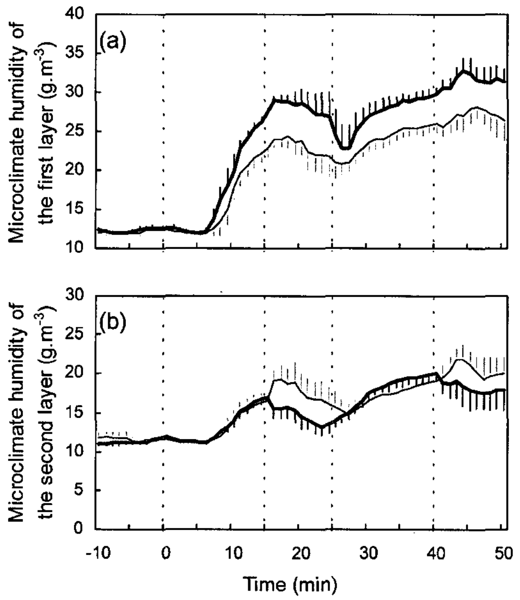
<Figure 2> A comparison of rectal temperature between C (thin line) and W (thick line)



<Figure 3> A comparison of mean skin temperature between C (thin line) and W (thick line)



<Figure 4> Time course of clothing microclimate temperature of the first layer (a) and the second layer (b) for the two kinds of clothing. Thin line, C; Thick line, W

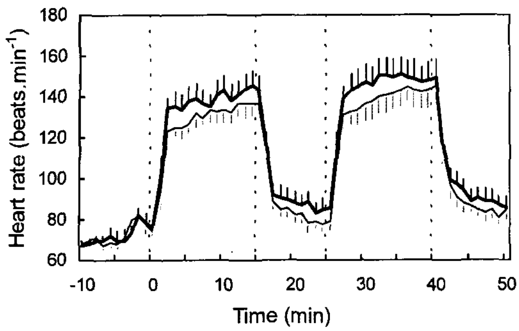


<Figure 5> Time course of clothing microclimate humidity of the first layer (a) and the second layer (b) for the two kinds of clothing. Thin line, C; Thick line, W

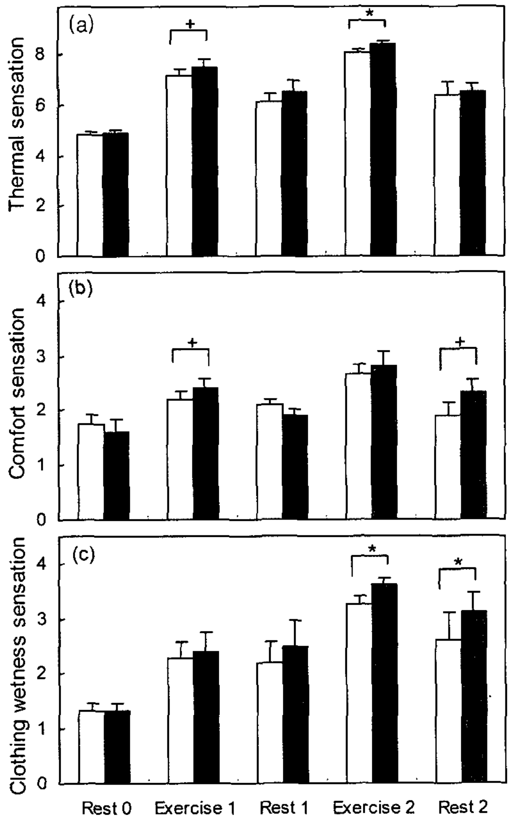
temperature (Figure 4-b), the changes were now less marked in the second layer, and there was no significant difference between the two clothing ensembles (see Figure 5-b).

Heart rate increased quickly with the start of exercise and fell during rest periods (see Figure 6). It was significantly higher in W than in C both during exercise and rest periods ($F=12.908$, $p<0.05$). However, the metabolic heat production was not significantly different between the two clothing ensembles (data not shown).

<Figure 7-a>, <Figure 7-b> and <Figure 7-c> show subjective ratings of the thermal sensation of the whole body, comfort sensation, and the sensation of clothing wetness, respectively. The data are the average scores for each period of rest and exercise. The rating of thermal sensation was significantly higher in W than in C during exercise 2 ($p<0.05$), and this difference



<Figure 6> A comparison of heart rate between C (thin line) and W (thick line)



<Figure 7> A comparison of thermal sensation (a), comfort sensation (b) and clothing wetness sensation (c) between C and W. Grey bar, C; Black bar, W. *p<0.05, + p<0.1

approached significance in exercise 1 (see Figure 7-a). Comfort sensation was not different significantly between the two kinds of clothing. As seen in <Figure 7-c>, when wearing wool rather than cotton, the subject felt wetter during the second exercise and rest periods ($p<0.05$).

The loss of body mass through the whole experimental period was 168.0 (SEM 9.1) g in C and 223.3 (SEM 22.1) g in W, the difference being significant at $p<0.05$.

IV. Discussion

This experiment demonstrates that rectal temperature was not significantly different with the two kinds of clothing, while mean skin temperature was significantly higher in W than in C (see Figures 2 and 3). Furthermore, heart rate was significantly higher in W than in C during the whole experiment (see Figure 6). Also, the total loss of body mass was significantly greater in W. These results suggest that intermittent exercise induced a greater heat load to the body when wearing wool rather than cotton. During exercise, clothing must allow metabolic heat and sweat to escape from the body to outside surroundings, thereby reducing heat strain to the body and preserving effective exercise performance. The relevant characteristics of clothing material for heat transport are insulation, water vapor resistance and moisture absorption (Lotens, 1993). Normally, when vapor absorption by a fabric takes place, the heat of absorption is liberated; consequently there is an increase in flow of dry heat and a decrease in flow of latent heat. Conversely, during the desorption phase, the temperature of the fabric falls. Wool, which is able to absorb large amounts of moisture also has a large heat of absorption (Stuart *et al.*, 1989). Yasuda *et al.* (1992, 1994) have claimed that the heat of absorption of water vapor is the dominant factor causing the temperature to rise in the air spaces of layered fabrics. Moreover, wool has a lower thermal conductivity than any other fiber. These characteristics of wool might be responsible for our results insofar as wool clothing would lead to a reduction in heat flow from the body to outside surroundings and consequently induce a greater heat load during exercise and at rest.

This suggestion could also account for the result that the temperature and humidity of the microclimate in the layer between the skin and underwear were higher in W than in C (see Figures 4 and 5). As wool fabric absorbed greater amounts of water vapor, the liberated heat of absorption increased the temperature of the microclimate, as a result of which, exercise-induced heat could not transfer as readily to the external environment. In turn, this might have lead to a greater cutaneous vasodilation, in an attempt to increase heat loss by radiation (Bell *et al.*, 1983), this also resulted in skin blood flow and an increase in temperature more in W than in C. Our interpretation might be supported by Li *et al.* (1992), who found that the predicted skin temperature was higher during exercise (5.6 $km \cdot h^{-1}$ walking for 40 minutes at 28°C and 30% RH) when wearing wool rather than polyester clothing. They interpreted the result due to the wool's greater release of heat following the absorption of water vapor. Furthermore, the higher values of the mean skin temperature and the microclimate temperature in the first layer in W than in C might be partly affected by the slightly higher thermal insulation of wool compared to cotton (see Table 1).

However, our results are not consistent with those of Ha *et al.* (1995b), who found higher rectal temperature and pulse rate during intermittent exercise at 24°C in polyester clothing compared with cotton clothing with higher moisture absorption. Also, Tokura and Natsume (1987) found that the local rate of sweating and frequency of sweat expulsion from the forearm at an ambient temperature of 34°C were significantly greater in women dressing in a polyester one-piece dress than in one made of wool. Possible reasons for the difference between the results might include environmental conditions, exercise intensity, clothing material and type of clothing, for example. It seems that the main reason for the discrepancy between the results of Ha *et al.* (1995b) and ourselves might be the different clothing ensembles used: in our experiments, long-sleeved shirts and full-length trousers made of cotton or wool fiber for the underwear and the outer clothes made of a blend of polyester/cotton were used; in their experiments, short-sleeved T-shirts, long-sleeved working dress and full-length trousers made of cotton or polyester fiber were used. As seen in <Figure 4>, the clothing microclimate temperature increased higher during exercise in the second layer (ca. +2 °C) than in the first layer (ca. +1 °C). In our study, the moisture absorbed by the underwear could not be transferred quickly into the surrounding air due to the second barrier from the outer garment that was made of a weakly hygroscopic material; as a result, the flow of latent heat due to evaporation occurred very slowly. In turn, it is very likely that this trapped heat had a significant contribution to the higher temperature increase of the outer microclimate during exercise compared to the inner microclimate. Thus, even though the wool underwear absorbed moisture with ease, heat transmission could not take place. Moreover, the absorption of moisture by wool clothing and the evolution of absorption heat have a stronger buffering effect to the body in conditions of relatively low temperature (Cassie, 1962; David 1965). Therefore, it is considered that the greater heat of absorption accumulated heat within the body and caused warmer and wetter sensations in the subjects wearing W clothing during heat strain produced by light exercise at an ambient temperature of 20°C.

V. Conclusion

In this study, the main findings were that when wearing wool rather than cotton underwear, intermittent exercise induced higher temperature and humidity of the microclimate between the skin and underwear and a greater heat load to the body due to wool's greater heat of absorption. In conclusion, under garments made of wool material with a higher hygroscopic property might not act as effectively as cotton to transfer exercise-induced heat from the body through clothing to the surrounding air, at least when the exercise is light and the ambient temperature is not hot.

Acknowledgements

The authors thank Dr. Jim Waterhouse, Liverpool John Moores University, United Kingdom, for his critical reading and editorial assistance. Also, the authors declare that the experiments comply with the current laws of Japan.

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Received August 3, 2005
Accepted November 5, 2005