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A Comparison of Skin Temperatures and Clothing Microclimate During Moderate Intermittent Exercise in the Cold Between One and Two Layers of Cotton and Polypropylene Underwear

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The purpose of this study was to compare the effects of 2 kinds of underwear made from hydrophobic and hydrophilic fabrics on the mean skin temperatures and clothing microclimate (temperature, humidity) in participants performing intermittent exercise in cold environmental conditions.

One or 2 layers of cotton underwear (C1, C2) with a 2-piece long-sleeved shirt and long-legged trousers, and 1 or 2 layers of polypropylene underwear (P1, P2) with a 2-piece long-sleeved shirt and long-legged trousers were used as experimental underwear. In addition, the participants wore a 2-piece ski suit as 100% polyester clothing including 100% polyester padding. Ten young adult females volunteered as participants. The experiments were performed in a climatic chamber at an ambient temperature (T_a) of 0 °C and an air velocity of 0.26 $m \cdot s^{-1}$.

The major findings are summarized as follows: (a) Although the clothing microclimate humidity was not different within the ski suit of outer clothing between C1 and P1, it was significantly higher in P2 than in C2; (b) Clothing

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microclimate temperature inside the ski suit did not differ between C1 and P1, whereas it was significantly higher in P2 than in C2; (c) The thermal gradient between innermost and outermost of clothing microclimate at back level did not show any difference between C1 and P1, but it was significantly higher in C2 than in P2. These results are discussed in terms of thermal physiology and clothing sciences.

mean skin temperature clothing microclimate
cotton polypropylene underwear

1. INTRODUCTION

Clothing systems for common winter sports comprise of two or more clothing layers: usually underwear, middle, and outer clothing layers. The underwear used in a cold environment is of physiological significance as thermal insulation (Farnworth & Dolhan, 1985). The underwear covers most of the skin surface, and produces clothing microclimate between outer clothing and the underwear itself.

The transport of heat and water vapour through a clothing system is perhaps the most important factor for thermal comfort in all climates. However, the transport of water vapour through clothing systems differs depending on the environmental condition. In winter, the transport of moisture vapour to the outside through clothing system is easier because the vapour pressure of the outside is generally low (Yasuda, 1992). Påsche (1991) has pointed out that the sweat accumulation in different clothing layers showed opposite distribution during 1-hr standardized work by the same participant in a warm and cold environment, that is, more sweat was found in the outer layer than the inner garment in a cold environment, whereas the reverse was the case in a warm environment. The evaporation and diffusion of water vapour through the clothing system is accompanied with the heat transport (Farnworth, 1986). Nielsen and Endrusick (1988) studied the physiological effect of different textile materials used for the underwear of an ensemble at an ambient temperature of 5 °C and found that the textile material in the underwear in a normal garment has very little influence on the insensible heat loss during intermittent exercise in the cold. Umbach (1988) asserted that for underwear worn next to the skin for work clothes, double-face fabrics are advantageous under heavily sweating conditions, in which the inside layer worn on the skin should be made from hydrophobic fibers and the outside layer from hydrophilic fibers. On the contrary, Tokura, Sasase, Hashimoto, and Midorikawa (1989) found that double-face fabrics with the inside and outside layers of cotton were best for the clothing humidity to be prevented from rising.

According to Farnworth and Dolhan (1985), there were not any discernible differences for heat loss through polypropylene and cotton underwear, using a sweating hot plate. Morooka and Morooka (1991) using a sweating hot plate reported that although no differences in dry heat loss were found among the wool underwear, cotton underwear, and polypropylene underwear in the cold under the conditions of no sweating, wool underwear had the largest thermal insulation under the conditions of increasing perspiration.

With these in mind, our hypothesis is that underwear should have enough hydrophilic properties rather than hydrophobic ones, because sweating may be transferred more greatly through underwear into outer garments when the participants wear underwear with hydrophobic properties, resulting in a reduction of thermal insulation in the outer garments by replacing air trapped within them by liquid water under the influence of ambient cold air. One or two layers might play a role for these physical reactions, as the sweating produced from the skin could be absorbed differently, depending on one or two layers. Therefore, the present experiment aimed to find out whether the underwear should be hydrophobic or hydrophilic for the best thermal insulation when sweating in the cold. Polypropylene and cotton underwear were used as experimental clothing with hydrophobic and hydrophilic properties, respectively. Furthermore, the effects of one and two layers of underwear on heat and vapour transport properties within the clothing system were compared.

2. METHODOLOGY

2.1. Experimental Garments

The characteristics of our experimental clothing are summarized in Table 1. Two different sizes of experimental clothing fitting the body shape of the participants were prepared.

Two kinds of underwear fabrics were designed to have, as closely as possible, the same thickness and density, so that they differed mostly in their water vapour and water uptake characteristics. Yarn type was the staple fiber in polypropylene. The physical properties of fabrics are listed in Table 2. The clothing was washed and line-dried before each experiment and stabilized in the environmental conditions (T_a 24 ± 1 °C, 30 ± 5% RH).

TABLE 1. Characteristics of Experimental Clothing

Clothing Item		Material	Clo Value
a	underwear (two-piece long-sleeved shirt, and long-legged trousers)	cotton one layer	0.97
		polypropylene one layer	1.03
		cotton two layers	1.13
		polypropylene two layers	1.18
b	outer clothing (ski suit, two-piece)	outer fabric; 100% acrylic padding; 100% polyester lining; 100% polyester	
c	cap	30% wool/70% acrylic	
	gloves	100% wool	
	socks	100% cotton	
		75% wool/25% nylon	
total clo value (a+b+c)		C1:	2.40
		P1:	2.34
		C2:	2.42
		P2:	2.47

TABLE 2. Physical Properties of Underwear Fabrics

Fabrics	Weight ($g·m^{-2}$)	Thickness (mm)	Density Wale, Course ($no·cm^{-1}$)	Moisture Regain (%)	Moisture Transfer ($g·m^{-2}·24\ hrs^{-1}$)	Air Permeability ($cc·cm^{-2}·s^{-1}$)
Cotton	242.2	1.83	11, 9	6.8	4647.7	147.4
Polypropylene	138.3	1.81	12, 9	0.5	4733.1	378.0

Notes. no—number.

2.2. Participants

Six adult female participants took part in the experiment of a one-layer underwear clothing ensemble. The participants' age was 21.6 ± 1 years

(*M* ± *SE*), height 157.5 ± 1.5 cm, body mass 53.0 ± 1.3 kg, and body surface area, calculated according to Fujimoto, Watanabe, Sakamoto, Yukawa, and Morimoto (1968) 1.48 ± 0.02 m^2. Seven adult female participants took part in the experiment of a two-layer underwear clothing ensemble. The participants' age was 21.7 ± 0.8 years (*M* ± *SE*), height 158.0 ± 1.3 cm, body mass 54.3 ± 2.2 kg, and body surface area 1.48 ± 0.03 m^2. Three out of the 7 participants also took part in the condition of a one-layer underwear ensemble. The experimental procedure was explained to the participants. Before participating in the experiments, they provided their voluntary and informed consent. The participants reported to the laboratory at the same time of the day in the same menstrual cycle phase to avoid differences due to circadian and menstrual cycle effects on the body temperatures.

2.3. Measurements

The rectal temperature (T_{re}) was measured using a thermistor probe (TAKARA Thermistor, accuracy ± 0.01 °C) inserted 12 cm beyond the anal sphincter. Skin temperatures (T_{sk}) were measured with thermistors (TAKARA Thermistor, accuracy ± 0.1 °C) taped at eight sites: forehead, forearm, hand, chest, back, thigh, leg, and foot. Temperature and humidity of clothing microclimates of the innermost layer (between skin and underwear) and the outermost layer (inside outer wear) at the back levels (at equivalent sites to those of the skin temperature measurements) were measured using thermistor and humidity sensors (Vaisala, HMP-35A, accuracy ± 3% RH). Before the experiment, the humidity sensors were calibrated by two saturated salt solutions, LiCl and K_2SO_4, at a constant temperature.

Pulse rate, monitored by a pulse rate sensor fixed to the ear lobe, was recorded every 30 s. The weight of the participants and garments was measured at the beginning and at the end of the experimental protocol. Metabolic heat production by the open circuit method was continuously measured by an Aeromonitor (AE-280, Minato Medical Science, Japan) during the whole experimental period.

Thermal sensation, clothing sensation, skin sensation, and shivering/sweating sensation for the whole body were rated every scheduled time. For the thermal sensation a 9-point scale was used: 9—very hot, 8—hot, 7—warm, 6—slightly warm, 5—neutral, 4—slightly cool, 3—cool, 2—cold, 1—very cold. The clothing sensation was evaluated using a 4-point scale: 1—dry, 2—slightly damp, 3—damp, 4—wet. For the skin sensation a 7-point scale applied: 7—sweat running off in many places, 6—main part of the body wet, 5—some part of the body wet, 4—main part of the body moist, 3—some parts of the body moist, 2—normal dryness, 1—more dry than normal. The shivering/sweating sensation was evaluated on a 7-point scale: 7—heavy sweating, 6—moderate sweating, 5—slight sweating, 4—not at all, 3—slight shivering, 2—moderate shivering, 1—vigorous shivering.

All parameters for temperature and humidity were recorded continuously on a pen recorder, and also sampled every 6 s by a computer through an A/D converter.

2.4. Experimental Protocol

Conditions were designed to mimic real-life situations in which sweating and chill during and after exercise would develop. Testing was done in a climatic chamber at an ambient air temperature of 0 °C and an air velocity of 0.26 $m \cdot s^{-1}$. The experimental clothing was stored in the antechamber at a T_a of 24 ± 1 °C, 30 ± 5% RH at least 2 hrs before the experiment began. The participants wore experimental garments in the antechamber. Each participant reported to the laboratory at the same time of the day for all experiments. Then, the participant was weighed in the semi-nude, a thermistor sensor for rectum was inserted by the participant and thermistors for skin temperatures were attached. Each piece of clothing was weighed and then put on the participant. The temperature and humidity sensors for the clothing microclimate of each layer were attached at the back level. After dressing, the participant was instructed to rest in a chair.

After the stabilization of rectal temperature, the participant entered a climatic chamber for the experiment. The mask for the measurements of oxygen uptake (Vo_2) and carbon dioxide (CO_2) output was put on, a pulse rate sensor was fastened on the ear lobe, and the participant sat on a bicycle ergometer. Then, the measurement started. Approximately 10 min after entering the climatic chamber, the participant began the 2-hr test. The test comprised a twice-repeated bout of a 30-min cycle exercise followed by a 30-min rest. Each participant exercised on the cycle ergometer (Ergociser, Model EC-1500 Cateye Co., Japan) at an intensity of 30 W and 60 W in the first and second exercise, respectively. The pedal frequency was kept at 60 rpm. After the whole experiment of

2 hrs, the participant left the test chamber, took off her clothes, and their weight was measured once more in the antechamber. The body weight was also measured.

2.5. Calculations and Statistical Analysis

Mean skin temperature ($\overline{T}_{sk}$) was calculated by the following modification of the Hardy-DuBois equation: $\overline{T}_{sk} = 0.07\ T_{head} + 0.14\ T_{arm} + 0.05\ T_{hand} + 0.18\ T_{chest} + 0.17\ T_{back} + 0.19\ T_{thigh} + 0.13\ T_{leg} + 0.07\ T_{foot}$. Mean body temperature ($\overline{T}_{b}$) was calculated by the equation: $\overline{T}_{b} = 0.6\ T_{re} + 0.4\ \overline{T}_{sk}$ (Nakahashi & Yoshida, 1990).

Metabolic heat production was calculated according to the following equation: M = 5.05 (0.23 R + 0.77) Vo_2 (60/BSA), where, M—metabolic heat production (W), Vo_2—total volume of oxygen consumed, where the volume was adjusted to STPD, Vco_2—total volume of carbon dioxide production, where the volume was adjusted to STPD, BSA—Body Surface Area (m^2).

The statistical significance between the means was assessed using repeated-measures analysis of variances (ANOVA) and a Student's *t*-test for paired comparisons. A *p*-value less than .05 was considered statistically significant.

3. RESULTS

Metabolic heat production was 145.2 $\pm$ 4.01 and 147.0 $\pm$ 4.83 $W \cdot m^{-2}$ in C1 and P1 during the first exercise, respectively; 43.5 $\pm$ 1.55 and 44.4 $\pm$ 1.70 $W \cdot m^{-2}$ in C1 and P1 during the first rest; 237.7 $\pm$ 5.34 and 238.2 $\pm$ 11.76 $W \cdot m^{-2}$ in C1 and P1 during the second exercise; 43.0 $\pm$ 1.54 and 44.0 $\pm$ 2.66 $W \cdot m^{-2}$ in C1 and P1 during the second rest. These values were not significantly different between the two clothing conditions during exercise and rest. Also, there were not any differences in metabolic heat production between C2 and P2 during exercise and rest.

The pulse rate was 105.5 $\pm$ 2.26 and 109.1 $\pm$ 2.21 $beats \cdot min^{-1}$ in C1 and P1 during the first exercise, respectively; 71.4 $\pm$ 1.82 and 70.5 $\pm$ 2.49 $beats \cdot min^{-1}$ in C1 and P1; during the first rest; 137.8 $\pm$ 3.80 and 139.8 $\pm$ 4.10 $beats \cdot min^{-1}$ in C1 and P1 during the second exercise; 78.5 $\pm$ 2.62 and 76.2 $\pm$ 2.71 $beats \cdot min^{-1}$ in C1 and P1 during the

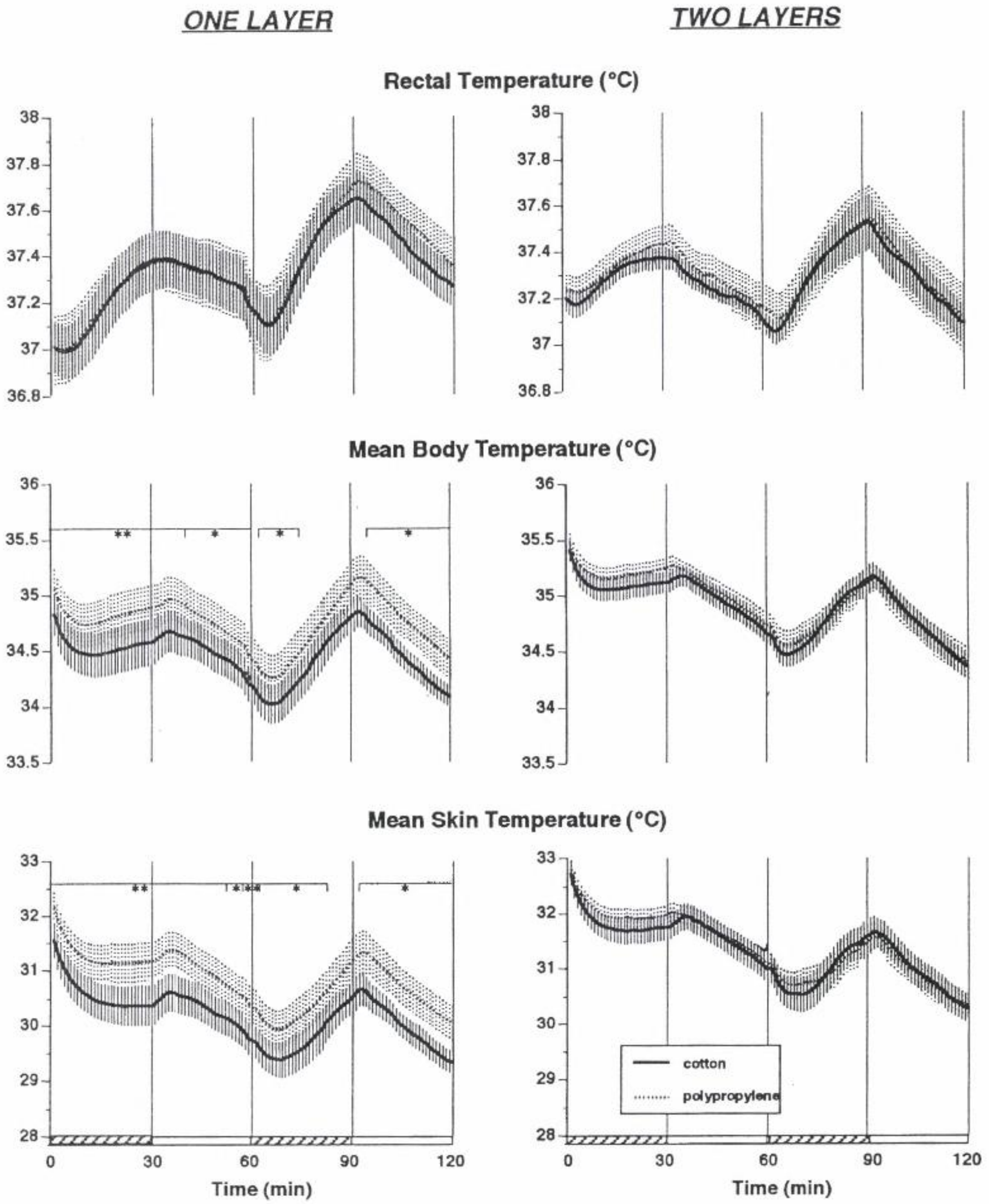

Figure 1. ***Left*** **A comparison of rectal temperature (top), mean body temperature (middle) and mean skin temperature (bottom) between C1 and P1. Solid line: C1. Dotted line: P1. Values are** $M \pm SE$ **(**$n = 6$**).** ***Right*** **A comparison of rectal temperature (top), mean body temperature (middle) and mean skin temperature (bottom) between C2 and P2. Solid line: C2. Dotted line: P2. Values are** $M \pm SE$ **(**$n = 7$**).** *Notes.* * $p < .05$ and ** $p < .01$ were obtained from the *t*-test for paired comparisons.

second rest. These values were not significantly different between the two clothing conditions during exercise and rest. Also, there were no differences in pulse rate between C2 and P2 during exercise and rest.

The body mass loss was 163.6 $\pm$ 7.49 and 157 $\pm$ 11.04 g in C1 and P1, 210.4 $\pm$ 9.83 and 191.0 $\pm$ 12.90 g in C2 and P2. There were no differences in body mass loss between C1 and P1, C2 and P2.

Figure 1 shows a comparison of T_{re}, $\overline{T}_b$ and $\overline{T}_{sk}$ between C1 and P1 (left) and between C2 and P2 (right). There were no significant differences in T_{re}. $\overline{T}_b$ and $\overline{T}_{sk}$ were significantly higher in P1 than in C1 ($F = 9.92$, $p < .01$ for $\overline{T}_b$, $F = 16.91$, $p < .01$ for $\overline{T}_{sk}$; middle and bottom left), whereas they did not show any differences between C2 and P2 (middle and bottom right).

Figure 2 shows a comparison of the clothing microclimate humidity between C1 and P1 (left), and between C2 and P2 (right). The clothing microclimate humidity between the skin surface and underwear at the

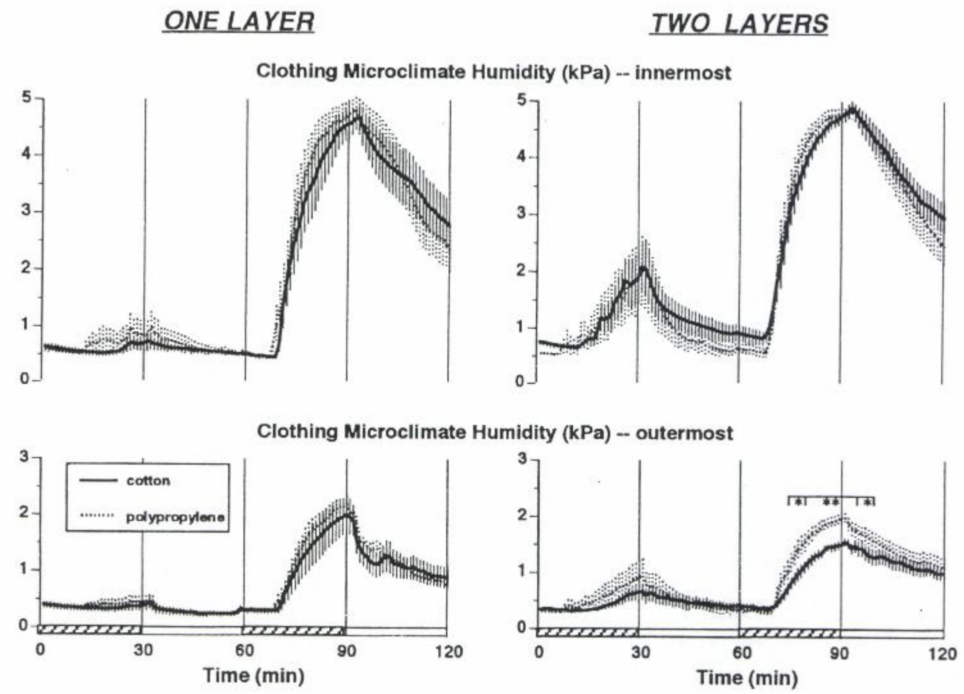

Figure 2. ***Left*** **A comparison of clothing microclimate humidity of innermost (top) and outermost (bottom) between C1 and P1. Solid line: C1. Dotted line: P1. Values are $M \pm SE$ ($n = 6$).** ***Right*** **A comparison of clothing microclimate humidity of innermost (top) and outermost (bottom) between C2 and P2. Solid line: C2. Dotted line: P2. Values are $M \pm SE$ ($n = 7$).** *Notes.* * $p < .05$ and ** $p < .01$ were obtained from the *t*-test for paired comparisons.

back level (innermost) did not differ between C1 and P1 (top left), and between C2 and P2 (top right). Although it was not different within the ski suit of outer clothing (outermost) between C1 and P1 (bottom left), it was significantly higher in P2 than in C2 (bottom right, $F = 5.09$, $p < .05$).

C1 underwear weight increased by 2.8 $\pm$ 0.81 g and P1 by 1.1 $\pm$ 0.43 g throughout the experiment in one layer. However, C2 underwear

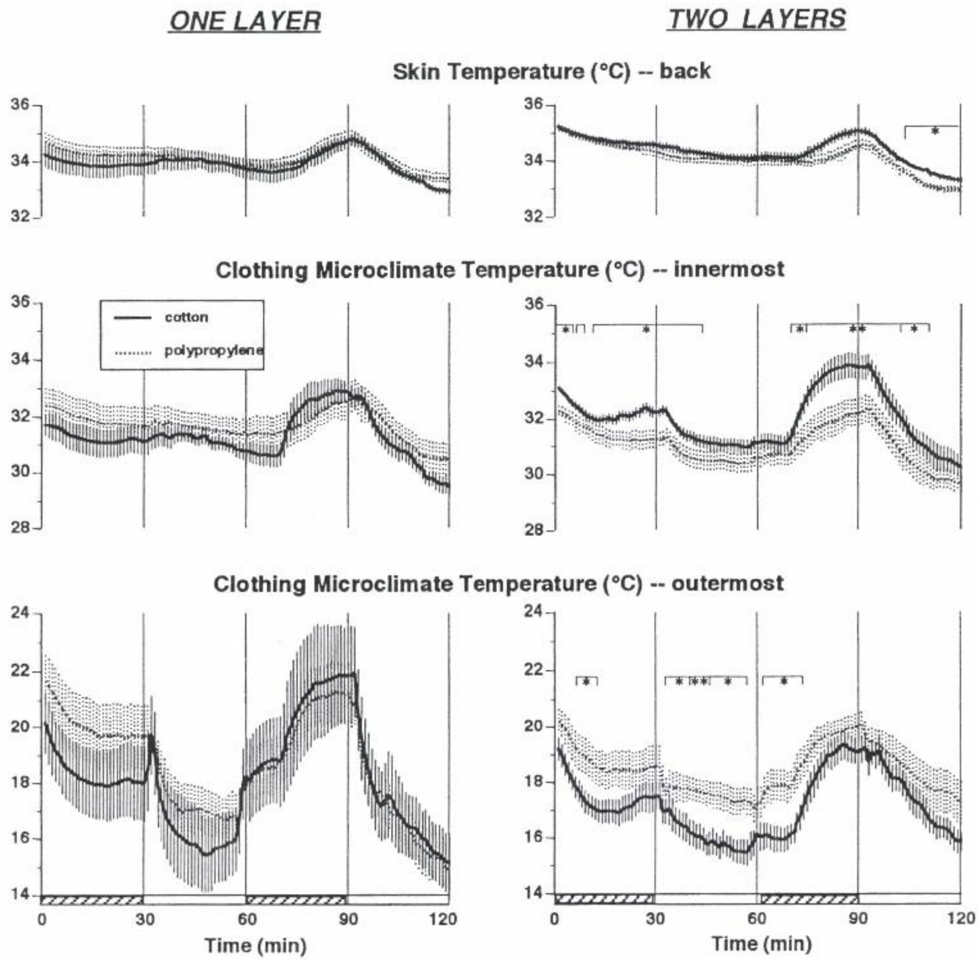

Figure 3. ***Left*****: A comparison of skin temperature on the back (top), clothing microclimate temperature of innermost (middle) and outermost (bottom) between C1 and P1. Solid line: C1. Dotted line: P1. Values are $M \pm SE$ ($n = 6$).** ***Right*****: A comparison of skin temperature on the back (top), clothing microclimate temperature of innermost (middle) and outermost (bottom) between C2 and P2. Solid line: C2. Dotted line: P2. Values are $M \pm SE$ ($n = 7$).** *Notes.* * $p < .05$ and ** $p < .01$ were obtained from the *t*-test for paired comparisons.

weight increased by 10.6 ± 2.19 g and P2 weight by 2.5 ± 0.98 g ($p < .01$). The ski suit mass increased by 3.28 ± 0.45 g in the C1 ensemble and by 3.28 ± 0.80 g in the P1 ensemble between the beginning and end of the experiment in one layer, and in the C2 ensemble ski suit mass increased by 4.08 ± 0.65 g in the P2 ensemble by 4.04 ± 0.83 g. These values were not significantly different.

Figure 3 shows a comparison of the skin temperature on the back and the clothing microclimate temperatures between C1 and P1 (left), and between C2 and P2 (right). Although the skin temperature on the back did not differ between C1 and P1 (top left), it was significantly higher in C2 than in P2 ($F = 11.09$, $p < .01$, top right). The clothing microclimate temperature between the skin surface and underwear on the back (innermost) did not differ between C1 and P1 (middle left). However, it was significantly higher in C2 than in P2 ($F = 29.66$, $p < .01$, middle right). It was not different inside the ski suit of outer clothing (outermost) between C1 and P1 (bottom left), whereas it was significantly lower in C2 than in P2 ($F = 19.19$, $p < 0.01$, bottom right).

Figure 4 shows a comparison of the differences between the innermost and outermost of clothing microclimate temperature at the back level in C1 and P1 (left) and C2 and P2 (right). There were no differences

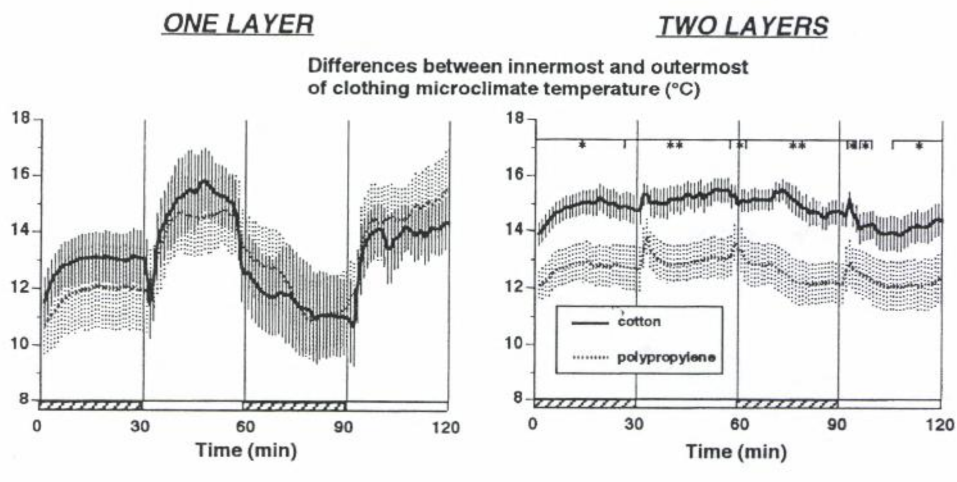

Figure 4. ***Left:*** **A comparison of differences between innermost and outermost of clothing microclimate temperature between C1 and P1. Solid line: C1. Dotted line: P1. Values are** $M \pm SE$ **($n = 6$).** ***Right:*** **A comparison of differences between innermost and outermost of clothing microclimate temperature between C2 and P2. Solid line: C2. Dotted line: P2. Values are** $M \pm SE$ **($n = 7$).** *Notes.* * $p < .05$ and ** $p < .01$ were obtained from the t-test for paired comparisons.

between C1 and P1, but they were significantly higher in C2 than in P2 ($F = 44.05$, $p < .01$).

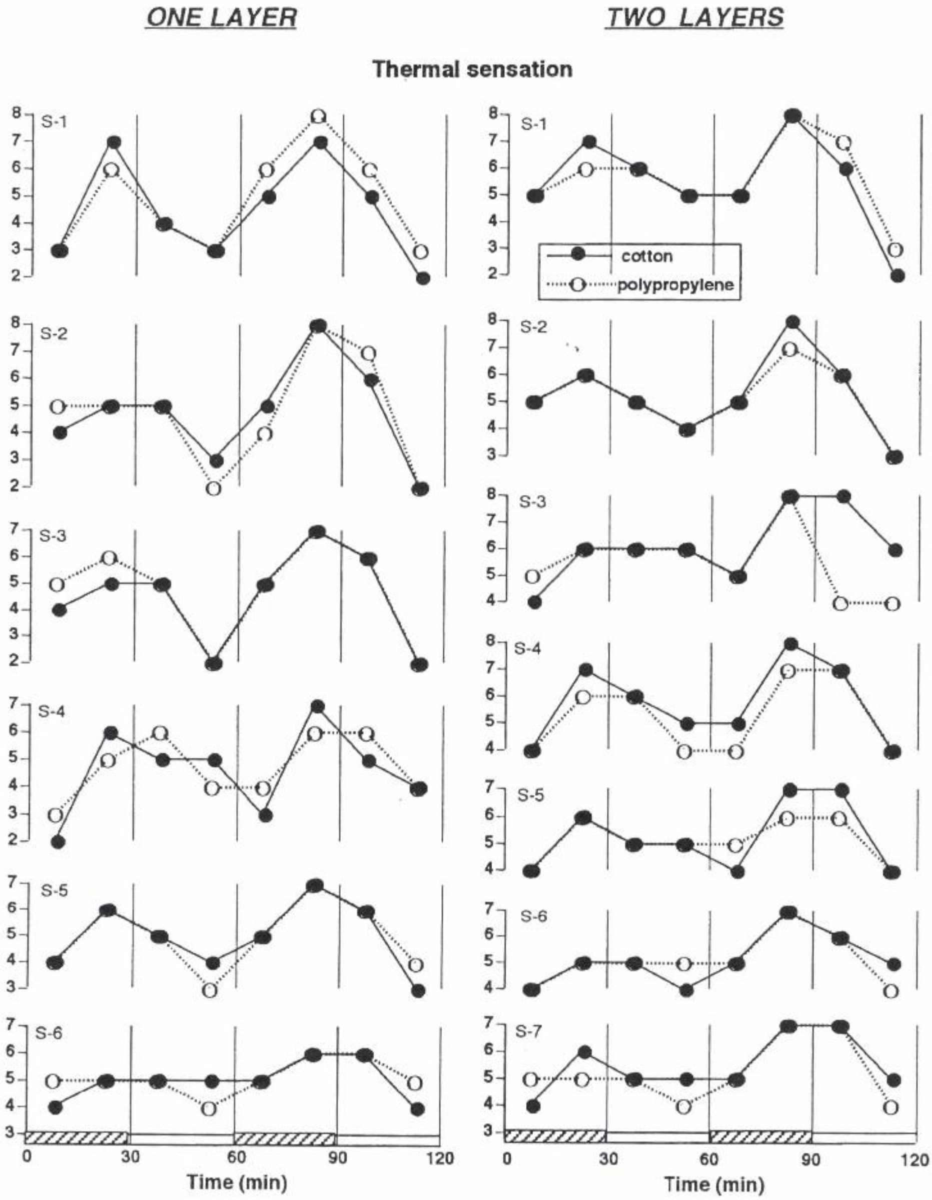

Figure 5. ***Left*****: A comparison of whole body thermal sensation in 6 individual participants between C1 and P1. Solid circles: C1. Hollow circles: P1.** ***Right*****: A comparison of whole body thermal sensation in 7 individual participants between C2 and P2. Solid circles: C2. Hollow circles: P2.** *Notes.* Scale: 9—very hot, 8—hot, 7—warm, 6—slightly warm, 5—neutral, 4—slightly cool, 3—cool, 2—cold, 1—very cold.

Figure 5 shows an individual comparison of the whole body thermal sensation between C1 and P1 (left), and between C2 and P2 (right). Five out of 6 participants felt colder in C1 than in P1 during the second rest, whereas 4 out 7 participants felt warmer in C2 than in P2 during the second rest.

The clothing sensation, skin sensation, and shivering/sweating sensation did not differ systematically between C1 and P1, and between C2 and P2.

4. DISCUSSION

The findings that clothing microclimate humidity of the inside ski suit was not different between C1 and P1, and was significantly lower in C2 than in P2 could be probably ascribed to either one or two layers of cotton underwear; that is, two layers of cotton underwear could absorb moisture more greatly than one layer, resulting in lower level of clothing microclimate humidity of the inside ski suit in C2. Cotton absorbs moisture better than polypropylene, whereas polypropylene is more permeable to air than cotton (Table 2). Due to these different physical properties, the clothing microclimate humidity between skin surface and underwear was kept nearly equal between C1 and P1, and also between C2 and P2. Clothing microclimate humidity of the inside ski suit was not different between C1 and P1. This is because one layer of cotton underwear could not absorb moisture to a greater extent, compared with two layers of cotton underwear, resulting in a higher level in C1 than in C2 (1.97 ± 0.31 kPa in C1 and 1.54 ± 0.06 kPa in C2 at the end of second exercise, bottom of Figure 2).

Why was the clothing microclimate temperature of the inside ski suit significantly higher in P2 than in C2? It is presumably correlated with a higher level of clothing microclimate humidity of the inside ski suit in P2 (Figure 2). As T_a was 0 °C, the outer clothing, especially its outermost part was cooled. Therefore, the higher moisture of the outer clothing in P2 became probably water drop in part, resulting in lowering its thermal insulation and causing probably the flow of dry heat from the innermost to the outermost easier in P2 and a higher clothing microclimate temperature in P2 than in C2. The actual flow of heat is difficult to estimate because both heat and mass (moisture) transfer could occur. Actually, the saturation pressure at 19–20 °C is just above 2 kPa, which was close to a condensation zone at least in the P2 case (right bottom of Figure 2). According to a preliminary report by Tokura (1985), the clothing microclimate humidity of the inside outer clothing increased more in the polyester underwear than in the wool underwear during exercise by a cycle ergometer at T_a of 5 °C, resulting in a higher clothing microclimate temperature of the inside outer clothing in the polyester undershirt. In other words, the higher clothing microclimate humidity of the inside outer clothing was accompanied by the higher microclimate temperature of the inside outer clothing, suggesting that the flow of dry heat occurred more effectively from innermost clothing to outermost.

According to unpublished data (M. Niwa, personal communication), similar results of clothing microclimate (temperature, humidity) to those obtained in our present experiments were obtained by the usage of a hot plate experiment. This suggests that the results of the clothing microclimate obtained by the human participant experiment were confirmed also by a physical model.

Heat transfer is complex to analyze as both dry heat and mass (moisture) transfer are involved. One possible explanation for the differences between C2 and P2 may be as follows: C2 underwear absorbs more moisture by direct absorption from wet skin, thereby reducing its thermal insulation. Hence, the innermost microclimate temperature for C2 should be lower than for P2. But, this is not the case. In P2, more humid air reaches the outer layers (the ski suit) and part of it condenses. Heat is released and local temperature is increased. In addition, the local thermal insulation of parts of the ski suit layers may be reduced due to wetting and contribute to dry heat loss and higher temperature in comparison with C2. With these in mind, the higher innermost microclimate temperature in C2 might probably reflect partly the less reduced thermal insulation of the ski suit in C2 and also the heat in C2 liberated by absorbing moisture (Wang & Yasuda, 1991). The final outcome, however, appears to be a heat balance maintained at the same levels of mean skin and rectal temperature. Apparently, heat balance is achieved by controlling moisture accumulation in the underwear in C2 at the risk of getting wet close to the skin. In P2, heat balance is controlled by keeping dry underwear at the risk of getting condensation in the ski suit. Farnworth and Dolhan (1985) could not find any differences in heat loss between polypropylene and cotton underwear using a hot plate. Also, Morooka and Morooka (1991) found using a sweating hot plate that dry heat loss occurred more greatly in cotton underwear than in polypropylene and wool. However, these authors did not try to compare the different effects between one and two layers of underwear on dry heat loss. As shown in Figure 4, the differences between the innermost and outermost of clothing microclimate temperature were significantly higher in C2 than in P2. This means that the flow of dry heat from the space between the skin surface and the underwear to that inside the outermost clothing was smaller in C2 than P2. The fact that $\overline{T}_{sk}$ was not different between C2 and P2 might reflect a compromise of reduced thermal insulation of cotton underwear (C2) by absorbing moisture and that of the ski suit via higher clothing microclimate humidity in P2. Nielsen and Endrusick (1988) reported that $\overline{T}_{sk}$ was not different between cotton underwear and polypropylene underwear at T_a of 5 °C in the participant with intermittent exercise.

In the one-layer experiment most participants felt cooler in C1 than in P1, whereas the reverse was true in the two-layer experiment. Lower mean skin temperature in C1 might be responsible for cooler thermal sensation in C1. Although $\overline{T}_{sk}$ was not significantly different in C2 and P2, higher back skin and clothing microclimate temperatures might be responsible for the warmer thermal sensation in C2 in the two-layer experiment.

5. CONCLUSION

Thus, if the moisture absorbing properties of cotton underwear like that used in the experiment are enough to inhibit the increase of clothing microclimate humidity inside the outer clothing, outer clothing like a ski suit does not increase its clothing microclimate humidity, and hence, does not reduce its thermal insulation. The participant could feel warmer in the cold under such conditions.

Whether these different values of physiological and clothing microclimate parameters between C1 and P1, and between C2 and P2 might be of practical importance for daily life remains to be studied in the future.

REFERENCES

Farnworth, B. (1986). A numerical model of the combined diffusion of heat and water vapor through clothing. *Textile Research Journal*, *56*, 653–665.

Farnworth, B., & Dolhan, P.A. (1985). Heat and water transport through cotton and polypropylene underwear. *Textile Research Journal*, *55*, 627–630.

Fujimoto, S., Watanabe, T., Sakamoto, A., Yukawa, K., & Morimoto, K. (1968). Studies on the physical surface area of Japanese; Part 18. Calculation formulas in three stages over all age. *Japanese Journal of Hygiene*, *23*, 443–450. (In Japanese).

Morooka, H., & Morooka, H. (1991). Thermal and water transport properties of clothing systems in a very cold environment, in a case of sudden ambient temperature change. *Journal of Home Economics of Japan*, *42*, 849–855. (In Japanese).

Nakahashi, M., & Yoshida, K. (1990). *Physiology of clothing*. Tokyo: Nankoudou. (In Japanese).

Nielsen, R., & Endrusick, T.L. (1988). The role of textile material in clothing on thermoregulatory responses to intermittent exercise. In F. Aghazadeh (Ed.), *Trends in ergonomics/Human factors V* (pp. 449–456). Copenhagen, Denmark: North-Holland, Elsevier Science.

Påsche, A. (1991). Cold climate work clothing. In R.E. Reinertsen, A.O. Brubakk, & A. Påsche (Eds.), *Working and survival in the cold* (pp. 1–13). Trondheim, Norway: SINTEF UNIMED.

Tokura, H. (1985). Effects of shirt material on thermoregulatory responses and clothing climate in sedentary and exercising women at warm and cold ambient temperatures. In S. Kawabata, R. Postle, & M. Niwa (Eds.), *Objective measurement: Applications to product design and process control* (pp. 365–373). Osaka, Japan: Textile Machinery Society of Japan.

Tokura, H., Sasase, A., Hashimoto, S., & Midorikawa, T. (1989). Thermophysiological studies of double-face knitted fabrics under cycle ambient temperatures. *Descente Sport Science*, *10*, 203–208.

Umbach, K.H. (1988). Physiological optimization of textiles for sportswear and work-wear. In H. Tokura (Ed.), *Proceedings of International Symposium on Clothing Comfort Studies in Mt. Fuji* (pp. 123–148). Osaka, Japan: The Japan Research Association for Textile End-Users.

Wang, J.H., & Yasuda, H. (1991). Dynamic water vapor and heat transport through layered fabrics, Part 1: Effect of surface modification. *Textile Research Journal*, *61*, 10–20.

Yasuda, H. (1992). Dynamic heat and water vapor transport through layered fabrics; a model study for out-door sport wear fabrics. *Descente Sport Science*, *13*, 75–84. (In Japanese).