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ORIGINAL ARTICLE

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Physiological significance of hydrophilic and hydrophobic textile materials during intermittent exercise in humans under the influence of warm ambient temperature with and without wind

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Abstract The purpose of this present study was to compare the physiological effects of the hydrophilic and hydrophobic properties of the fabrics investigated in exercising and resting subjects at an ambient temperature of 30°C and a relative humidity of 50% with and without wind. Three kinds of clothing ensemble were tested: wool and cotton blend with high moisture regain (A), 100% cotton with intermediate moisture regain (B), 100% polyester clothing with low moisture regain (C). The experiments were performed using seven young adult women as subjects. They comprised six repeated periods of 10-min exercise on a cycle ergometer at an intensity of 40% maximal oxygen uptake followed by 5 min of rest (20 min for the last rest). The experiments comprised two sessions. During session I (first three repetitions of exercise and rest) the subjects were exposed to an indifferent wind velocity and during session II (last three repetitions of exercise and rest) they were exposed to a wind velocity of $1.5 \mathrm{~m} \cdot \mathrm{s}^{-1}$. Rectal temperature and skin temperatures at eight sites, pulse rate and clothing microclimate were recorded throughout the whole period. The main findings can be summarized as follows: rectal temperature during session II was kept at a significantly lower level in A than in B and C. Clothing microclimate humidity at the chest was significantly lower in A than in B and C during session II. Skin and clothing microclimate temperatures at the chest were significantly lower in A than in B and C during session II. Pulse rate was significantly higher in C than in A and B during sessions I and II. It was concluded that the hydrophilic properties of the fabrics studied were of physiological significance for reducing heat strain during exercise and rest especially when influenced by wind.

Key words Hydrophilic and hydrophobic fibre · Clothing microclimate · Wind effect · Heat strain · Rectal temperature

Introduction

Even though humans live in an environment of great variability, the human body maintains a tightly regulated core temperature. It has been shown that the stability of core temperature is dependent upon the balance of heat production together with heat gain from the environment and loss to the environment through the transfer of heat by conduction, convection, radiation and evaporation (Ingram and Mount 1975). Clothing, as an interactive barrier, greatly affects thermal balance. Some of this interaction is derived from the physical properties of the clothing materials and their spacing around the body. Clothing systems must be carefully planned to facilitate heat transfer with the environment. It has been shown that this reduces potential heat storage and loss that may decrease work capacity (Fourt and Hollies 1970; Watkins 1984).

Under normal stationary conditions, it has been demonstrated that the human body produces little sweat or saturated water vapour, and the wearer does not experience any significant discomfort while wearing either a cotton or a polyester shirt (Hollies 1977). But, as the dry heat flux by conduction, convection and radiation is not sufficient to match metabolic heat production in a warm climate, while the human is exercising or working, it has been shown that sensible sweating is started with the aim of creating a latent heat flux by the evaporation of sweat at the skin surface (Folk 1974).

The layer of fabric next to the skin determines the partial pressure of water vapour in the air space between the skin and the first layer of fabric. It has been reported that the lower the partial pressure of water in the air

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space next to the skin, the more comfortable the subjects feel in general (Wang and Yasuda 1991). Natural fibres such as wool and cotton which are hygroscopic, have been shown to have the ability to absorb large amounts of moisture (Smith and Block 1982). Some investigators have reported that a greater amount of sweat was absorbed in woollen clothing than in polypropylene and polyester when total sweat production was the same (Hall and Poltke 1956; Nielsen and Endrusick 1988). Ha et al. (1995a) have studied the effects of two kinds of clothing, with either hydrophobic or hydrophilic fabrics, on the rate of sweating at an ambient temperature (T_a) of 37°C and found that the local sweating rate was higher in polyester than in cotton.

However, according to Bakkevig (1995), the absorbed moisture in hydrophilic textiles like cotton and wool could be a boundary against effective moisture transfer and be released slowly into the surrounding air. Since synthetic fibres such as polyester, nylon and acrylics are not hygroscopic, they absorb only comparatively small amounts of moisture. However, because of their hydrophilic fibre surface, they have an ability to transfer moisture. Vokac et al. (1976) and Holmér (1985) have tried to study the physiological responses under the influence of different materials of underwear during intermittent exercise, but they have not found any difference. It is necessary for more data to be collected for a systematic understanding of the relationship between textile materials and physiological responses.

Wind is a tremendously important factor in heat dissipation. It has been reported that wind can quickly carry away warm air surrounding the body and act to evaporate liquid sweat and dissipate the resulting warm vapour (Watkins 1984). Adams et al. (1992) have observed that total body sweat loss was significantly greater in wind speeds of $0.2\ \mathrm{m \cdot s^{-1}}$ than $3.0\ \mathrm{m \cdot s^{-1}}$ at T_a of 24°C and 35°C and that mean skin temperature ($\overline{T}_{sk}$) was higher in at the $0.2\ \mathrm{m \cdot s^{-1}}$ wind speed at both T_a during exercise. Havenith et al. (1990) have reported on the individual and combined effects of sitting, walking at two speeds and three wind speeds on the insulation value of three clothing ensembles and found that total clothing insulation was reduced by up to 53% by the combined effects of posture and wind speed. The insulation of the surface air layer was decreased by up to 80% by the combined effect of posture and wind speed.

According to Nielsen et al. (1985), the combination of an increased air velocity ($1.1\ \mathrm{m \cdot s^{-1}}$) and walking have been found to reduce air insulation by 31% when compared with walking in still air. Thus, there are several reports concerned with the influence of wind on thermal insulation, as mentioned above, however, there have been few physiological studies on the combined effects of moisture absorption by fabrics and slight wind.

The aim of this paper was to study the relationship between the different absorption properties of fibre and physiological parameters such as body temperature, microclimate, heart rate and the subjective rating when wearing different textile materials during exercise and rest under the influence of slight wind in a warm environment.

Methods

Subjects

Seven healthy females subjects participated in the study. The general purpose, procedures and risks were fully explained and informed consent was given by all the subjects. The subjects were mean age 20.42 (SEM 0.57) years, mean height 161.14 (SEM 1.49) cm, mean body mass 52.26 (SEM 2.09) kg and mean body surface area (BSA), 1.49 (SEM 0.03) $\mathrm{m^2}$, calculated by the equation of Fujimoto et al. (1968). The subjects were not informed concerning the details of the selection of clothing materials to avoid any influence on their subjective ratings. The subjects reported to the laboratory at the same time of day to minimize circadian effects on the body temperature and they were all at the same luteal phase of the menstrual cycle.

Garments tested

Three kinds of clothing ensemble were examined:

1. Wool and cotton blend with high moisture regain (A)
2. 100% cotton with average moisture regain (B)
3. 100% polyester with low moisture regain (C).

The ensembles consisted of long-sleeved shirts, full trousers and 100% cotton socks. The physical properties of the fabrics are listed in Table 1. The clothing was laundered without using a detergent to prevent the characteristics of the textiles from changing during the experiment and was dried before each experiment and stabilized in the chosen environmental conditions [T_a of 20 ± 5°C, 30 ± 5% relative humidity, rh].

Measurements

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

Table 1 Physical properties of the clothing fabrics. *n* Number

Fabrics	Materials	Mass ($\mathrm{g \cdot m^{-2}}$)	Thickness (mm)	Density ($n \cdot \mathrm{inch^{-1}}$) (warp, filling)	Moisture regain[a] (%)	Moisture transfer ($\mathrm{g \cdot m^{-2} \cdot h^{-1}}$)	Air permeability ($\mathrm{m \cdot kPa^{-1} \cdot s^{-1}}$)	Water absorbency ($\mathrm{cm \cdot 10\ min^{-1}}$) (warp, filling)
A	Wool/cotton	120.8	0.50	70, 62	8.7	518.4	4.12	8.6, 8.2
B	Cotton	125.2	0.49	84, 61	6.8	525.6	4.20	8.9, 7.1
C	Polyester	127.2	0.41	78, 74	0.4	518.4	3.68	4.9, 4.3

[a] Moisture regain was defined as the water content of fibres at 65% relative humidity per 100 g of dry fibre

thermistors (Takara Thermistor, accuracy ±0.1°C) taped at eight sites: forehead, forearm, hand, chest, back, thigh, leg and foot. Clothing microclimates (temperature and humidity) at the level of the chest and back (at equivalent sites to those for the measurements of chest and back T_{sk}) were measured by thermistor and humidity sensors (Vaisala HMP-35 A, accuracy ±3% rh). The clothing surface temperatures were also measured using thermistors (Takara Thermistor, accuracy ±0.1°C) on the chest and back (at equivalent sites to those on the skin).

Before the experiment, the humidity sensors were calibrated by two saturated salt solutions, LiCl and K_2SO_4, at a constant temperature. The pulse rate was recorded every minute.

Before the experiment sessions, the maximum oxygen uptake ($\dot{V}O_{2max}$) was determined using a cycle ergometer (Ergociser, model EC-1500 Cateye Co., Japan). The intensity of exercise used in the experiment was 40% of the $\dot{V}O_{2max}$.

At the beginning and end of each experiment, the body mass of the subjects and the mass of the garments were measured using balances (Sartorius, accuracy ±1 g for body mass; Electronic balance, accuracy ±10 mg for garment mass).

The scaled reactions of the subjects, sensations in respect of clothing comfort, temperature, sweating, clothing humidity and skin wettedness were obtained every 5 min. The scales for each sensation are listed in Table 2. All the parameters for temperature and humidity were recorded continuously, and sampled every 6 s by a computer through an A-D converter.

Experiment protocol

A climatic chamber with a controlled T_a of 30°C, rh of 50% and air velocity of 0.14 m · s^{-1} was maintained for at least 2 h before the experiment. The experiment clothing was stabilized in the antechamber [T_a of 20 ± 5°C, and rh of 30 ± 5%] for at least 2 h before the experiment began. The subjects, wearing only underpants and a brassiere, entered the antechamber. After their body mass had been measured, a thermistor sensor for T_{re} was inserted into the rectum by the subject herself, and thermistor sensors for T_{sk} were attached. The temperature and humidity sensors for the clothing microclimate were attached at the level of the chest and back.

The subject put on the experiment ensemble (chosen at random from A, B, and C). The mass of these garments was recorded just before dressing. After dressing, the subjects were instructed to rest in a chair.

After stabilization of T_{re}, the subject entered the climatic chamber for the experiment. She sat on a cycle ergometer, a pulse rate sensor was fastened to the lobe of one ear and measurements were started (Fig. 1). After a 15-min rest, 10-min sessions of exercise followed by 5-min rest (20 min during the last rest) were repeated six times. From the fourth period of exercise onwards, the fan was turned on (wind velocity of 1.5 m · s^{-1} when measured at chest level). The subjective ratings were given every 5 min. At the end of the 120-min of the experiment, the subjects took off the garments and body and clothing mass were again measured.

Table 2 Subjective sensations

Clothing comfort sensation
0. Neutral
1. Slightly uncomfortable
2. Uncomfortable
3. Very uncomfortable

Thermal sensation
1. Very cold
2. Cold
3. Cool
4. Slightly cool
5. Neutral
6. Slightly warm
7. Warm
8. Hot
9. Very hot

Sweating sensation
0. Not at all
1. Slightly sweating
2. Moderately sweating
3. Heavily sweating

Clothing humidity sensation
0. No sensation
1. Slightly damp
2. Damp
3. Wet

Skin wettedness
0. Dry
1. Slightly wet
2. Wet
3. Too wet

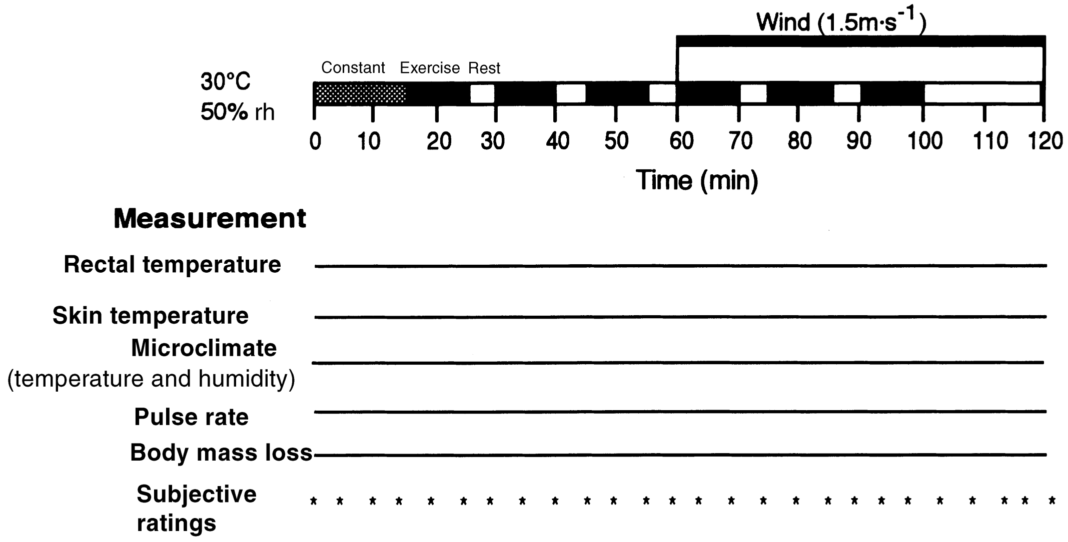

Fig. 1 Experiment schedule. *rh* Relative humidity

Calculations and statistical analysis

The $\overline{T}_{\mathrm{sk}}$ was calculated from the following modification of equation of Hardy-Dubois (1938): $\overline{T}_{\mathrm{sk}} = 0.07T_{\mathrm{head}} + 0.14T_{\mathrm{arm}} + 0.05T_{\mathrm{hand}} + 0.18T_{\mathrm{chest}} + 0.17T_{\mathrm{back}} + 0.19T_{\mathrm{thigh}} + 0.13T_{\mathrm{leg}} + 0.07T_{\mathrm{foot}}$. Mean body temperature ($\overline{T}_{\mathrm{b}}$) was calculated as: $\overline{T}_{\mathrm{b}} = 0.8T_{\mathrm{re}} + 0.2\overline{T}_{\mathrm{sk}}$. Heat storage ($S$) was calculated using the following equation: $S = (0.83 \cdot M_{\mathrm{b}}/\mathrm{BSA})(\Delta\overline{T}_{\mathrm{b}}/\Delta t)(\mathrm{kcal} \cdot \mathrm{m}^{-2} \cdot \mathrm{h}^{-1})$, where the constant ($0.83\ \mathrm{kcal} \cdot \mathrm{kg}^{-1} \cdot {}^{\circ}\mathrm{C}^{-1}$) is the specific heat of the body, M_{b} (kilograms) is body mass, BSA (metres squared) is body surface area and $\Delta\overline{T}_{b}$ is the change in mean body temperature and Δt is the time interval.

The statistical significances between the means were assessed using a two-way repeated-measures analysis of variances (ANOVA) for A versus B, B versus C and A versus C, and separately for the two periods of session I (from the measuring start to the third rest, i.e. the condition of no wind) and session II (from the fourth exercise to the end of the experiment, i.e. the condition with wind of $1.5\ \mathrm{m} \cdot \mathrm{s}^{-1}$). A paired Students t-test was used for the change in mass of the garments, loss of M_{b} and S. A P-value less than 0.05 was considered statistically significant.

Results

Body temperatures and S

A comparison of temporal changes in T_{re}, $\overline{T}_{\mathrm{sk}}$ and mean $\overline{T}_{\mathrm{b}}$ among the three kinds of clothing conditions is shown in Fig. 2.

The T_{re} gradually increased on the whole with a greater rise during exercise and a small fall during rest. There was no significant difference in T_{re} among the three kinds of clothing during session I, while T_{re} was significantly lower in A than in B and C ($F = 8.57$, $P < 0.05$ for A vs B; $F = 12.66$, $P < 0.01$ for A vs C) during session II.

The $\overline{T}_{\mathrm{sk}}$ increased on the whole during session I, while it became abruptly lower during session II. Close observation showed that $\overline{T}_{\mathrm{sk}}$ fell during the first half of the exercise and then began to increase during the second half of the exercise and rest during sessions I and II. There was no significant difference among A, B and C during session I, while $\overline{T}_{\mathrm{sk}}$ was significantly higher in C than in A and B ($F = 108.33$, $P < 0.01$ for A vs C; $F = 122.44$, $P < 0.01$ for B vs C).

The $\overline{T}_{\mathrm{b}}$ indicated a similar pattern to $\overline{T}_{\mathrm{sk}}$. No difference was found for $\overline{T}_{\mathrm{b}}$ among A, B and C in session I, while $\overline{T}_{\mathrm{b}}$ was significantly higher in C than A and B ($F = 89.70$, $P < 0.01$ for A vs C; $F = 81.49$, $P < 0.01$ for B vs C).

The average S (kilocalories per metre squared per hour) during the 2-h experiment was 5.87 (SEM 0.11) for A, 6.03 (SEM 0.12) for B and 7.31 (SEM 0.14) for C; which was significantly higher in C than in A ($F = 8.24$, $P < 0.05$), but was no difference for A vs B and B vs C.

The clothing microclimate humidity at the level of the chest and back

A comparison of temporal changes in the clothing microclimate humidity ($\mathrm{H}_{\mathrm{micro}}$) for the chest and back among A, B and C is shown in Fig. 3.

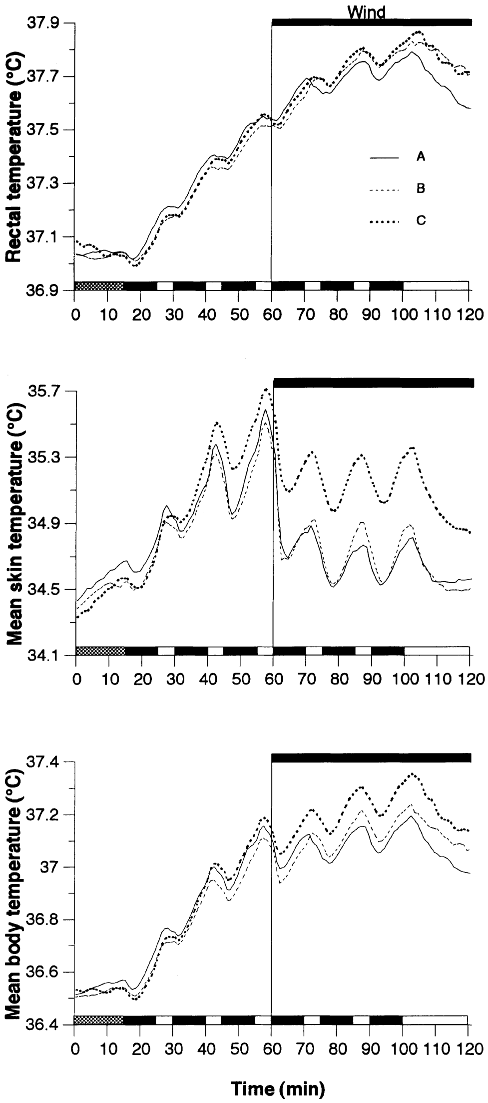

Fig. 2 A comparison of temporal changes in rectal temperature (*top panel*), mean skin temperature (*middle panel*) and mean body temperature (*bottom panel*) among three clothing ensembles ($n = 7$). For definitions of *A*, *B* and *C* see Table 1 and Methods

As seen in the figure, $\mathrm{H}_{\mathrm{micro}}$ gradually increased at both the chest and back levels during session I and abruptly fell especially at the chest level during session II. The $\mathrm{H}_{\mathrm{micro}}$ began to increase almost simultaneously with the start of exercise and to decline soon after the start of rest at both chest and back levels during session I. The $\mathrm{H}_{\mathrm{micro}}$ at the chest level was significantly higher in C than in A and B ($F = 6.44$, $P < 0.05$ for C vs A; $F = 8.18$, $P < 0.05$ for C vs B) during session I and significantly higher in C than in B ($F = 38.93$, $P < 0.01$) and significantly higher in B than A ($F = 6.87$, $P < 0.05$) during session II. The $\mathrm{H}_{\mathrm{micro}}$ at the back level was significantly higher in C than A and B ($F = 26.94$, $P < 0.01$; C vs A; $F = 17.63$, $P < 0.01$ for C vs B) during session I, significantly higher in C than in B ($F = 60.40$, $P < 0.01$) and significantly

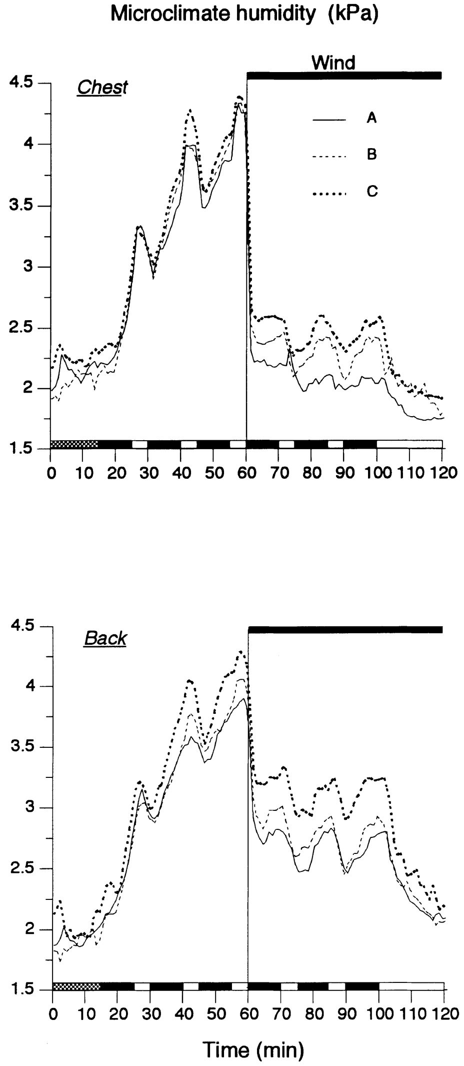

Fig. 3 A comparison of temporal changes in microclimate humidity at the chest (*top panel*) and back (*bottom panel*) among three clothing ensembles ($n = 7$). For definitions of *A*, *B* and *C* see Table 1 and Methods

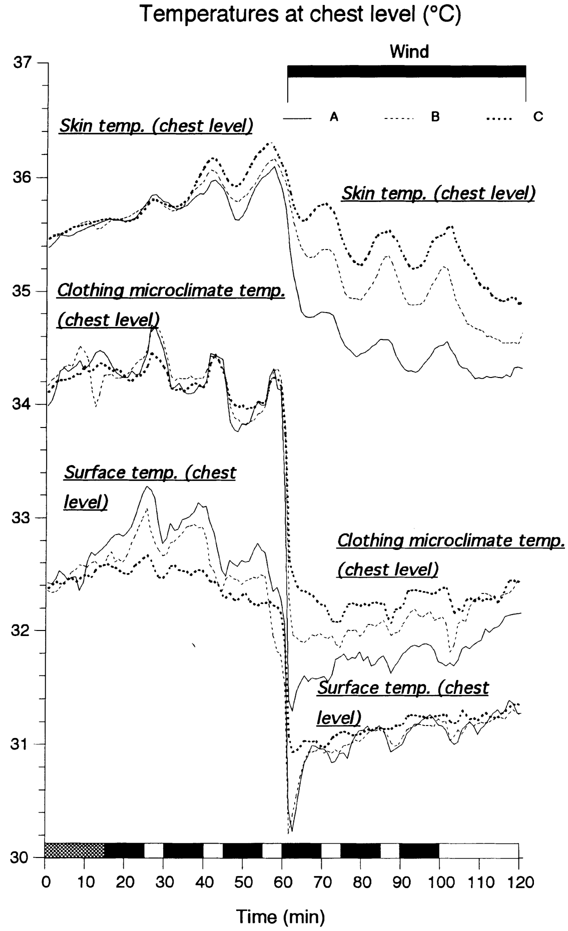

Fig. 4 A comparison of temporal changes in the skin temperature at the chest (*top panel*), microclimate temperature at chest (*middle panel*) and clothing surface temperature at chest (*bottom panel*) among the three clothing ensembles ($n = 7$). For definitions of *A*, *B* and *C* see Table 1 and Methods

higher in B than in A ($F = 8.55$, $P < 0.05$) during session II.

The temperature parameters at the chest level

Figure 4 shows a comparison of skin, clothing microclimate, and clothing surface temperatures at the chest level during sessions I and II among A, B and C. It should be noticed that skin, clothing microclimate and surface temperature at chest levels fell sharply with the transition from sessions I to II.

The T_{chest} were significantly higher in C than in A ($F = 7.83$, $P < 0.05$) during session I, while they were significantly lower in A than in B ($F = 67.45$, $P < 0.01$) and in B than in C ($F = 39.18$, $P < 0.01$) during session II (top of the figure). There was no significant difference with clothing microclimate temperature at the chest level during session I, while it was significantly lower in A than in B ($F = 57.04$, $P < 0.01$), and in B than in C ($F = 19.68$, $P < 0.01$) during session II (middle of the figure).

Clothing surface temperatures were significantly higher in A than in B ($F = 19.28$, $P < 0.01$), and B than in C ($F = 20.43$, $P < 0.01$) during session I, while there was no significant difference during session II (among A, B, C).

Pulse rate

Figure 5 shows a comparison of average pulse rates during sessions I and II among A, B and C. The pulse rate quickly increased with the onset of exercise and fell with cessation. As seen in the figure (top), the pulse rate was significantly higher in C than in B during session I ($F = 12.22$, $P < 0.01$), while it was higher in C than in A and B during session II ($F = 9.03$, $P < 0.01$ for C vs A; $F = 12.22$, $P < 0.01$ for C vs B). The change in pulse rate (bottom) was significantly higher in C than A

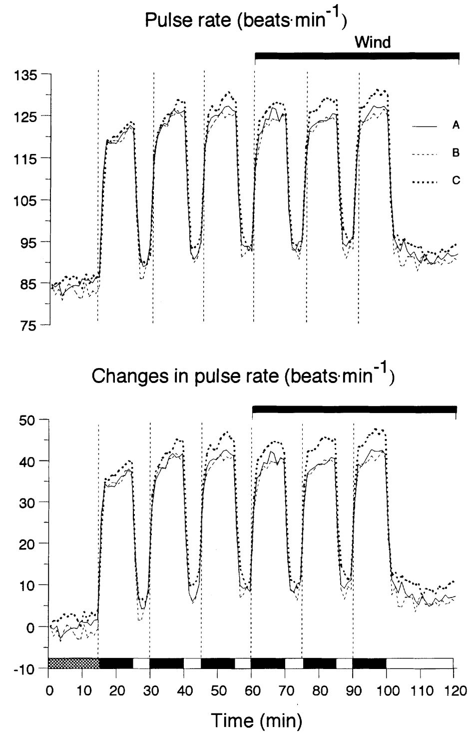

Fig. 5 A comparison of temporal changes in pulse rate (*top panel*) and the changes in pulse rate (*bottom panel*) among the three clothing ensembles ($n = 7$). For definitions of *A*, *B* and *C* see Table 1 and Methods

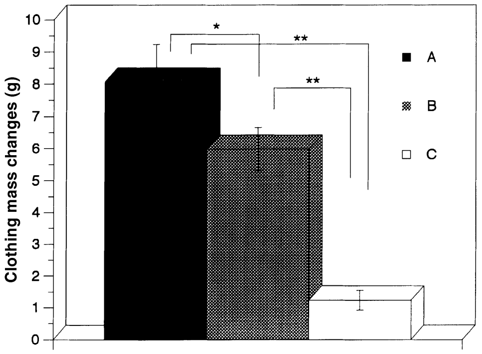

Fig. 6 A comparison of changes in clothing mass among the three clothing ensembles ($n = 7$). For definitions of *A*, *B* and *C* see Table 1 and Methods. Mean and SEM, *$P < 0.05$ **$P < 0.01$

and B during session I ($F = 22.22$, $P < 0.01$ for C vs. A; $F = 45.72$, $P < 0.01$ for C vs B) and session II ($F = 30.38$, $P < 0.01$ C vs A; $F = 59.01$, $P < 0.01$ for C vs B).

Changes in clothing mass, amount of sweating, and subjective rating

The changes in the clothing mass between the beginning and the end of the experiment were 8.06 (SEM 0.48) g in A, 5.98 (SEM 0.28) g in B, and 1.23 (SEM 0.31) g in C, respectively (Fig. 6). The changes in clothing mass were statistically greater in A than in B ($P < 0.05$), in B than in C ($P < 0.01$) and in A than in C ($P < 0.01$).

The amount of sweating, which was calculated from loss of body mass throughout the experiment was 117.68 (SEM 9.37) g in A, 125.02 (SEM 20.93) g in B, and 139.59 (SEM 21.47) g in C, respectively (Fig. 7). As seen in the figure, the amount of sweating was significantly greater in C than in B ($P < 0.05$) and in A ($P < 0.01$).

There was no significant difference in any subjective sensations among A, B and C.

Discussion

What physiological mechanism could account for our main finding that T_{re} during session II was kept at a significantly lower level in A (wool combined with cotton) than in B (cotton 100%) and C (polyester 100%), although there was no significant difference during session I (Fig. 2)?

As seen in Fig. 3 (top), the absolute $\mathrm{H}_{\mathrm{micro}}$ was the lowest in A during session II compared with those in B and C, suggesting that evaporative heat loss might have occurred most effectively in A, being evidenced by the fact that T_{chest} was lowest in A (Fig. 4). Furthermore, the finding that the T_{chest} and clothing microclimate temperature in A during session II was the lowest in spite of identical surface temperature at the chest level among A, B and C would indicate the greatest heat flow from the chest skin surface through the clothing to the surrounding air in A. Thus, the larger evaporative and dry heat flow in A might have been responsible for the lowest level of T_{re} during session II in A.

As shown in the Fig. 4, the surface temperature (top) was significantly higher in A than in B, in B than in C during session I. According to Wang and Yasuda (1991), when a fibre absorbs moisture, a certain amount of heat is liberated. Yasuda et al. (1994) have measured the surface temperature and water vapour pressure at T_{a} of 20°C with wool and polyester. They have found that the surface temperature rose more rapidly with wool than

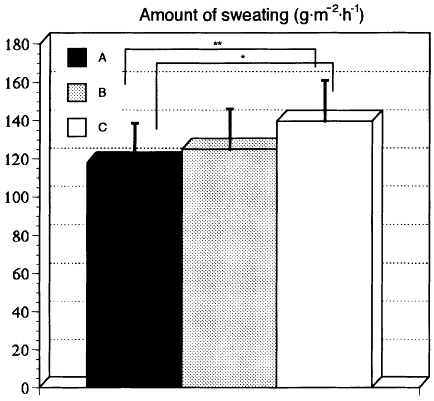

Fig. 7 A comparison of amount of sweating among the three clothing ensembles ($n = 7$). For definitions of *A*, *B* and *C* see Table 1 and Methods. Mean and SEM, *$p < 0.05$ **$P < 0.01$

with polyester, and also confirmed that the heat of water vapour absorption by fabric was an important factor in increasing the temperature of the surface of the fabric. Actually, according to Ha et al. (1995b), surface temperatures have been found to be higher in cotton with better moisture regain than in polyester with poor moisture regain at T_a of 24°C, illustrating that the amount of uptake of water vapour was significantly higher in cotton. In our present study, the surface temperature was higher in A than in B, in B than in C during session I. The absolute H_{micro} at the level of chest and back was significantly the lowest in A during session I, reflecting the highest amount of moisture regain in A.

When sweat production increases with exercise, the water-drops accumulated on the fabric surface and its inside could occupy the space for absorbing moisture with the lapse of time. This could prevent the fabric from dissipating water vapour.

If the wind could partly sweep away the accumulated perspiration, the clothing would recover its ability for absorbing moisture. In our study the 1.5 $m \cdot s^{-1}$ wind is fanned the subject from the fourth period of exercise until the end of the experiment. The wind diminished H_{micro} the most in A at the level of both chest and back, indicating that the vaporization had occurred most effectively in A under the influence of wind. As the air permeability and moisture transfer were nearly identical, the highest moisture regain in A might probably have been responsible for the most reduced H_{micro} (Table 1).

Judging from temperature profiles in Fig. 4, the dry heat flow from the trunk area through the clothing to the surrounding air during sessions I and II seemed to be the greatest in A. It was also related to the highest moisture regain in A, because it has been shown that the thermal insulation becomes most reduced in A by absorbing moisture (Hall and Poltke 1956). Thus, the reduced thermal insulation might be responsible for the highest heat flow from the trunk area through clothing to air.

Pulse rate was significantly higher in C than in A and B during sessions I and II (Fig. 5). The highest T_{sk} in C was responsible for the highest pulse rate during sessions I and II at least in part (see Lotens 1993). It has been found that tympanic temperature is positively correlated with heart rate (Cabanac and Caputa 1979). Pulse rate increased gradually during session I, while it became stable during session II, suggesting that an increase of tympanic temperature might have been inhibited by fanning the face. Although tympanic temperature was not measured in our present experiment, the highest pulse rate during exercise might perhaps have reflected the highest tympanic temperature in C.

It was concluded that the hydrophilic properties of fabrics are of physiological significance for reducing heat strain during exercise and rest especially under the influence of wind.

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