Textile Research Journal Article

Thermal Comfort Properties of Wearing Caps from Various Textiles

Abstract The purpose of this research was to explore the effects of textile properties on the microclimate inside caps and on subjective wearing sensations. Physical tests on heat and moisture transfer properties of cap fabrics were conducted, as well as tests on the sensations from subjects wearing the caps. The temperature and humidity inside caps were influenced by the thickness, moisture retention properties, water absorption properties, and thermal conductivity of cap fabrics. High water absorbency property was the most important factor in lowering the temperature inside caps. Air permeability and water vapor transmission rate did not affect the microclimate. It seemed to be difficult for air or water vapors to move from the skin to the outer environment because the hair was densely packed between the skin and the cap, forming a stable air layer. Thermal sensation and thermal comfort were influenced by the thickness, water absorption properties, thermal conductivity, and Qmax of fabrics. Subjective sensations were closely related to the temperature inside caps. In the temperature range of 30 to 33°C, no change in wearing sensation was found. In the temperature range above 33°C, however, subjects started feeling uncomfortable.

Key words cap, microclimate, moisture sensation, thermal comfort, thermal sensation

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Clothing comfort can be induced by thermal, pressure-related, and tactile properties, etc. Among these factors affecting clothing comfort, the thermal factor is the most decisive one affecting the comfort level. Many researchers have conducted studies to evaluate and analyze thermal comfort. They examined the effects of the fiber type and the fabric composition on thermal comfort. The fiber composition and the fabric structure or the presence of layers were revealed to affect the heat and moisture transfer properties of textiles [1–6]. Studies on thermal comfort by wearing tests showed that fabric properties influenced the subjective wearing sensations and the microclimate inside the clothing; however, these effects varied with the environmental conditions or physical activity levels [7–12].

However, research on caps has so far been limited, especially on the wearer's perceptions of comfort and satisfaction. Researchers and manufacturers of caps have focused mainly on the protective properties or aesthetic aspects of caps, rather than on the comfort properties [13–

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Figures 1–6, 9–11 appear in color online: http://trj.sagepub.com

Table 1 Characteristics of the specimens.

	Fiber content	Weave structure	Weight (g/yd)	Thickness (mm)
SPET-A	polyester (modified cross section) : cotton : polyurethane = 76 : 21 : 3	twill	266	0.483
SPET-B	polyester (modified cross section) : polyurethane = 97 : 3	twill	290	0.516
AW	acryl : wool : polyurethane = 87 : 11 : 2	twill	323	0.762
W	wool : polyurethane = 98 : 2	twill	346	0.800
Ct	cotton : polyurethane = 97 : 3	twill	275	0.512
Bamboo	bamboo : cotton : polyurethane = 62 : 36 : 2	twill	284	0.558
Mesh_P	polyester : polyurethane = 97 : 3	tricot	237	0.912
Mesh_N	nylon : polyurethane = 84 : 16	tricot	340	0.793

15]. As a result, it has not been shown clearly to what extent the wearer's perceptions of comfort and satisfaction are influenced by textile properties or environmental conditions. Recent research on caps has been in two areas: first, subjective responses to functional hats made of ultraviolet protective fabrics and with ventilation structures; second, objective measurements of pressure distribution within a cap [16–19].

In this study we set out to elucidate the effects of textile properties on the microclimate inside caps and the consequent thermal sensations felt by the wearer. The first phase of the study was to measure the temperature and the humidity inside caps made of various textiles. The second phase was to determine the subjective thermal sensations arising from wearing the same caps. A correlation analysis was performed on the resulting data.

Experimental

Materials

Eight cap fabrics were selected from the market and tested for physical characteristics. The cap fabrics were then made up into the baseball caps in size to fit the subjects for wearing tests. All fabrics were obtained from commercial sources and made into baseball caps. Table 1 shows the characteristics of the fabrics used in this study.

Experimental procedure

Measuring the Textile Properties

The heat and moisture transfer properties of the selected fabrics were tested. Air permeability was measured according to ISO 9237. Moisture regain was measured with the oven method. Water vapor transmission rate (WVTR) was measured at 40°C, 50 % RH according to ASTM E 96 upright cup method. Water absorption was evaluated by the vertical strip method and drop spot tests. KES Thermo Labo II was employed to measure thermal conductivity and Qmax. Dry thermal resistance (Rct) was measured at 20°C, 65 % RH and evaporative resistance (Ret) was measured at 34°C, 50 % RH using sweating guarded hot plate (MTNW) according to ISO 11092.

Wearing Test

Test caps of the same size and design were produced from the selected fabrics. Six healthy and non-smoking males of 20 to 24 years old participated as subjects for the wearing tests. The subjects were selected to have similar height, weight, and head size. The physical characteristics of subjects are given in Table 2. Wearing tests were designed to simulate activity in a hot summer environment. The test protocol is shown in Table 3 and the test condition was set

Table 2 Physical characteristics of the subjects participating in the wearing test.

Subjects	Age (year)	Weight (kg)	Height (cm)	*BSA (m^2)
S1	26	69	173	1.82
S2	22	67	173	1.80
S3	20	72	174	1.86
S4	23	76	175	1.91
S5	22	67	170	1.78
S6	20	70	181	1.89

*BSA: body surface area (m^2) by Dubois equation.

Table 3 Wearing test protocol.

Time (min)	10	20	30	40	50	60	70
Procedure	rest		exercise		rest		

Table 4 Rating scales of subjective wearing sensations.

Subjective sensation	Rating	
	–5 –4 –3 –2 –1 0 1 2 3 4 5	
Thermal sensation	cold	hot
Moisture sensation	dry	wet
Thermal discomfort	comfortable	uncomfortable

to 30 ± 0.5°C, 50 ± 5 % RH. Briefly, the protocol was as follows: the subject put on a cap, entered the environmental chamber and sat on a chair for 20 minutes; he then exercised for 20 minutes and again sat for 20 minutes. In the exercise period, the subject walked up onto and down from the step box of 20 cm height repeating 20 times per minute. Every ten minutes during the whole test period, the subject was asked to vote their sensations: the thermal sensation, the moisture sensation, and the comfort sensation on a scale of (–5) to (+5) (Table 4). The microclimate inside the caps and the body temperature were also measured every 10 seconds. A sensor was attached to the face side of the cap fabric in the vertex of the head for measuring the microclimate inside the caps. Each subject completed a wearing trial without a cap and then eight trials for eight different caps in a random order. The tests were carried out at the same time of the day on different days, with at least one day of rest between the tests.

Results and Discussion

The heat and moisture transfer properties of cap fabrics

The heat and moisture transfer properties of the test caps are given in Tables 5 and 6. The data showed that water absorbency of each fabric was distinct and ranged from the

Table 5 The heat transfer properties of the cap fabrics.

Fabrics	Air permeability ($\mathrm{cm^3/cm^2/sec}$)	Thermal conductivity (10^{-4} × $\mathrm{W/cm\cdot °C}$)	Heat transfer coefficient (10^{-3} × $\mathrm{W/cm^2\cdot °C}$)	Qmax ($\mathrm{w/m^2}$)	Rct ($\mathrm{m^2\cdot °C/W}$)
SPET-A	6.43 (0.43)	3.96 (0.06)	8.20 (0.01)	0.130 (0.003)	0.0204 (0.0003)
SPET-B	5.53 (0.45)	4.02 (0.08)	7.79 (0.02)	0.135 (0.002)	0.0141 (0.0013)
AW	10.48 (0.22)	4.26 (0.03)	5.59 (0.01)	0.099 (0.003)	0.0301 (0.0005)
W	14.38 (0.19)	3.17 (0.03)	3.96 (0.00)	0.083 (0.002)	0.0301 (0.0005)
Ct	5.33 (0.39)	4.57 (0.05)	8.92 (0.01)	0.135 (0.005)	0.0146 (0.0003)
Bamboo	6.23 (0.18)	4.67 (0.12)	8.37 (0.02)	0.138 (0.001)	0.0197 (0.0004)
Mesh_P	198.00 (10.00)	3.87 (0.04)	4.24 (0.00)	0.071 (0.001)	0.0165 (0.0009)
Mesh_N	242.00 (4.00)	4.87 (0.04)	6.15 (0.00)	0.117 (0.002)	0.0148 (0.0008)

Standard deviations are shown in parentheses.

Table 6 The moisture transfer properties of the cap fabrics.

Fabrics	Moisture regain (%)	WVTR ($\mathrm{g/m^2 \cdot hr}$)	Wickability (mm)	Ret ($\mathrm{m^2 \cdot Pa/W}$)
SPET-A	1.85 (0.02)	172 (17)	110 (0)	2.0063 (0.0509)
SPET-B	0.70 (0.01)	180 (12)	145 (6)	0.7211 (0.0580)
AW	1.87 (0.01)	129 (31)	75 (0)	5.3258 (0.1387)
W	10.56 (0.08)	201 (22)	0 (0)	7.2345 (0.4323)
Ct	7.12 (0.08)	175 (12)	59 (0)	4.0629 (0.1970)
Bamboo	10.14 (0.03)	215 (23)	70 (2)	6.0118 (0.0677)
Mesh_P	0.31 (0.02)	220 (36)	95 (3)	3.1405 (0.1315)
Mesh_N	3.03 (0.01)	345 (58)	5 (0)	4.2758 (0.0261)

Standard deviations are shown in parentheses.

Table 7 The correlation coefficients among textile properties of twill fabrics.

Textile properties	Rct	Ret
Thickness	0.91*	0.59
Thermal conductivity	–0.44	–0.03
Heat transfer coefficient	–0.83*	–0.42
Qmax	–0.91*	–0.50
Air permeability	0.88*	0.54
WVTR	–0.32	0.21
Moisture regain	0.30	0.83*
Wickability	0.68	–0.87*

*$p < 0.5$.

highest wickability of 145 mm for SPET-B to the lowest of 0 mm for W. Heat transfer properties of W were the lowest, resulting in the highest insulation (Rct). WVTR and air permeability of twills were lower than those of tricots. There was no clear difference among twills in air permeability.

The dry and evaporative heat transfer properties of the selected fabrics were measured with sweating guarded hot plate. The dry heat resistance (Rct) correlated with fabric thickness, and the thermal conductivity and the evaporative resistance (Ret) with WVTR. Considering the effects of fabric structures, the properties of twill fabrics only were compared. Pearson correlation analysis was conducted to determine the relationship between the results of sweating guarded hot plate test and the other test results. The results are given in Table 7. Rct was correlated with thickness, the heat transfer coefficient, and Qmax, but not significantly with thermal conductivity. It appeared that the thermal conductivity was the inherent value regardless of the fabric thickness, but Rct, the heat transfer coefficient, and Qmax were calculated only heat transfer though fabrics and thus were affected by the thickness.

Ret measured with sweating guarded hot plate did not correspond to the WVTR measured by the upright cup method. It seemed that the air layers on either side of the fabric tested by the upright cup method provided resistance to water vapor transmission, causing small differences in WVRT between fabrics of similar structures. On the other hand, there was no air layer between the fabric and the sweating hot plate. Thus the WVTR and Ret data did not correspond to each other because the presence or absence of the air layer may have led to different water vapor pressure gradients across the fabric, which is the driving force for water vapor diffusion [20].

The coefficients of correlation between Ret and moisture regain, and between Ret and wickability were 0.83 and –0.87, respectively. Moisture regain is generally determined by the hydrophilicity, as well as microstructure of the fiber. The reason why hydrophilic fabric showed high Ret in this study was probably because the hydrophilic fabrics could absorb an amount of moisture and they did not easily emit the absorbed moisture. Furthermore, because the water vapor transmission is shown to be influenced by the fiber swelling and change of the pore area when hydrophilic fabrics absorb moisture [21, 22]. On the other hand, the wickability of fabrics and Ret had a negative relationship. As the fabrics of high wickability were made of modified polyester or treated with absorbent finish in this study, they showed high liquid absorbency and could quickly discharge the water out of the fabric.

Microclimate inside caps on wearing test

The effects of fabric properties on the microclimate inside caps made of eight different fabrics were investigated. Six subjects performed wearing tests in an environmental chamber controlled at 30°C, 50 % RH. We selected five different caps (made of SPET-B, AW, W, Mesh_P, Mesh_N) out of eight whose physical characteristics and microclimate were distinctive, and plotted the data gathered on them with no caps data (see Figures 1 and 2).

During the rest period, the temperature inside the caps, measured between the forehead and the cap, gradually increased and stabilized at the temperature 2 °C lower than the forehead skin temperature. When subjects started exercise, the temperature rapidly rose by 5 to 6 °C to close to the forehead skin temperature (see Figures 1 and 3). After the exercise, however, the temperature returned to that of the rest period. In the rest period, the microclimate inside the caps did not vary with textile properties of the different fabric types; however, it did vary in the exercise period because the subjects started sweating and the moisture transfer properties of fabric types became decisive for the thermoregulation of the body.

The lowest microclimate temperature was found in SPET, most probably because SPET absorbed sweat and dried quickly so as to dissipate the body heat quickly. The humidity data showed similar tendency as the temperature data. The humidity inside SPET caps was the lowest, followed by Mesh_N, AW, Mesh_P, and W. Thus, the microclimate in SPET caps was shown to be more comfortable than the microclimates of other caps.

Subjective wearing sensations

Figures 4, 5, and 6 illustrate the average subjective sensations of the six subjects wearing caps of five different fabrics. It can be seen that at the rest period subjects felt rather low thermal or moisture sensation and less thermal discomfort, but they began to feel high thermal or moisture sensation and more thermal discomfort during the exercise period. During the rest period, subjective sensations showed differences depending on the fabric type, but little difference was noted during the rest period. This was prob-

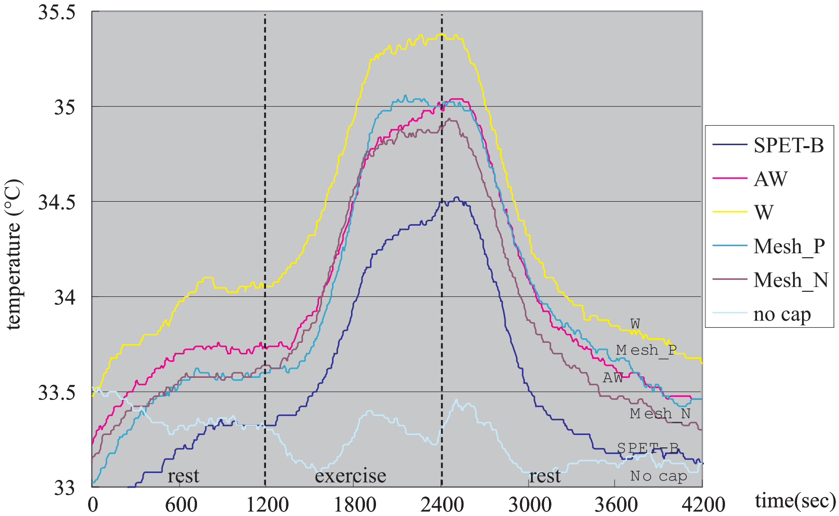


Figure 1 Microclimate temperature inside caps made of various fabrics.

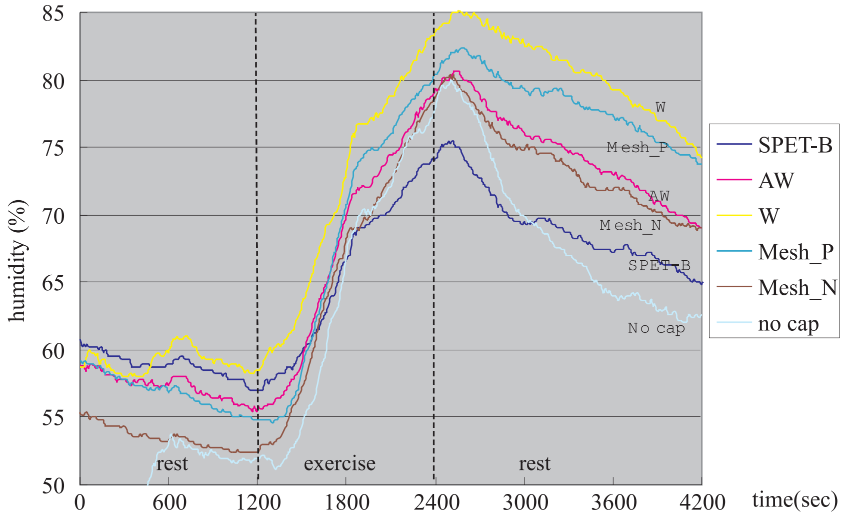


Figure 2 Microclimate humidity inside caps made of various fabrics.

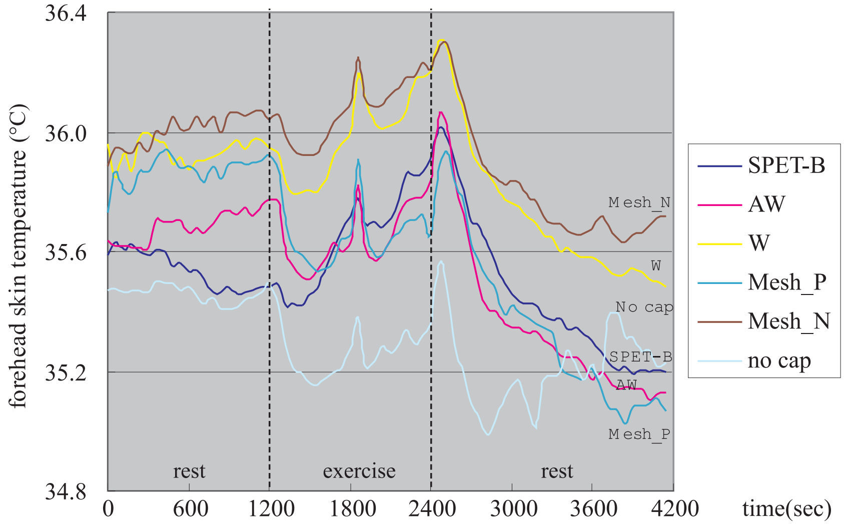


Figure 3 Forehead skin temperature inside caps made of various fabrics.

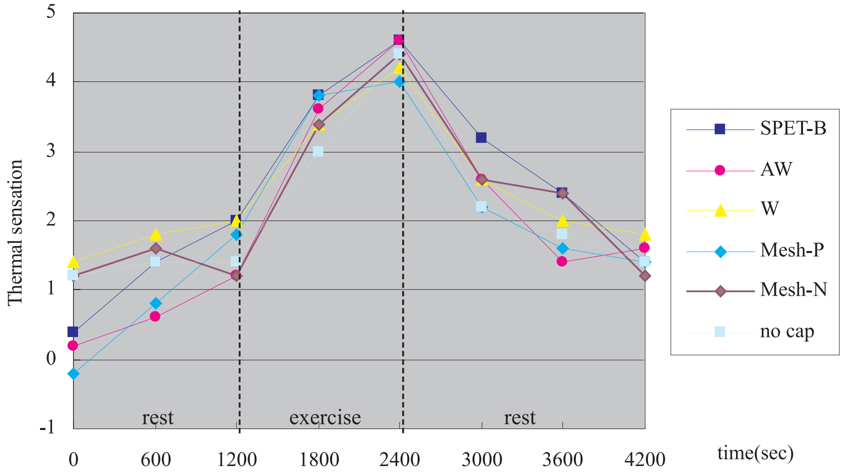


Figure 4 Subjective thermal sensation of the caps made of various fabrics.

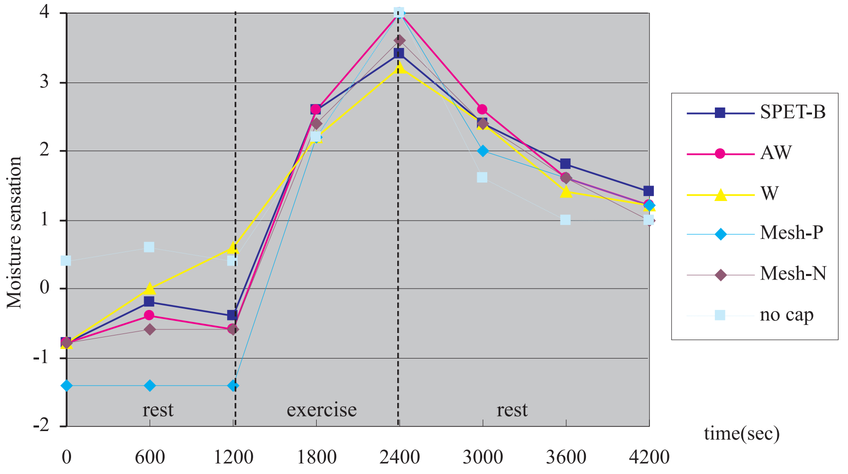


Figure 5 Subjective moisture sensation of the caps made of various fabrics.

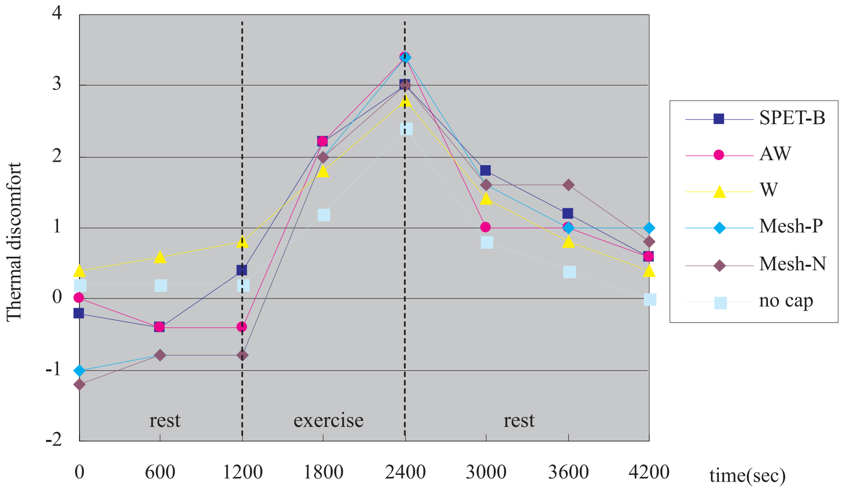


Figure 6 Subjective thermal discomfort of the caps made of various fabrics.

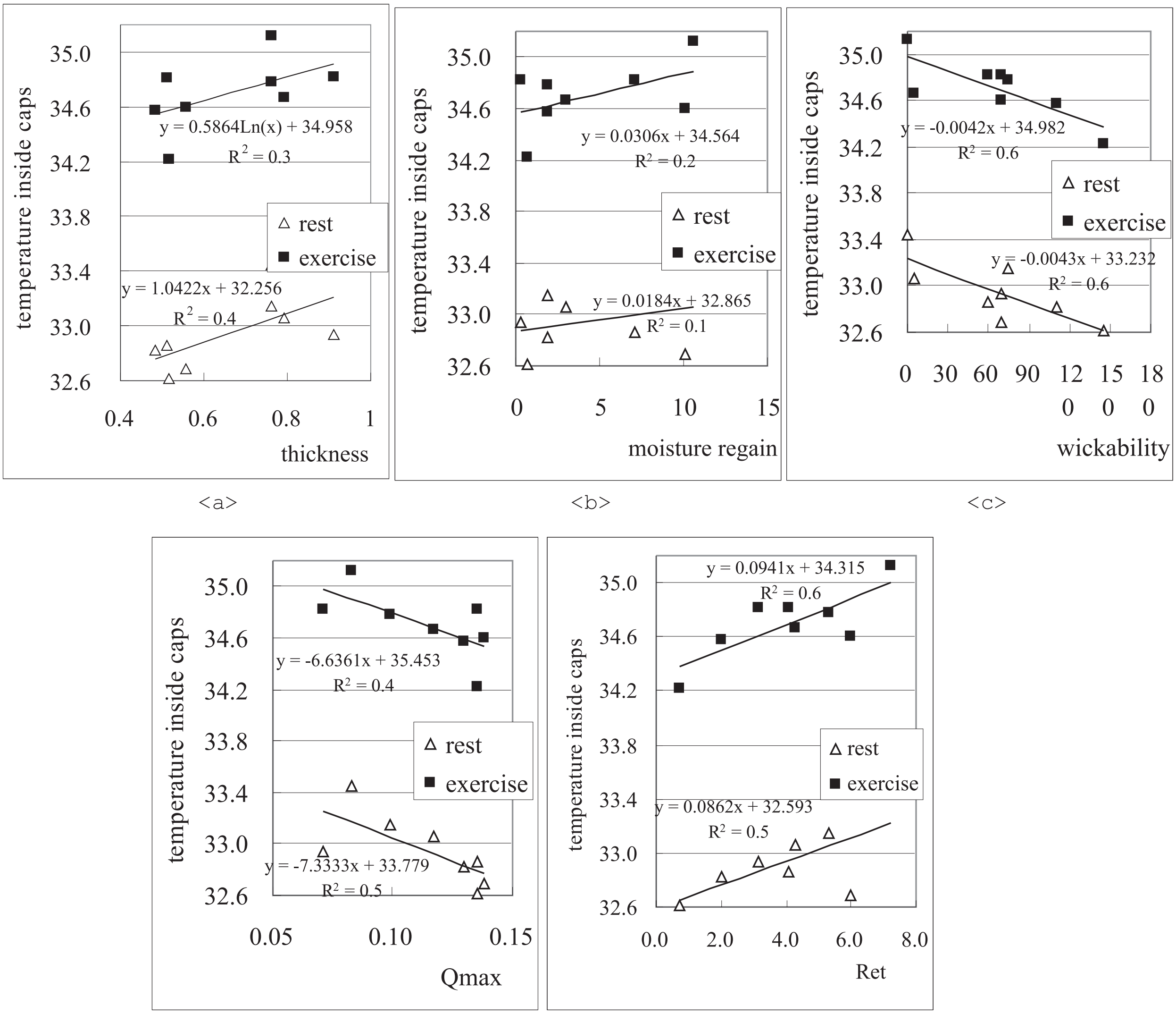
ably because the temperature inside the caps increased close to the hot skin temperature while exercising and thus all the subjects felt very uncomfortable.

It was interesting to note that thermal or moisture sensation of W was rather higher during the rest period compared with the others, but maintained lower values during the exercising period. This was probably because subjects may have felt less dampness due to the rough texture as well as the high moisture absorption of W. Plante et al. [23] found that dampness perception and fiber hygroscopicity were interrelated. Wool, which is highly hygroscopic, was perceived to be significantly drier than other weakly hygroscopic fibers.

On the other hand, SPET, Mesh_P, or Mesh_N showed lower thermal or moisture sensations for the rest period, but they exhibited rather higher thermal or moisture sensations for the exercising period. In other words, during the rest, SPET, Mesh_P, or Mesh_N was felt more comfortable, but W was less uncomfortable during the exercising.

The relationship between textile properties and microclimate inside caps

Human hair is a hydrophilic fiber with 10–15 % of moisture regain and is able to absorb water up to 45 % at 100 %



<a> <b> <c>

<d> <e>

Figure 7 Temperature inside caps versus thermal properties of fabrics. (a) Thickness; (b) moisture regain; (c) wickability; (d) Qmax; and (e) Ret of fabrics.

RH. Hair that absorbs moisture swells up to 10–15 % in width direction [24]. Therefore, the environment inside a cap is assumed a multilayered structure consisting of skin, hydrophilic fibers, and cap fabric layer. In a layered structure, higher water vapor transport results when hydrophilic fabric is exposed to lower vapor pressure and hydrophobic fabric is exposed to higher vapor pressure because moisture transfer through the layered fabric is prohibited by the fiber swelling and blocking the pores when hydrophilic fibers are placed on the surface towards the environment of high vapor pressure [21]. The clothing comfort can be affected by the moisture absorbency of fibers that directly contact the skin; the higher the moisture absorbency of the fibers next to the skin, the slower the vapor transmission of the multilayered fabric, influencing the clothing comfort [22, 25, 26]. Human hair has the capacity of absorbing a considerable amount of vaporous perspiration and once the moisture is absorbed, hair does not easily emit the absorbed moisture, but retains it. In addition, the multiple air layers formed by dense arrangement of hair in a cap may make the transport of moisture through the cap fabrics difficult.

Figures 7 and 8 show the relationship between textile properties and microclimate inside caps. During the resting period, the microclimate inside caps was affected by thickness and Qmax of fabrics. During the resting period, only insensible perspiration was continuously generated from the body surface and no clear differences were found in the humidity inside caps. During the exercising period, fabric thickness, moisture regain, wickability, and Qmax of fabrics were shown to have an effect on the microclimate inside caps. The microclimate temperature and humidity were high when the fabric was thicker and had higher moisture regain. The textile properties to transport liquid moisture from the body to the environment were crucial to the microclimate inside caps because heavy sensible perspiration during exercise was generated by activity. As the high liquid-absorbent fabrics were made of modified polyester or treated with absorbent finish in this study, they showed high absorbency and could quickly discharge the sweat out of the fabric. Thus, wickability was very important to the microclimate inside caps. As far as vapor absorbancy is concerned, hygroscopic fabrics such as wool absorb significantly more sweat and remove more moisture from the microclimate than fabrics of low hygroscopicity during exercise [27, 28]. In this study, however, the moisture buffering effect of hygroscopic fabric was not clearly shown. It seemed that the liquid moisture managing ability of fabric was a more affecting factor controlling microclimate during heavy perspiration situation than the vapor moisture management ability of fabric and highly hygroscopic human hair already influenced the microclimate humidity inside caps.

Unlike other garments, air permeability and WVTR did not greatly influence the temperature and humidity inside caps, presumably due to the influence of hair. Hair with high moisture regain greatly absorbs perspiration and holds the absorbed perspiration without discharging it. The hair in the space between the skin and the cap was densely arranged, forming a dead air layer and made it difficult for the air or the moisture to be transported. However, hair surface has water repellency, so as for liquid transport, it can move between the hair fast, directly transferred to the cap via the contact regions like the forehead. Therefore, it was thought that absorption and dryness of the cap fabrics most significantly influenced the climate inside caps.

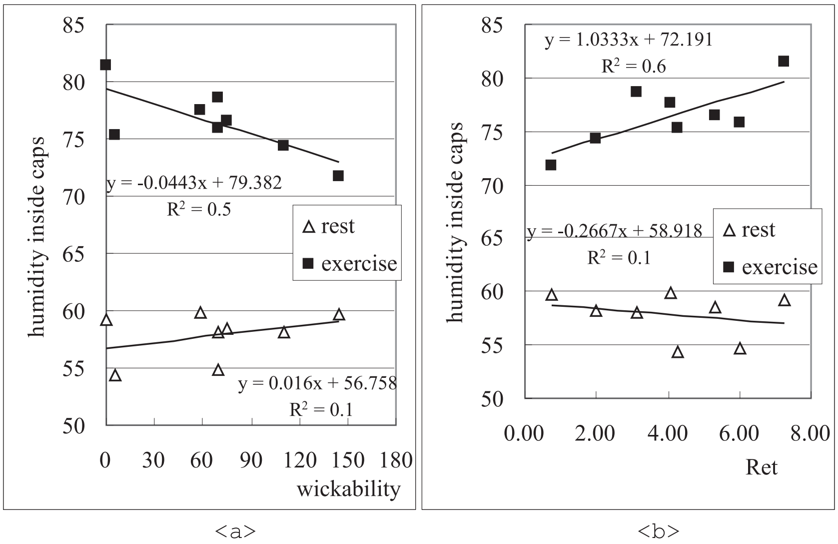


Figure 8 Humidity inside caps versus moisture properties of fabrics. (a) Wickability and (b) Ret of fabrics.

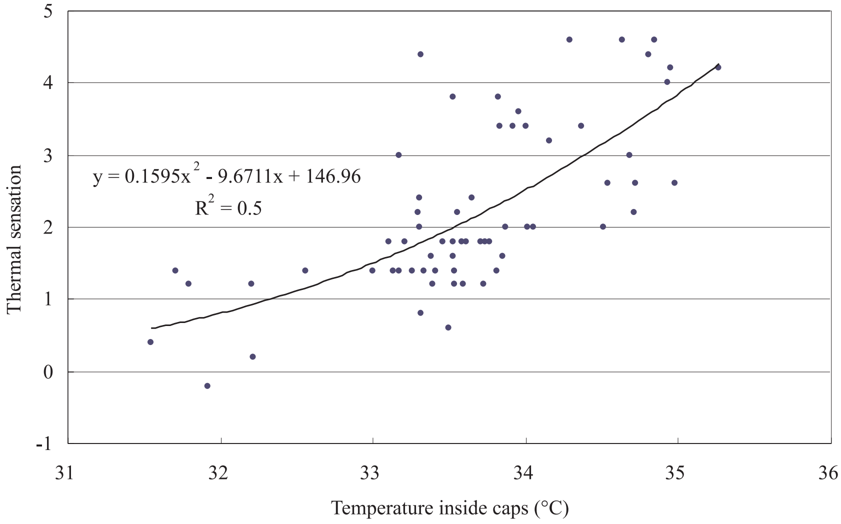


Figure 9 The relationship between subjective thermal sensation and temperature inside caps.

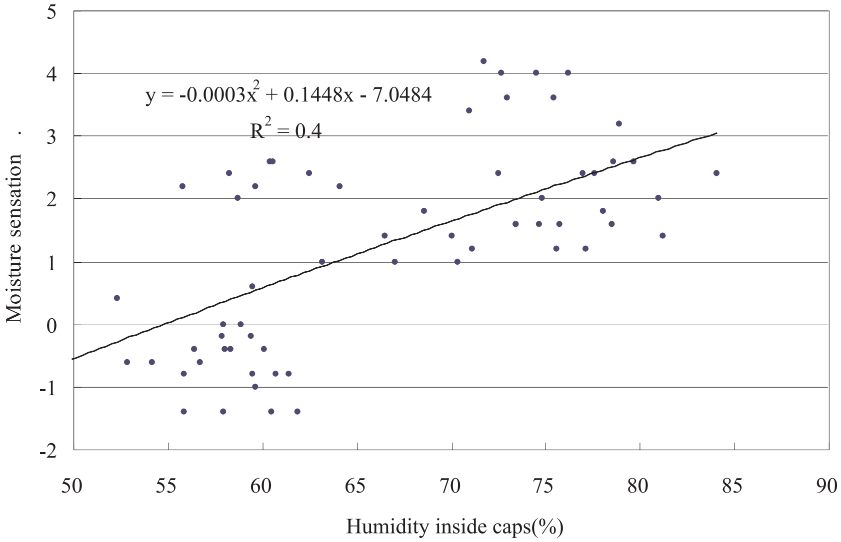


Figure 10 The relationship between moisture sensation and humidity inside caps.

The relationship between subjective sensations and microclimate inside caps

Figures 9, 10, and 11 show the relationship between the subjective sensations and the microclimates inside the caps. The thermal sensation and the thermal discomfort increased in proportion to the temperature inside the caps. In the temperature range of 30 to 33°C, there was no difference in thermal sensations. However, in the temperature range above 33°C, thermal sensations started to rise. The moisture sensation increased along with increasing humidity, but it was also dependent on the fabric type. This could be explained by the differences in the moisture regain and surface characteristics of textiles that affect the wet feeling [23]. It is known that the roughness of the fabric surface reduces wet and sticky feelings. Thermal discomfort showed a similar tendency as the thermal sensations, with the uncomfortable feeling rapidly increasing over 33°C. Thermal discomfort continued until a wearer felt "slightly warm", but uncomfortable feeling started after that.

Conclusions

The purpose of this study was to analyze the relationship between the fabric properties and the thermal comfort of wearing caps. The microclimates inside caps showed the obvious differences according to the textile properties during the exercise period, when wearers started sweating. The water absorbency of fabrics mostly influenced the tem-

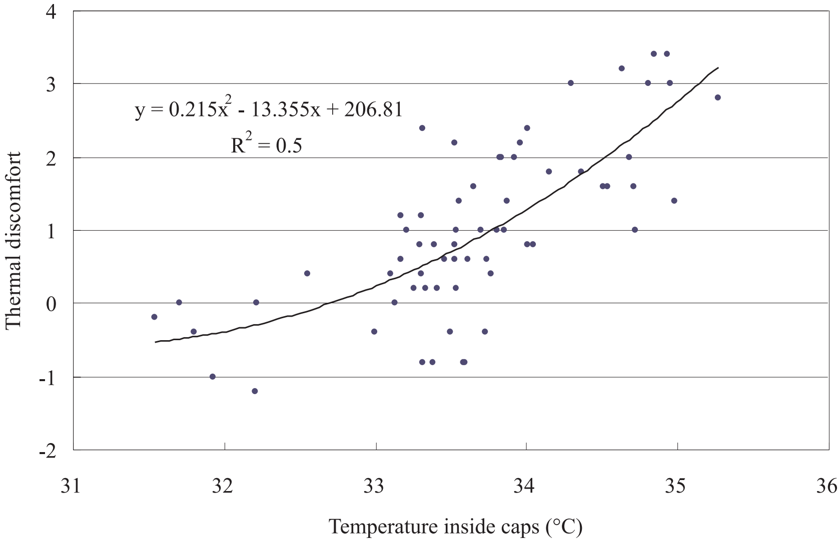


Figure 11 The relationship between thermal discomfort and temperature inside caps.

perature and humidity of the microclimates. However, air permeability and water vapor transmission did not affect the microclimate as expected. It seemed that air or water vapor could not move easily from skin to the outer environment because hair was densely arranged between the skin and the cap, resulting in a stationary air layer. Subjective sensations showed differences during the rest period, while all of the subjects felt uncomfortable during the exercise period. Thickness, water absorbency, thermal conductivity, and Qmax of the fabrics influenced thermal sensations and thermal comfort. In the temperature range of 30 to 33°C inside the caps, no change in wearing sensation was found. In the temperature range above 33°C, however, subjects started feeling uncomfortable.

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