

## Effects of Skin Surface Temperature Distribution of Thermal Manikin on Clothing Thermal Insulation

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**Abstract.** Effects of the distribution of skin surface temperature were investigated on thermal insulation of clothing for whole and each body part. The experiments were carried out with a thermal manikin in a climatic chamber. The two types of clothing ensemble were measured. The measurement with nude thermal manikin were also conducted. The three variations of skin temperature distribution were set with the thermal manikin. The values of the thermal insulation of nude skin surface ( $I_a$ ), the total thermal insulation of clothing ( $I_t$ ) and the basic thermal insulation of clothing ( $I_{cl}$ ) were measured with this thermal manikin under each skin temperature distribution. As a result, the values of  $I_a$  and  $I_t$  were not affected by skin temperature distributions of the range of typical experimental conditions. However,  $I_{cl}$  is necessary to carefully use the values of the thermal insulation of clothing for the body parts, because these values were more influenced by the skin temperature distribution than those for the whole body.

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**Keywords:** thermal manikin, clothing, skin temperature, total thermal insulation, basic thermal insulation

### Introduction

Thermal insulation of clothing affects work efficiency of workers under several environmental conditions (Fanger, 1973). Comprehensive database concerning the thermal insulation of clothing have been published by using thermal manikins (Hanada and Mihira, 1985; McCullough et al., 1985; Olesen et al., 1982; Tamura and Iwasaki, 1985, etc.). The pattern of skin surface temperature distribution, which is required for measurements, has been defined by each researcher. When a manikin has only one body part, a single value may apply to its set point of skin temperature. However, when a manikin has several body parts, the thermal

manikin may have a variety of skin temperature distributions. How the distribution of skin temperatures affects the thermal insulation of clothing has not yet been determined.

The thermal insulation of clothing is usually expressed with the unit of clo. This clo-unit was defined by Gagge et al. (1941). By this definition 1clo equals to  $0.155 \text{ m}^2\text{C/W}$  and is the amount of insulation necessary to maintain in comfort such a sitting and resting subject in a normally ventilated room with a relative humidity of less than 50 percent.

Mihira and Ohno (1977) measured the clothing insulation with a thermal manikin to keep its skin surface temperature close to that of an average nude person at the air temperature of  $20^\circ\text{C}$ .

Olesen et al. (1982) used a skin-surface-temperature controlled manikin. The skin surface temperatures were controlled automatically based on the heat loss of each body part. By using the Equations 1 and 1' (Madsen 1971) the mean skin temperature of the manikin is strongly correlated with that of a real human subject.

$$ts, n = 36.4 - 0.054Q_a \quad \dots(1)$$

$$ts, cl = 36.4 - 0.054Q_t \quad \dots(1)'$$

where,

Q<sub>a</sub>: Heat loss from the whole nude thermal manikin ( $\text{W/m}^2$ )

Q<sub>t</sub>: Heat loss from the whole dressed thermal manikin ( $\text{W/m}^2$ )

ts, cl: Mean skin temperature of the dressed thermal manikin ( $^\circ\text{C}$ )

ts, n: Mean skin temperature of the nude thermal manikin ( $^\circ\text{C}$ )

Hanada and Mihira (1985) studied with a thermal manikin. In their experiments the skin temperature of each part was equaled to that of a nude person under thermal neutrality, but the head, the hands, the feet and the joints of thermal manikin were not heated.

McCullough et al. (1985) used a thermal manikin for

their clothing studies. The temperatures of extremities were set slightly lower than those of other parts, and the mean skin temperature was at  $33.3 \pm 0.5^\circ\text{C}$ . In their studies, the air temperature was normally kept at the  $22 \pm 0.5^\circ\text{C}$  level.

Tamura and Iwasaki (1985) studied with a thermal manikin. The measuring of thermal insulation was conducted in a climatic chamber, where the air temperature was  $20^\circ\text{C}$ . The skin temperature of each part was determined based on data collected from 27 human female subjects, who were exposed to  $28^\circ\text{C}$  air temperature and 50% relative humidity.

Tanabe et al. (1994) investigated calculation methods of basic thermal insulation of clothing with a thermal manikin with a heater. The temperature of each part was controlled to a uniform temperature. The skin temperature of each part of the thermal manikin is determined based on the thermal conductivity of its shell.

In the ASTM standard it is recommended that the mean skin temperature set should be set between  $32^\circ\text{C}$  and  $35^\circ\text{C}$  and that the temperatures of the hands and the feet should be lower than those of other parts for studies in cold or moderate environment. Local deviations from the mean skin temperature must not exceed  $\pm 3^\circ\text{C}$ .

There are three types of the skin surface temperature distribution patterns for measuring the thermal insulation of clothing with a thermal manikin. Namely, 1) the same distribution pattern as that of human subjects (e.g. Mihira and Ohno, 1977; Olesen et al., 1982; Tamura and Iwasaki 1985), 2) a distribution where extremities are kept at temperatures lower than

that of other parts (e.g. ASTM standard, McCullough et al., 1985), and 3) a distribution where the skin temperatures of all body parts are kept uniform (e.g. Tanabe et al., 1994). In this study, the effects of the skin surface temperature distribution pattern were investigated on the thermal insulation of clothing for the whole body and each body part.

## Experimental Methods

### Experimental conditions

Experiments were carried out during April, 1994, in a climatic chamber at Ochanomizu University. A schematic of the climatic chamber is shown in Fig. 1. This chamber has plastic inside walls so that the wall temperature is equal to the air temperature.

### Thermal manikin

The thermal manikin was used in a standing posture. This manikin is electrically and thermally divided into 19 parts, and its posture can be changed to standing or seated position by using ball-bearing joints without changing its skin surface area. The skin temperature of each body part was controlled with electric heated wire.

Before measurements, the air temperature and the mean radiant temperature in the chamber and the skin temperatures of the thermal manikin were determined to be stable. The data samples were collected once a minute. The mean of the last five samples were used for analysis (Tanabe et al., 1994). The data from both sides of the body were almost the same, because the climate of chamber was uniform. In this study the collected data was adapted, averaged and used for analysis.

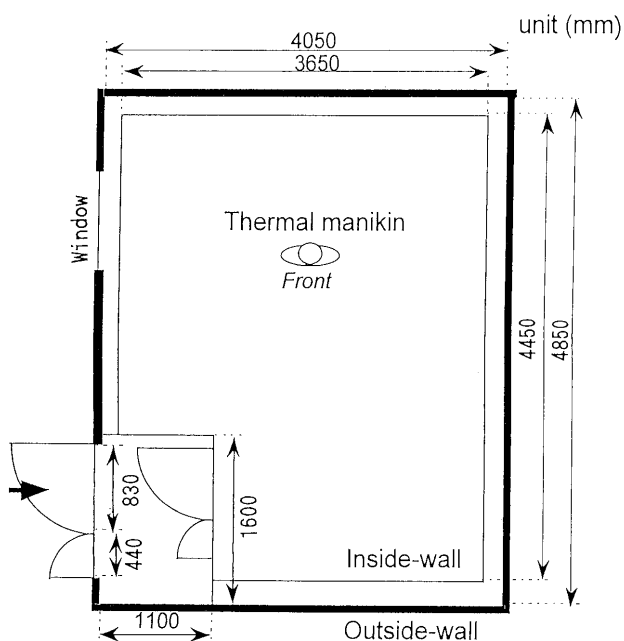


Fig. 1 Plane of the climatic chamber

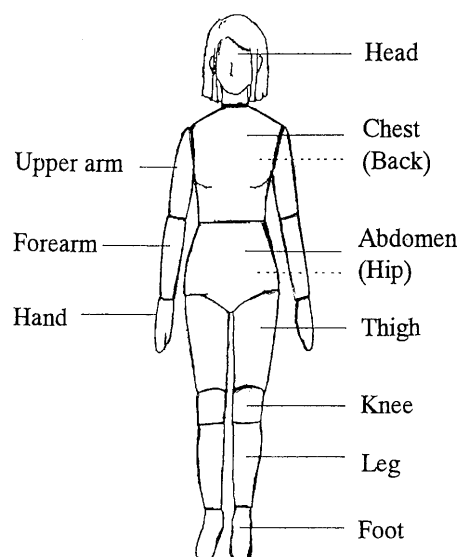


Fig. 2 Thermal manikin (Nude)

**Table 1** Experimental conditions

Air temperature = Mean radiant temperature	
Humidity	50 %r.h.
Air velocity	0.15 m/s

*Apparatus and points for measuring*

The air temperature and the skin temperatures were measured with copper-constantan thermocouples. Air velocities of the points near the manikin (the levels of the foot, the knee, and the shoulder) were measured with a climatic analyzer (B & K 1213) after the skin temperature measurements were taken and the manikin removed. This data was collected by a data logging system.

*Environmental conditions*

The air temperature was equal to the wall temperature, and the air velocity was under 0.15 m/s in the climatic chamber. The air temperature was used as the operative temperature in this report. The experimental conditions are shown in Table 1.

*The setting of the skin temperature distribution*

Case A (Tamura, 1980; Tamura and Iwasaki, 1985): Tamura et al. measured skin temperature distributions of naked persons under 28°C air temperature in a climatic chamber. The same skin temperature distribution as Tamura et al. obtained was called "Case A" in this study. All skin temperature distributions of this study were set under 28°C air temperature in a climatic chamber as the "Case A". The mean skin temperature was kept at 32.7°C. This value also meets the ASTM standard.

Lower extremities (Case B): The skin temperatures of the hands and the feet were kept lower than that of those of the others. The mean skin temperature was kept at 32.7°C, as in Case A. In the ASTM standards, it is recommended that local deviations from the mean skin temperature shall not exceed  $\pm 3^\circ\text{C}$ . The skin temperatures of the hands and the feet were 30.1°C, and those of other parts were 33.1°C. This difference of 3°C was within the range of the ASTM standards.

Non-heated head, hands and feet (Case C): The head, the hands, and the feet were not heated for Case C (Hanada and Mihira 1985). The skin surface area of the whole body was calculated from that of each body part, except non-heated parts. The skin temperatures without non-heated parts were kept at 32.7°C.

Uniform skin temperature (Case D): The skin temperature at each body part was kept at 32.7°C. The mean skin temperature was kept at 32.7°C.

Uniform heater temperature (Case E): This method is the most simple way to control the thermal manikin used in this study. The heater temperature of each body part was set to a uniform temperature of 34°C. The wire

of heating was wound inside the manikin shell, which was made of aluminum. The skin temperature of the body part was due to its heater temperature, operative temperature, thermal insulation between skin surface and environment, and thermal conductivity of manikin shell. The aluminum manikin shell was about 5 mm thin, and the thermal conductivity of aluminum is high; 203.5 W/mK at air temperature of 20°C. Therefore, the value of skin temperature was close to that of heater temperature.

**Result of Skin Temperature Distribution**

The set skin temperatures and surface area of each body part is shown in Table 2. The skin temperature of each body part was measured at an operative temperature of 28°C. The differences between the set temperature and the measured temperatures for Cases A, B, C, and D were within  $\pm 0.3^\circ\text{C}$  for all body parts.

**Thermal Insulation of Clothing***Experimental conditions*

The air velocity was less than 0.15 m/s, and the relative humidity was 50%. The air temperature was equal to the mean radiant temperature for each measurement.

Clothing ensembles for tests are shown in Table 3. The materials and the weights of each garment are shown in Table 4. In this study, when the thermal manikin was nude, the condition was simply called the "nude"; with trousers, the condition was called "trousers ensemble"; with the ski outfit, the condition was called "ski ensemble"; with winter clothing, the condition was called "winter ensemble". On each occasion, the same long-sleeve shirts, bra, and shorts were used. In the trousers and the ski ensembles, same socks were used. In the winter ensemble, only gloves and socks were removed from the ski ensemble. The winter ensemble was used to investigate effects of clothing of non-heated body parts on the whole body thermal insulation.

The skin temperature of each body part was set by controlling heater temperature under the single operative temperature of 28°C. Although the heater temperature of each body part was fixed during measurement, due to the variance caused in the operative temperature and the thermal insulation of clothing, the skin temperature distribution of each cases may be different from what was initially expected. The skin temperatures of each body part were, however, nearly the same. The reason is that the manikin-shell is made from aluminum, and its thermal conductivity is high.

The operative temperatures (14–30°C) have been set in accordance with the specified clothing conditions of the manikin.

**Table 2** Set skin temperatures and surface area of each body part (Operative temperature = 28°C)

Body parts	Surface area (m <sup>2</sup> )	(°C)			
		Case A	Case B	Case C	Case D
Whole Body	1.4454	32.7*	32.7	32.7	32.7
Head	0.1255	34.7*	33.1	–	32.7
Chest	0.1418	34.1*	33.1	32.7	32.7
Back	0.1378	33.3*	33.1	32.7	32.7
Abdomen	0.0742	33.8*	33.1	32.7	32.7
Hip	0.1267	32.2*	33.1	32.7	32.7
R. Upper arm	0.0621	32.7*	33.1	32.7	32.7
L. Upper arm	0.0599	32.7*	33.1	32.7	32.7
R. Forearm	0.0360	32.7*	33.1	32.7	32.7
L. Forearm	0.0375	32.7*	33.1	32.7	32.7
R. Hand	0.0308	33.0**	30.1	–	32.7
L. Hand	0.0280	33.0**	30.1	–	32.7
R. Thigh	0.1077	32.3*	33.1	32.7	32.7
L. Thigh	0.1123	32.3*	33.1	32.7	32.7
R. Knee	0.0225	31.5**	33.1	32.7	32.7
L. Knee	0.0227	31.5**	33.1	32.7	32.7
R. Leg	0.0954	32.0*	33.1	32.7	32.7
L. Leg	0.0971	32.0*	33.1	32.7	32.7
R. Foot	0.0629	30.7**	30.1	–	32.7
L. Foot	0.0636	30.7**	30.1	–	32.7

– shows non-heated. R=Right; L=Left.

\*based on Tamura 1980

\*\*based on Tamura and Iwasaki 1985

**Table 3** Clothing ensembles

Nude	non
Trousers ensemble	long-sleeves shirts, bra, shorts, socks
Skiwear ensemble	ski outfit, long-sleeves shirts, bra, shorts, socks, gloves
Winter ensemble	ski outfit, long-sleeves shirts, bra, shorts

**Table 4** Material and weight of garment

Garment	Material	Weight (g)
bra	nylon 100%	27.6
gloves	wool 100%	37.6
long-sleeves shirts	cotton 100%	327.7
shorts	cotton 100%	18.7
skiwear	polyester 100% (front and inside)	609.8
	nylon 100% (back)	(without a belt)
socks	cotton 100%	54.7
straight trousers	cotton 100%	504.5

#### Equations for calculation of thermal insulation

The thermal insulation of nude skin surface ( $I_a$ ), the total thermal insulation of clothing ( $I_t$ ), and the basic thermal insulation of clothing ( $I_{cl}$ ) were calculated with the following equations: The value of  $I_a/f_{cl}$  was used for calculating of  $I_{cl}$  instead of the thermal insulation of clothing outer surface (ISO 9920, Tanabe et al., 1994). Equation (5) is quoted from McCullough et al. (1985).

$$I_a = (t_s, n - t_o) / 0.155Q_a \quad \dots(2)$$

$$I_t = (t_s, cl - t_o) / 0.155Q_t \quad \dots(3)$$

$$I_{cl} = I_t - I_a' \div I_t - I_a/f_{cl} \quad \dots(4)$$

$$f_{cl} = 1 + 0.3I_{cl} \quad \dots(5)$$

where,

$I_a$ : The thermal insulation of nude skin surface per nude skin surface ( $cl_o$ )

$I_a'$ : The thermal insulation of the clothing outer

surface per the clothing outer surface (clo)  
 Icl: The basic thermal insulation of clothing (clo)  
 It: The total thermal insulation of clothing, between skin surface and environment (clo)  
 fcl: Clothing area factor, clothing outer surface per nude skin surface (-)  
 to: Operative temperature (°C)

The thermal insulation of the skin surface of each nude part of the body (Iai) and the total thermal insulation of clothing for each body part (Iti) were calculated by using the following equations:

$$Iai = (tsi, n - to) / 0.155Qai \quad \dots(6)$$

$$Iti = (tsi, cl - to) / 0.155Qti \quad \dots(7)$$

where,

Iai: The thermal insulation of nude skin surface of each body part (clo)  
 Iti: The total thermal insulation of clothing of each body part (clo)  
 Qai: Heat loss from each nude body part (W/m<sup>2</sup>)  
 Qti: Heat loss from each body part with cloth (W/m<sup>2</sup>)  
 tsi, cl: The skin temperature of each body part in cloth (°C)  
 tsi, n: The skin temperature of each nude body part (°C)

## Results of the Experiment

### *Skin temperature and heat loss*

As described below, Mihira and Hanada (1991) proposed the relationships between the operative

temperature and the heat loss of the thermal manikin, and between the operative temperature and the skin temperature in a specific range of the operative temperature.

$$Qa = a \times to + b \quad \dots(8)$$

$$Qt = a \times to + b \quad \dots(8)'$$

$$ts, n = c \times to + d \quad \dots(9)$$

$$ts, cl = c \times to + d \quad \dots(9)'$$

where,

a: a slope of a linear equation (W/m<sup>2</sup>°C)  
 b: a y-cutting point of a linear equation (W/m<sup>2</sup>)  
 c: a slope of a linear equation (-)  
 d: a y-cutting point of a linear equation (°C)

The slopes, y-cutting points and r<sup>2</sup>-value of linear equations are shown in Table 5 for heat loss and skin temperature against the operative temperature. The statistical value of r<sup>2</sup> was almost unity, and these relationships were linear.

The operative temperatures for all the experimental conditions, which were the combination of the clothing and the cases, were calculated with Equations (8), (8') and Table 5, when Qa or Qt equals to 44.2 watt per square meter. The mean skin temperatures were calculated at these operative temperatures with Equations (9), (9') and Table 5. The values of the operative and the mean skin temperatures were used for calculation of Icl (Tanabe et al., 1994).

### *Thermal insulation of the nude skin surface (Ia)*

The thermal insulation of nude skin surface (Ia) and the total thermal insulation of clothing (It) are shown

**Table 5** Coefficients of linear equations for heat loss and skin temperature

		Q (W/m <sup>2</sup> )			ts (°C)		
		a	b	r <sup>2</sup>	a	b	r <sup>2</sup>
Nude	Case A	-9.4	307.4	1.000	0.06	31.1	0.998
	Case B	-9.3	306.1	0.999	0.06	31.0	0.997
	Case C	-9.6	315.7	1.000	0.06	31.0	0.996
	Case D	-9.4	308.1	0.999	0.06	31.0	1.000
	Case E	-9.4	318.1	1.000	0.06	32.0	0.993
Trousers ensemble	Case A	-5.2	169.9	1.000	0.04	31.9	0.996
	Case B	-5.0	164.9	0.997	0.05	31.5	0.972
	Case C	-4.1	139.9	0.995	0.03	32.0	0.911
	Case D	-4.8	162.5	0.998	0.04	31.8	0.978
	Case E	-5.0	171.2	0.999	0.04	32.8	0.765
Ski ensemble	Case A	-3.2	107.0	0.999	0.03	32.4	0.880
	Case B	-3.4	107.7	1.000	0.02	32.4	0.822
	Case C	-2.5	80.9	1.000	0.01	32.7	0.985
	Case D	-3.3	108.1	1.000	0.02	32.3	0.943
	Case E	-3.3	111.4	0.999	0.02	33.6	0.852
Winter ensemble	Case C	-2.3	78.9	0.997	0.01	32.7	0.854
	Case D	-3.7	119.9	0.999	0.03	32.2	0.851

with standard deviations in Table 6. The values of  $I_a$  and  $I_t$  were the average of the output of each experiment. Each standard deviation was within 1 to 3% of the mean, which was small enough to ignore. Therefore, it was found that the difference in the operative temperature did not affect the thermal insulation of the nude skin surface ( $I_a$ ) and the total thermal insulation of clothing ( $I_t$ ) for the whole body in the range of the operative temperatures of this study.

Although the value of  $I_a$  for Case C was the smallest in the five cases, the range was narrow: 0.64 to 0.67 clo. The effect of the skin temperature distribution on the value of  $I_a$  for the whole body was relatively small. The thermal insulation of the nude skin surface of each body part was shown in Fig. 3.

#### Total thermal insulation of clothing

The measured total thermal insulation values of trousers ensemble ( $I_t$ ) by different cases were between 1.21 and 1.34 clo. The largest value of  $I_t$  was observed at Case C, and the smallest value of  $I_t$  at Cases D and E. The value of each body part of  $I_{ti}$  was shown in Fig. 4. In this ensemble the head and the hands were not clothed,

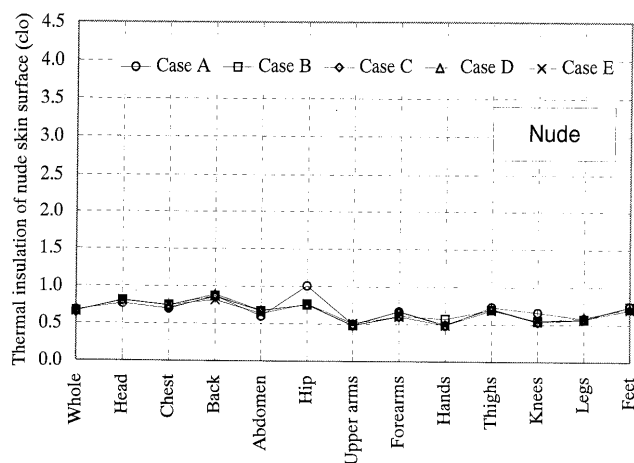
and the feet were clothed only with socks. For that reason, the values of  $I_{ti}$  of these parts were smaller than those of others. The  $I_t$  value of the whole body for Case C was the biggest among all distributions, because the values of  $I_{ti}$  of the head, the hands and the feet were excepted from the value of  $I_t$  of the whole body.

The measured total thermal insulation values of the ski ensemble ( $I_t$ ) by different cases were between 1.95 and 2.49 clo. The largest value of  $I_t$  was observed at Case C, and the smallest value of  $I_t$ , at Cases A and E. The value of each body part of  $I_{ti}$  was shown in Fig. 5. In this ensemble the head was not clothed, but the hands were clothed with gloves only, and the feet with socks only. Therefore, the values of  $I_{ti}$  of these parts were smaller than those of others. The value of  $I_t$  of whole body for Case C was the largest among all distributions, because the values of  $I_{ti}$  of the head, the hands and the feet were excepted from the value of  $I_t$  of the whole body.

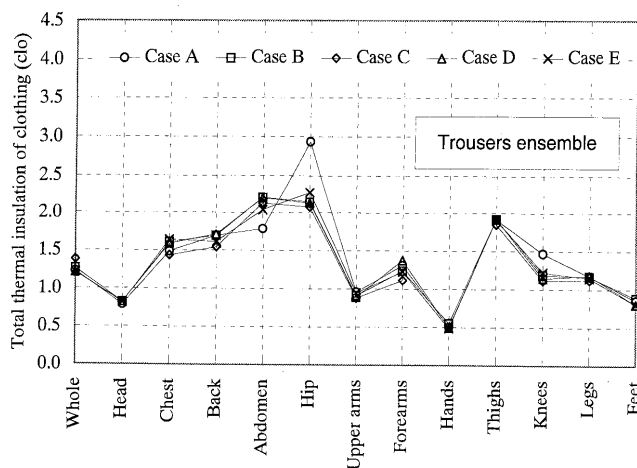
The measured total thermal insulation values of the winter ensemble ( $I_t$ ) by different cases were between 2.43 clo for Case C, and 1.78 clo for Case D. The difference between those values of  $I_t$  was 0.65 clo. The value of each body part of  $I_{ti}$  was shown in Fig. 6. In this

**Table 6** Thermal insulation of nude skin surface and total thermal insulation of clothing

mean $\pm$ s.d.		Case A		case B		Case C		Case D		Case E	
		(clo)	(m <sup>2</sup> K/W)	(clo)	(m <sup>2</sup> K/W)	(clo)	(m <sup>2</sup> K/W)	(clo)	(m <sup>2</sup> K/W)	(clo)	(m <sup>2</sup> K/W)
Nude	$I_a$	0.67 $\pm$ 0.01	0.104	0.66 $\pm$ 0.01	0.102	0.64 $\pm$ 0.01	0.099	0.67 $\pm$ 0.01	0.104	0.66 $\pm$ 0.00	0.102
Trousers ensemble	$I_t$	1.22 $\pm$ 0.01	0.189	1.26 $\pm$ 0.02	0.195	1.34 $\pm$ 0.04	0.208	1.21 $\pm$ 0.02	0.188	1.21 $\pm$ 0.01	0.188
Ski ensemble		1.95 $\pm$ 0.00	0.302	2.02 $\pm$ 0.02	0.313	2.49 $\pm$ 0.01	0.386	1.96 $\pm$ 0.01	0.304	1.95 $\pm$ 0.01	0.302
Winter ensemble						2.43 $\pm$ 0.03	0.377	1.78 $\pm$ 0.02	0.276		



**Fig. 3** Insulation of skin surface at each body part (Nude)



**Fig. 4** Total thermal insulation of clothing at each body part (Trousers ensemble)

ensemble the head, the hands, and the feet were not clothed. For that reason, the values of  $I_{ti}$  of these parts were smaller than those of others. The value of  $I_{ti}$  of whole body for Case C was the largest among all distributions, because the values of  $I_{ti}$  of the head, the hands and the feet were excepted from the value of  $I_{ti}$  of the whole body, as well as for the trousers and the ski ensembles.

#### Basic thermal insulation of clothing ( $I_{cl}$ )

Basic thermal insulation of clothing ( $I_{cl}$ ) is shown in Table 7. In the trousers ensemble, the values of  $I_{cl}$  were 0.66 clo for Case A, 0.72 clo for Case B, 0.85 clo for Case C, 0.63 clo for Case D, and 0.65 clo for Case E. The largest value of  $I_{cl}$  was for Case C and the smallest one of  $I_{cl}$  was for Case D. The difference between the largest value and the smallest one of  $I_{cl}$  was 0.22 clo.

In the ski ensemble, the values of  $I_{cl}$  were 1.48 clo for Case A, 1.57 clo for Case B, 2.70 clo for Case C, 1.49 clo for Case D, and 1.50 clo for Case E. The largest value of  $I_{cl}$  was for Case C, and the smallest value of  $I_{cl}$  was for Case A. The difference between the largest value and the smallest one of  $I_{cl}$  was 0.59 clo.

In the winter ensemble, the values of  $I_{cl}$  were 2.06 clo for Case C and 1.30 clo for Case D. The difference between these values of  $I_{cl}$  was 0.76 clo.

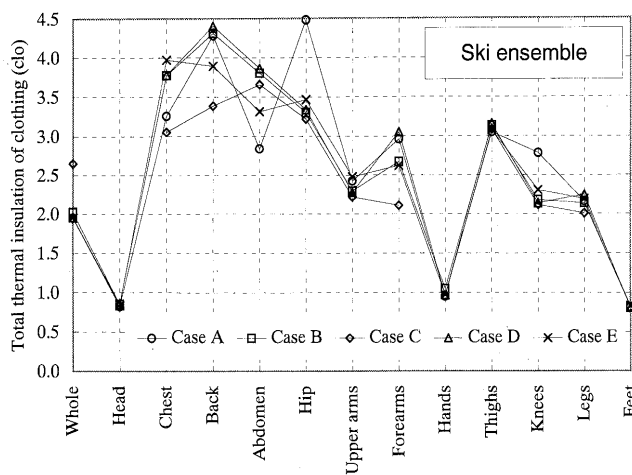


Fig. 5 Total thermal insulation of clothing at each body part (Ski ensemble)

## Discussion

#### The thermal insulation of clothing outer surface

The thermal insulation of nude skin surface ( $I_a$ ) and the total thermal insulation of clothing ( $I_t$ ) were calculated with equations (2) and (3) under the several conditions of the operative temperature. The thermal insulation of clothing outer surface is mainly affected by the temperature difference between the surface and the environment under natural convection. However, the values of  $I_a$  and  $I_t$  were not affected by the temperature differences between the skin and the environment (see the standard deviation in Table 6). Moreover, the mean skin temperature of the nude manikin was close to the temperature of outer clothing surface in this report. In practice, therefore, it seems to be reasonable to use the thermal insulation of skin surface instead of the thermal insulation of clothing outer surface for calculation of the basic thermal insulation of clothing ( $I_{cl}$ ).

#### Measurement of thermal insulation for case C

In the ski ensemble, gloves and socks were added to the winter ensemble. The added insulation of gloves and socks was calculated, which was the difference between the insulation of the ski ensemble and insulation of the

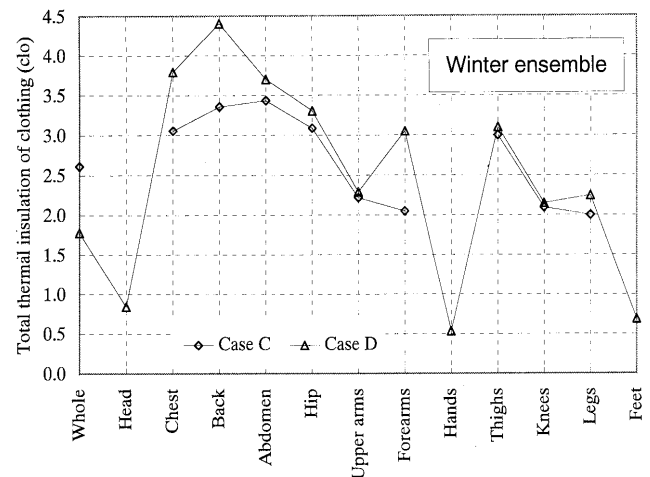


Fig. 6 Total thermal insulation of clothing at each body part (Winter ensemble)

Table 7 Basic thermal insulation

$I_{cl}$	Case A		Case B		Case C		Case D		Case E	
	(clo)	( $m^2K/W$ )	(clo)	( $m^2K/W$ )	(clo)	( $m^2K/W$ )	(clo)	( $m^2K/W$ )	(clo)	( $m^2K/W$ )
Trousers ensemble	0.66	0.102	0.72	0.112	0.85	0.132	0.63	0.098	0.65	0.101
Ski ensemble	1.48	0.229	1.57	0.243	2.07	0.321	1.49	0.231	1.50	0.233
Winter ensemble					2.06	0.319	1.30	0.202		

winter ensemble under each skin temperature distribution. That value of  $I_t$  for Case C was 0.06 clo, and for Case D was 0.18 clo. That value of  $I_{cl}$  for Case C was 0.01 clo, and for Case D was 0.19 clo.

The total thermal insulation of clothing for the whole body was affected by the thickness of air layer between the skin surface and the outer surface of clothing (Iwasaki et al., 1987). In the ski ensemble the air layer of other garments was not affected by gloves and socks in this study; therefore, the values of  $I_t$  and  $I_{cl}$  of the ski ensemble must be more than those of the winter ensemble. Nevertheless, the thermal insulation values of the ski ensemble and the winter ensemble for Case C were almost the same. It was found that the values of  $I_{ti}$  of non-heated parts covered with clothing were under estimated for Case C.

#### *Effects of the mean skin temperature on thermal insulation*

The skin temperature distributions were almost uniform in Cases D and E. For Cases D and E, therefore, the effect of the mean skin temperature on thermal insulation was examined. The mean skin temperature was 32.7°C for Case D and 33.7°C for Case E. The difference between those temperature was 1.0°C. The value of  $I_a$  for Cases D and E were almost equal, and the value of  $I_t$  for Cases D and E was also almost equal. It was found that the difference of 1.0°C did not affect significantly the thermal insulation values for the whole body under Cases D and E.

#### *Measurement of the total thermal insulation of clothing of whole body*

The concept of thermal resistance is derived from Newton's Law of Cooling, which states that the heat loss from human body is in proportion to the temperature difference between the skin and the environment.

When one body part can have homogeneous skin temperature and thermal resistance, the following equation is used:

$$Q_{ti} = (t_{si} - t_o) / R_{ti} \quad \dots(10)$$

where,

$R_{ti}$ : The thermal resistance of clothing of each body part ( $m^2 \cdot C/W$ )

$Q_{ti}$ : Heat loss from one body part ( $W/m^2$ )

$t_{si}$ : Skin temperature of one body part ( $^{\circ}C$ )

The total heat loss is shown as follows:

$$Q_t = \sum \{A_i (t_{si} - t_o) / R_{ti} / A\} \quad \dots(11)$$

where,

A: Area of the whole body ( $m^2$ )

$A_i$ : Area of each body part ( $m^2$ )

One of the following two conditions have to be fulfilled in order to decide the total thermal insulation of a whole body:

Condition I:

When  $R_{ti}$  is uniform in each part, the equation (11) should be modified as follows:

$$Q_t = (1 / R) \sum \{A_i (t_{si} - t_o) / A\} \quad \dots(11')$$

where,

R: The total thermal insulation of clothing of a whole body, when the values of the  $R_{ti}$  of all body parts are uniform ( $m^2 \cdot C/W$ )

To be exact, the total thermal insulation of clothing of the whole body is defined as R in the equation (11').

Condition II:

When the skin temperature of each part of a body is uniform, the equation (11) should be modified as follows:

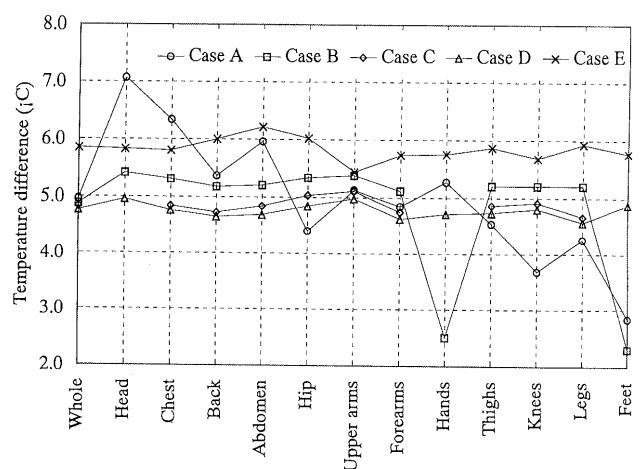
$$Q_t = (t_{si} - t_o) \sum \{A_i / A / R_i\} \quad \dots(11'')$$

To be exact, the total thermal insulation of clothing of the whole body can be obtained by using this equation.

When measured with the manikin, as indicated in the Fig. 7, the uniform control of the skin temperature of each body part in the nude condition cannot unify the thermal insulation of each body part.

In order to unify the thermal insulation of all body parts, minor adjustments of skin temperatures by part were required, which is considered very troublesome.

It is possible to control to unify the skin temperatures of the whole body of the manikin when it is nude. However, when it is dressed, distribution of temperatures within one body part should be observed because of various covering conditions. Therefore, it is



**Fig. 7** The difference between skin and operative temperature ( $t_{si} - t_o$ ) at each body part (Nude). Operative temperature under each case was almost 28°C



difficult to accurately set uniform skin temperature of the whole body when it is dressed.

Consequently, it is extremely difficult to obtain an exact value of the thermal insulation of clothing of the whole body when dressed. Our research follows previous research and defines the total thermal insulation of the whole body as the thermal insulation calculated from the heat loss from the whole body and the mean skin temperature.

#### *Setting of skin temperature distribution*

It was difficult to precisely measure the thermal insulation of clothing with Case C. In other distribution cases values of  $I_{cl}$  were almost the same.

When all conditions were the same, except for skin temperature, the thermal insulation of clothing of each body part must be larger at its lower skin temperature. Therefore, when the thermal insulation of each body part is described, the skin temperature distribution and the environmental condition must be clearly shown with that insulation value.

### Conclusions

Five variations of skin temperature distribution were tested with a thermal manikin. The values of  $I_a$ ,  $I_t$  and  $I_{cl}$  were measured with this thermal manikin under each skin temperature distribution. These values were compared and examined.

- 1) The total thermal insulation of nude skin surface ( $I_a$ ) were not affected by skin temperature distributions in this study.
- 2) It was difficult to measure precisely the thermal insulation of clothing for Case C.
- 3) In Cases A, B, D and E the values of the thermal insulation of clothing of the whole body were almost equal. The values of  $I_t$  and  $I_{cl}$  were also able to be precisely measured with Case E, which is simply set for the thermal manikin of this study.
- 4) It is necessary to carefully use the values of  $I_{ai}$  and  $I_{ti}$  of the body parts, because these values were more influenced by the skin temperature distribution than the values of  $I_a$  and  $I_t$  of the whole body.
- 5) It was found that the actual values of the total thermal insulation of clothing included the minor differences derived from the distribution of the total thermal insulation of body parts.

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