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Layering Effects on Clothing Microclimate, Clothing Insulation and Physiological Responses

This study investigated the relationship of clothing microclimate and physiological responses in order to examine the layering effects on the clothing microclimate as an index to predict clothing thermal insulation (I_{cl}). Experiments were conducted in a 15°C environment on six physically active males. Increased clothing layers resulted in higher mean temperature inside the clothing ($\overline{T}_{cl}$) and I_{cl}. The I_{cl} had a high correlation with: $\overline{T}_{cl}$ ($r = 0.556$), the difference between the innermost surface temperature and the outermost surface temperature at the chest (DST) ($r = 0.549$) and the temperature inside clothing at the abdomen ($r = 0.478$). $\overline{T}_{cl}$ had the highest correlation with the temperature inside clothing at the abdomen ($r = 0.889$). $\overline{T}_{cl}$ also had the highest correlation with $\overline{T}_{sk}$ ($r = 0.860$). The results showed that the relationship between I_{cl} and $\overline{T}_{cl}$ was linear ($p < .01$). Thermal comfort had a negative correlation with $T_{cl\text{-}thigh}$ ($r=-0.411$) and $\overline{T}_{cl}$ ($r = -0.323$) ($p < .01$.)

Clothing represents the nearest thermal environment for humans; subsequently, a significant knowledge of clothing thermal insulation is required due to the functional role of clothing to maintain an acceptable physiological thermal state. Human subjects, thermal manikins and employment of an index-based conversion method are used to measure the thermal insulation offered by clothing. The human subject method provides realistic results. However, a thermal manikin method has been proposed as an alternative to the human subject method due to the numerous individual differences and complicated time-consuming experimentation process requirements. The thermal manikin method has excellent reproducibility (Anttonen *et al.*, 2004; Holmer & Nilsson, 1995) and many studies employ thermal manikins to predict clothing thermal insulation using moisture vapour resistance (ISO 9920, 1995; Lotens & Havenith, 1991; Qian & Fan, 2006). However, thermal manikins are designed and made by different companies that use of different construction materials as well very in shape, structure and number of segments (Konarska *et al.*, 2006; Kuklane *et al.*,2004). Thermal manikins are also very expensive and not identical to human physiology. Clothing weight or the number of clothing layers (one of the conversion index methods) is used (McCullough *et al.*, 1985; Yaglou & Drinker, 1928) since the measurement is simple and numerous clothing items can be measured simultaneously (Cena & Clark, 1978). Clothing weight is an important factor in the clothing thermal insulation index (McCullough *et al.*, 1985); however, clothing weight has demerits because it requires periodical correction according to changes in fabrics and fashion (McCullough *et al.*, 1983).

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These circumstances facilitate the necessity to find another index that can predict clothing thermal insulation from the human wear test method. Clothing microclimate is the microclimate established between the human body and clothing. This microclimate is affected by human factors (sex, age, and body fat), clothing factors (fabric properties, fit, proportion of the covered body, and wearing methods) and environmental factors (temperature, humidity, and air velocity) (Cena & Clark, 1978). It is also a positive indicator of the thermal load (Cortili *et al.*, 1996). Clothing thermal insulation affects the clothing microclimate control function (Newburgh, 1968; Kwon & Choi, 2013); consequently, it is necessary to examine the clothing microclimate as an index to predict clothing thermal insulation. Considerable work has been conducted on how to predict the thermal insulation of clothing and about comfortable clothing microclimates (Humphreys, 1977); however, there have been limited human subject studies on the relationship of clothing thermal insulation and clothing microclimate in a cool environment.

It is important to study the effect of the outdoor environment on the human body; in addition, it is necessary to examine the clothing microclimate range when the thermal environment is variously controlled using clothing as well as the relationship of clothing microclimate and clothing thermal insulation on physiological responses. Other clothing studies have examined the relationship of temperature inside clothing and clothing thermal insulation; subsequently, fabric, garment design and fit have been proven to influence clothing thermal insulation (McCullough *et al.*, 1983; Park & Choi, 2008).

This study reports the results of excluding fabrics and design effects. We address the issue of how an increase of temperature inside clothing (due to increased layers of clothing) influences physiological responses when only clothing layers increase without effects of fabrics and design and if clothing thermal insulation can be predicted with a clothing microclimate in a controlled fabric conditions.

METHODS

Participants

Six physically-active males (age 22±2 yr, height 177±3 cm, body mass 66±7 kg, body surface area 1.82±0.1 m^2) participated in trials. Body surface area was calculated using the Dubois and Dubois formula (1916). All participants provided prior informed consent. Trials were conducted for one hour on separate days at identical times to exclude a circadian rhythms effect and the order of the three experiments was determined randomly. Participants were instructed on how to rate their thermal sensations and if each thermal stimulus was comfortable.

Experimental Clothing

Clothing microclimate and physiological responses were investigated with one to three layers of upper and lower clothing that had the same material and design. Experimental clothing consisted of upper and lower training wear (PET 100%) comprised of single-layered (SL), double-layered (DL) and triple-layered (TL) clothing of different sizes (Table 1). Each subject wore the right size clothing as SL and then the next size-up (DL and TL) clothing were added. Each participant wore the same socks, underpants and footwear; subsequently, tests were conducted on two of each ensemble.

Experimental Protocol

Participants did not intake food or drink two hours before the experiment. Each participant rested in the

Table 1. *Experimental Clothing*

	SL	DL	TL
Fabric	Polyester 100%	Polyester 100%	Polyester 100%
Type	A layer of training wear	Two layers of training wear	Three layers of training wear
Weight (g/m^2)	310 ± 15	630 ± 27	950 ± 44

anteroom (21±0.5°C, 40±5%RH) for 20 minutes and then entered the climatic chamber after being equipped with test instruments and dressed. Subjects were placed in the chair after the attachment of the measurement equipment (which took 15 minutes) and the initial measurements were made after 20 min of rest. They remained sitting on a chair throughout all tests.

Physiological tests were performed in a climatic chamber that controlled for temperature, relative humidity and a wind velocity of 15°C, 58%RH and 0.1m/s, respectively. The 15°C was established through pre-tests conducted to identify air temperature where people could feel 'a little cool' to 'a little warm' under the conditions of different clothing layers. Random tests were performed on two different days.

Measures

Skin temperature was measured at seven sites with uncovered thermistors (K923, Takara Inc., Japan); in addition, rectal temperature (T_r) was measured using a flexible rubber-covered thermistor inserted approximately 15 cm into the anal sphincter. The temperature inside clothing at six sites (chest, abdomen, arm, thigh, leg and foot), humidity inside clothing at two sites (chest and thigh), innermost surface temperature (IST) and outermost surface temperature (OST) at the chest as clothing microclimate were measured using a thermistor (K923, Takara Inc., Japan). Measurements were taken every five minutes.

The mean skin temperature ($\overline{T}_{sk}$) was calculated from weighting factors that reflected regional proportions of the total body surface area through seven points according to the Hardy and Dubois method (1937). Mean body temperature ($\overline{T}_b$) was calculated from T_r and $\overline{T}_{sk}$ using relative weightings of 2:1. Body heat content (S) and the increase of body heat content (ΔS) were calculated by the equation $S = 0.83 \times W \times \overline{T}_b$ (W: body mass (kg)) and $\Delta S=0.83 \times W \times \Delta \overline{T}_b$, respectively. Also measured were metabolism (Quark b^2, COSMED Inc., Italy) and body weight loss (F150S, Sartorius Corp., German). Heart rate was measured with a Polar Sports Tester (POLAR ELECTRO Inc., Finland). Body fat was measured at the chest, abdomen and thigh using a Skinfold caliper (Beta Technology, USA) and was calculated according to the devised Jackson and Pollock method (1978).

Clothing thermal insulation (I_{cl}) was calculated with the Winslow and Herrington method (Winslow & Herrington, 1949) using physiological responses such as skin and rectal temperature, metabolism, and insensible perspiration as well as environmental factors such as temperature and air velocity. The mean temperature inside clothing ($\overline{T}_{cl}$) was calculated as the arithmetic mean of five points (abdomen, arm, thigh, leg, and foot). DST is the differences of IST and OST at the chest.

Subjective sensations were determined by ratings of thermal sensation (9-point scale, +4 = very hot, -4 = very cold), thermal comfort (5-point scale, 0 = comfortable, 4 = extremely uncomfortable) and tolerance (5-point scale, 0 = perfectly tolerable, 4 = intolerable) recorded every 5 minutes (ISO 10551, 1995).

Statistical Analysis

Analyses were performed with statistical software package PASW Statistics 18 (SPSS, Inc., Chicago, IL, USA). Descriptive statistics (means, SD) were calculated for each physiological measure during each test. A regression analysis was used to investigate clothing thermal insulation predictability using a clothing microclimate. Relationships between physiological measurements were determined using Pearson's correlation coefficient; in addition, relationships between physiological measures and subjective sensations were determined with a Spearman's correlation coefficient. A one-way repeated measures analysis of variance examined physiological responses and subjective sensations for three experimental conditions.

RESULTS

Layering Effects on Physiological Responses

Skin temperatures except for foot and $\overline{T}_b$ were the highest in TL, rectal temperature was significantly higher in SL and TL than in DL; subsequently, $\overline{T}_{sk}$ was 31.26°C, 32.07°C and 32.31°C in SL, DL and TL,

Table 2. *Physiological Responses, Clothing Microclimate, I_{cl} And Subjective Sensations Between Three Types of Clothing*

		SL	DL	TL
Skin temperature (°C)	Forehead	33.58 (0.5)[b]	33.54 (0.5)[b]	33.76 (0.5)[a]
	Abdomen	32.84 (1.5)[b]	33.70 (1.1)[a]	33.90 (1.2)[a]
	Arm	31.69 (0.8)[c]	32.31 (0.6)[b]	33.11 (0.7)[a]
	Hand	26.91 (2.9)[b]	28.10 (3.0)[a]	28.30 (3.3)[a]
	Thigh	29.98 (1.3)[b]	31.07 (0.9)[a]	31.13 (1.0)[a]
	Leg	30.28 (0.9)[c]	31.23 (0.9)[b]	31.63 (1.1)[a]
	Foot	28.54 (1.8)	29.16 (2.1)	28.64 (2.6)
	$\overline{T}_{sk}$	31.26 (0.7)[c]	32.07 (0.6)[b]	32.31 (0.6)[a]
Decrease of mean skin temperature		0.75 (0.4)[a]	0.52 (0.37)[b]	0.40 (0.1)[b]
Rectal temperature (°C)		37.34 (0.3)[a]	37.21 (0.2)[b]	37.31 (0.3)[a]
Decrease of rectal temperature		0.50 (0.3)[a]	0.34 (0.1)[b]	0.34 (0.1)[b]
$\overline{T}_b$ (°C)		35.21 (0.3)[c]	35.41 (0.3)[b]	35.56 (0.3)[a]
Metabolic rate (kcal/m²/hr)		53.03 (6.5)	49.02 (7.4)	48.84 (5.9)
Body weight loss (g/m²/hr)		21.96 (6.6)	24.65 (4.7)	26.9 (5.6)
Body heat content (kcal)		1940.6 (204)	1940.9 (212)	1961.1 (206)
Increase of body heat content (kcal)		33.12 (16.7)[a]	22.07 (8.7)[b]	19.79 (8.7)[b]
Heart rate (beats/min)		74.12 (5.8)[b]	73.11 (6.6)[b]	76.10 (7.3)[a]
Clothing microclimate	$T_{cl\text{-}chest}$ (°C)	31.59 (1.63)[c]	32.30 (1.58)[b]	33.58 (0.60)[a]
	$T_{cl\text{-}abdomen}$ (°C)	30.44 (2.78)[c]	32.69 (2.00)[b]	32.72 (1.96)[a]
	$T_{cl\text{-}arm}$ (°C)	28.48 (2.17)[c]	30.25 (1.92)[b]	31.19 (1.68)[a]
	$T_{cl\text{-}thigh}$ (°C)	28.49 (1.82)[b]	29.75 (1.65)[a]	29.83 (1.38)[a]
	$T_{cl\text{-}leg}$ (°C)	26.91 (2.07)[c]	27.85 (2.36)[b]	28.49 (1.98)[a]
	$T_{cl\text{-}foot}$ (°C)	27.36 (1.48)	27.52 (1.93)	27.00 (2.74)
	$H_{cl\text{-}chest}$ (%RH)	12.1 (0.6)[b]	12.5 (1.3)[b]	14.6 (2.7)[a]
	$H_{cl\text{-}thigh}$ (%RH)	11.2 (1.2)[b]	11.4 (1.0)[b]	11.9 (0.6)[a]
	$\overline{T}_{cl}$ (°C)	29.16 (1.3)[c]	30.63 (1.1)[b]	30.86 (0.9)[a]
Surface temperature of clothing (°C)	IST	27.88 (2.4)[c]	29.09 (1.7)[b]	31.00 (1.6)[a]
	OST	22.40 (1.6)[c]	21.02 (1.3)[b]	20.44 (1.4)[a]
	DST	5.45 (1.6)[c]	8.07 (1.4)[b]	10.57 (2.0)[a]
I_{cl}	(clo)	1.51 (0.32)[b]	1.91 (0.34)[a]	2.04 (0.23)[a]
	($m^2 \cdot {}^{\circ}C \cdot W^{-1}$)	0.23 (0.05)[b]	0.30 (0.05)[a]	0.32 (0.34)[a]
Thermal sensations		-1.98 (0.61)[c]	-0.66 (0.44)[b]	0.05 (0.30)[a]
Thermal comfort		0.24 (0.18)[a]	0.00 (0.00)[b]	0.00 (0.00)[b]
Tolerance		0.32 (0.37)[a]	0.00 (0.00)[b]	0.00 (0.00)[b]

Notes: Values are means (S.D.). $\overline{T}_{sk}$ means the mean weighted skin temperature using 7-points, and $\overline{T}_b$ means the mean body temperature ($p < .05$). Superscripts means group divided by ANOVA and Duncan's post hoc test (a > b > c). SL, DL and DL mean single-layered clothing, double-layered clothing and triple-layered clothing, respectively. $T_{cl\text{-}}$____ and $H_{cl\text{-}}$____ mean the temperature and humidity inside the clothing at each body parts, respectively. IST, OST and DST mean the innermost surface temperature, the outermost surface temperature and the difference between IST and OST, respectively.

respectively. The increase of body heat content was the highest in SL (33.12 kcal) and this parameter decreased in the following order: DL (22.1 kcal) < TL (19.8 kcal). The heart rate of TL (76.10 beats/min) was higher than that of both clothing with SL (74.12 beat/min) and DL (73.11 beats/min) ($p < .05$, Table 2).

Table 3. *Relationship among Clothing Weight, Clothing Number, Clothing Microclimate and Clothing Thermal Insulation (I_{cl})*

		Total clothing weight	Upper clothing weight	Lower clothing weight	Total clothing number	Upper clothing number	Lower clothing number
$T_{cl\text{-}chest}$		0.497**	0.508**	0.497**	0.469**	0.469**	0.469**
$T_{cl\text{-}abdomen}$		0.423**	0.442**	0.429**	0.391**	0.391**	0.391**
$T_{cl\text{-}arm}$		0.538**	0.543**	0.538**	0.525**	0.525**	0.525**
$T_{cl\text{-}thigh}$		0.355**	0.375**	0.360**	-	-	-
$T_{cl\text{-}leg}$		-	0.358**	0.335**	-	-	-
$T_{cl\text{-}foot}$		-	-	-	-	-	-
$H_{cl\text{-}chest}$		0.525**	0.510**	0.521**	0.531**	0.531**	0.531**
$H_{cl\text{-}thigh}$		-	-	-	-	-	-
$\overline{T}_{cl}$		0.544**	0.565**	0.550**	0.510**	0.510**	0.510**
Surface temperature of clothing	I ST	0.604**	0.622**	0.609**	0.591**	0.591**	0.591**
	OST	-0.514**	-0.486**	-0.508**	-0.552**	-0.552**	-0.552**
	DST	0.824**	0.823**	0.825**	0.835**	0.835**	0.835**
I_{cl}		0.609**	0.626**	0.619**	0.591**	0.591**	0.591**

Notes: $T_{cl\text{-}}$____ and $H_{cl\text{-}}$____ mean the temperature and humidity inside the clothing at each body parts, respectively. IST, OST and DST mean the innermost surface temperature, the outermost surface temperature and the difference between IST and OST, respectively ($p < .01$).

$\overline{T}_{cl}$ had the highest correlation with $\overline{T}_{sk}$ ($r = 0.860$) and the temperature inside clothing at the abdomen ($r = 0.889$) ($p < .01$). Body fat (%) had a significant correlation with body heat content ($r = 0.846$), $\overline{T}_{sk}$ ($r = -0.358$) and $\overline{T}_{cl}$ ($r = -0.358$) ($p < .01$).

Clothing Microclimate and Clothing Weight

DST had the highest correlation to clothing weight and the number of clothing item such as the upper clothing weight ($r = 0.823$), lower clothing weight ($r = 0.825$), total clothing weight ($r = 0.824$), upper number of clothing ($r = 0.835$), lower number of clothing ($r = 0.835$) and total number of clothing ($r = 0.835$). I_{cl} had the highest correlation with their upper clothing weight ($r = 0.626$) ($p < .01$, Table 3).

Clothing Microclimate and Clothing Thermal Insulation (I_{cl})

Additional clothing layers on the participants' bodies resulted in a higher $\overline{T}_{cl}$ and I_{cl} (Fig. 1). Temperature and humidity inside clothing increased in the order of: SL < DL < TL. I_{cl} also increased higher as the clothing layers increased ($p < .05$, Table 2). The temperature inside clothing was the highest on the chest. IST increased in the order of: SL < DL < TL and OST decreased in the same order. DST was shown to be the highest in TL ($p < .05$, Table 4).

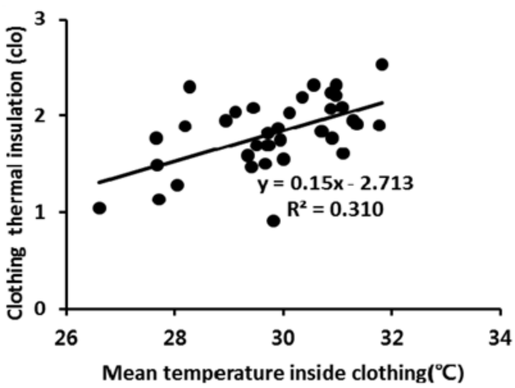

Figure 1. *Relationship of Mean Temperature Inside Clothing ($\overline{T}_{cl}$) and Clothing Thermal Insulation (I_{cl})*

I_{cl} had a high correlation with $\overline{T}_{cl}$ ($r = 0.556$), DST ($r = 0.549$) and $T_{cl\text{-}abdomen}$ ($r = 0.478$) ($p < .01$, Table 4). $\overline{T}_{cl}$ had the highest correlations with $T_{cl\text{-}abdomen}$ ($r = 0.889$) ($p < .01$).

The following equations could be deduced from the above results to predict the I_{cl}.

$$I_{cl} = 0.15 \times X_1 - 2.713 \ (R^2 = 0.310) \qquad \text{(Equation 1)}$$
(X_1 = mean temperature inside clothing ($\overline{T}_{cl}$))

$I_{cl} = 0.108 \times X_1 + 0.057 \times X_2 - 1.891$ ($R^2 = 0.437$) (Equation 2)

($X_1 = \overline{T}_{cl}$ (°C), X_2 = DST (°C))

$I_{cl} = 0.870 \times X_1 + 1.270$ ($R^2 = 0.384$) (Equation 3)

(X_1 = Total clothing weight, kg/m^2)

Layering Effects on Subjective Sensations

There were significant differences in thermal sensation, thermal comfort and tolerance that resulted from the layers of clothing. Thermal sensation was -1.98 in SL and increased when layers were increased. Both thermal comfort and tolerance were the lowest in SL at 0.24 and 0.32, respectively; in addition, the parameters in DL and TL were comfortable and perfectly tolerable, respectively ($p < .01$, Table 2).

Thermal sensation had a positive correlation with $\overline{T}_{cl}$ (r = 0.593) and $T_{cl\text{-}abdomen}$ (r = 0.445). Thermal comfort had a negative correlation with $T_{cl\text{-}thigh}$ (r = -0.411) and $\overline{T}_{cl}$ (r = -0.323) ($p < .01$, Table 5).

Table 4. *Correlation Coefficients between each Factor of Clothing Microclimate and Clothing Thermal Insulation (I_{cl})*

Clothing microclimate		Correlation coefficient
$T_{cl\text{-}chest}$		-
$T_{cl\text{-}abdomen}$		0.478**
$T_{cl\text{-}arm}$		-
$T_{cl\text{-}thigh}$		0.332**
$T_{cl\text{-}leg}$		0.364**
$T_{cl\text{-}foot}$		-
$H_{cl\text{-}chest}$		-
$H_{cl\text{-}thigh}$		-
$\overline{T}_{cl}$		0.556**
Surface temperature of clothing	IST	0.378**
	OST	-0.379**
	DST	0.549**

Notes: $T_{cl\text{-}}$____ and $H_{cl\text{-}}$____ mean the temperature and humidity inside the clothing at each body parts, respectively. IST, OST and DST mean the innermost surface temperature, the outermost surface temperature and the difference between IST and OST, respectively. ($p < .01$).

DISCUSSION

The temperature inside clothing was high when wearing clothing that had a high I_{cl}. Therefore, the studies about the relationship between I_{cl} and clothing microclimate are clearly needed. This study investigated the relationship of clothing microclimate and physiological responses when only clothing layer increased and examined the predictability of I_{cl} using clothing microclimate in a controlled condition of fabrics or design effects.

More clothing layers resulted in a higher temperature inside clothing (Table 2). This result was because the air layer volume within the clothing increased. Previous study has shown that a higher outdoor environment temperature results in a higher temperature inside the clothing (Kim & Choi, 1999).

Table 5. *Correlation Coefficients between Subjective Sensations and Clothing Microclimate*

	Thermal sensation	Thermal comfort	Tolerance
Thermal sensation	1.000	-0.372**	-0.478**
Thermal comfort	-0.372**	1.000	0.386**
Tolerance	-0.478**	0.386**	1.000
$\overline{T}$cl	0.593**	-0.323**	-0.343**
$T_{cl\text{-}chest}$	0.330**	-0.223**	-0.251**
$T_{cl\text{-}abdomen}$	0.445**	-0.226**	-0.268**
$T_{cl\text{-}thigh}$	0.429**	-0.411**	-0.274**
$H_{cl\text{-}chest}$	0.423**	-0.174**	-0.168**
$H_{cl\text{-}thigh}$	0.275**	-0.055**	-0.245**

Notes: $\overline{T}_{cl}$, $T_{cl\text{-}}$____ and $H_{cl\text{-}}$____ mean the mean weighted temperature inside clothing at 5 sites, temperature inside clothing and humidity inside clothing at each body parts respectively ($p < .05$).

Another previous study showed that the temperature of the space between the skin and garment is a good indicator of the thermal load and is related to environmental conditions (Cortili *et al.*, 1996). These results assume that more clothing produce a higher temperature inside the clothing when the atmospheric temperature is identical.

According to these expectations, a higher temperature inside clothing resulted in a higher I_{cl} only when the clothing layers increased in a controlled condition of fabrics or design effects in this study. The difference of the I_{cl} between one layer and two layers of clothing (Δ0.4clo) was higher than that of two layers and three layers of clothing (Δ0.1clo) and this indicated that the more clothing layers a person wears, the lower the increase of I_{cl} is (Table 2). This result means that the increase of I_{cl} by layering has limitations and is consistent with previous studies (Havenith *et al.*, 1990).

Humans cope with cold weather by wearing heavy clothing or increasing the number of clothing items. I_{cl} increases with more layering; however, this increase has a limitation that the contribution that each garment makes toward the clo value for an ensemble is usually less than the clo value for an individual garment (McCullough *et al.*, 1983, 1985, Nevins *et al.*, 1974). This is why I_{cl} decreases through the breaking of the still air layer. This result was indicated in a previous study (Havenith *et al.*, 1990) that compared the I_{cl} of overweight and thin people wearing the same clothing. Here, the I_{cl} of overweight people was lower than thin people and was why the still air layer was pressed according to body fit. In the previous study, more layered clothing resulted in a lower I_{cl} increase. The habit of wearing heavy clothing was shown to be largely responsible for the decline of physiological responses; subsequently, too much layering should be avoided during the cold season.

Researchers in Korea and Japan often use the clothing microclimate of the chest as one site of analysis, at the chest and thigh as two sites and at the chest, back and thigh as three sites. A previous study used the shoulder, hip and thigh as study sites (Muir *et al.*, 2001). However, there are rare studies that use more than three sites for examinations. The chest area is often used because it is the main part of the torso in human body; however, the abdomen area ($r = 0.478$) of individual sites was the most appropriate to predict the I_{cl} using temperature inside clothing according to results of this study (Table 4). The chest is part of the torso; however, the reasons that there was no correlation between the temperature inside the clothing at the chest and I_{cl} were the volume of air layer inside the clothing and the break of air layer caused by such factors as body movement. Further studies on women as well as analyses that consider the temperature inside clothing at the back area are needed since the results are related to gender differences and also because the ventilation in the back is less than for the chest. This study showed that the temperature inside clothing is appropriate to predict I_{cl} in body parts (such as the abdomen) and exclude the effect caused by opening the clothing.

Fig. 1 illustrates the linear relationship between $\overline{T}_{cl}$ and I_{cl} under the three experimental conditions. The prediction equation of I_{cl} using only $\overline{T}_{cl}$ had a weak relationship ($R^2 = 0.31$). Clothing weight (a good predictor of I_{cl}) also had a weak relationship of $R^2 = 0.38$; in addition, the temperature inside the clothing was significantly correlated with clothing weight in this study considering that the coefficients ranged from $r = 0.510$ to $r = 0.565$ (Table 3). The results show that $\overline{T}_{cl}$ could be a predictor of I_{cl}; however, the coefficient value was not high. Previous studies (Cortili *et al.*, 1996) indicated that the temperature of the space between skin and garment is a good indicator of the thermal load. DST was also an important factor (except for $\overline{T}_{cl}$) since it had a significant correlation ($r = 0.549$) with I_{cl} ($p < .05$). The coefficients in the current study are lower than the thermal manikin test; however, prediction equations of clothing insulation with clothing microclimates can be suggested because thermal manikins are different from real human physiology. Contrary to expectations, the reasons why the relationship between clothing insulation and micro-climates is not high are the small number of participants, the limited layer of the clothing condition, and the effects of the individual difference. In addition, a more significant correlation can be obtained when the number of layer increases.

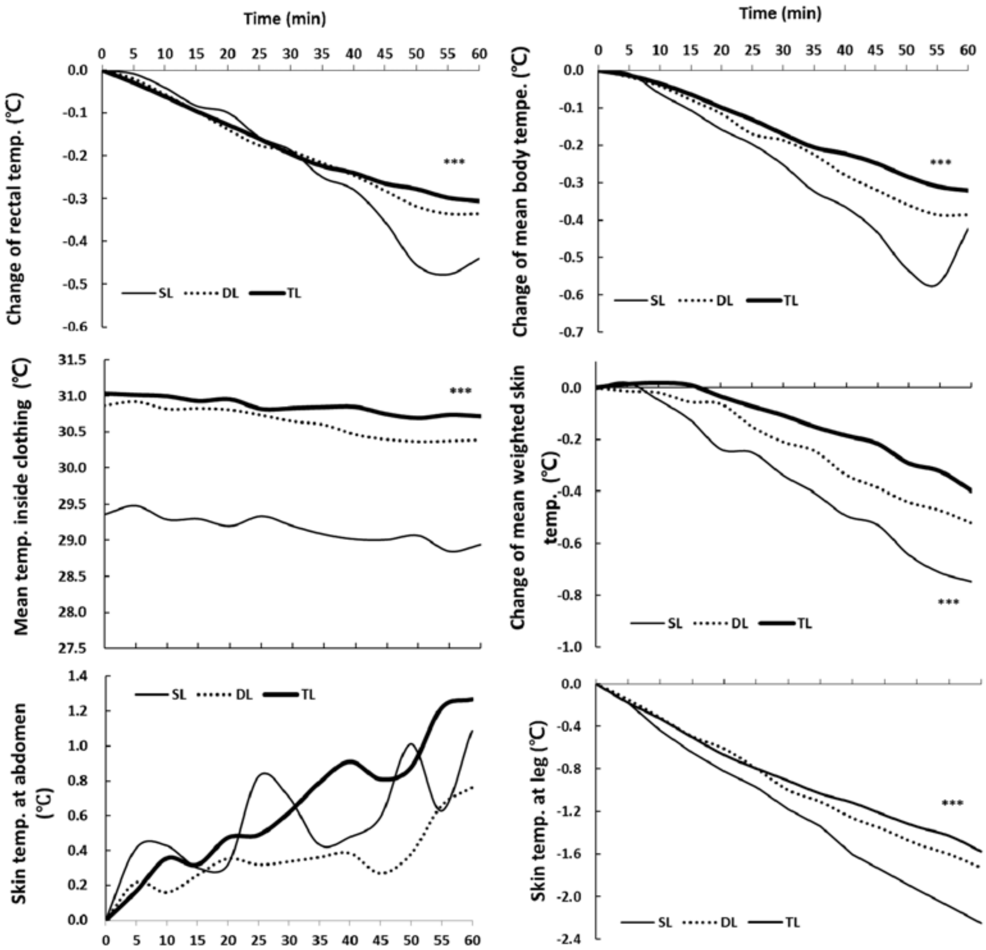

Figure 2. *Time Courses of Changes in Rectal, Mean Body And Mean Skin Temperature, Skin Temperature at Abdomen and Leg, and Mean Temperature Inside Clothing in Wearing SL, DL and TL at 15°C for 60 min* (***$p < .001$, The asterisk in each figure means significant differences among the experimental conditions during the whole exposure time.).

Each of the physiological parameters was examined according to clothing layers. Rectal temperature (regarded as a representative measurement of core temperature) in all experimental clothing consistently decreased over time in addition, the changes of the rectal temperature were lower with SL than with DL and TL. Regarding temperature inside clothing, the rectal temperature was significantly lower when $\overline{T}_{cl}$ showed a difference of 1.6°C. $\overline{T}_{sk}$, $\overline{T}_{b}$ and skin temperatures (except for the abdomen area) also decreased over time (Fig. 2). The skin temperature results had a similar tendency in that skin temperature and temperature inside the clothing were lower when the level of body fat was higher. Previous studies (Nielsen & Nielsen, 1984) also showed that I_{cl} affects the distribution of skin temperature.

The temperature inside clothing decreased over time and the human body showed a physiological mechanism in that the torso temperature increased and the extremity temperatures decreased. The abdomen area within the torso increased and the leg area within the extremities decreased over time (Fig. 2). The lower extremities are due to vasoconstriction that decreases blood volume in a cold environment.

Physiological responses have been investigated in relation to outdoor environments. A previous study (van Marken Lichtenbelt *et al.*, 2001) showed that outdoor temperature difference of 5°C between 22°C and 27°C influenced core temperature, skin temperature, and metabolic rate. However, is inconclusive whether some degree of temperature inside clothing influences physiological responses such as body temperature and metabolic rate. The difference of $\overline{T}_{cl}$ was about 1.6°C in this study and reflected the difference between wearing one layer and two layers of clothing. The difference of 1.6°C in $\overline{T}_{cl}$ affected skin temperature, rectal temperature, $\overline{T}_{b}$ and heart rate. Even with the 0.2°C of $\overline{T}_{cl}$, the difference between two layers and three layers of clothing showed a significant effect on some measures such as chest and leg skin temperature ($p < .01$). The small difference of temperature inside clothing provides a meaningful result because of the narrow range of the temperature inside clothing. Therefore, further studies about temperature inside clothing based on clothing and human physiology sections should be conducted to quantitatively measure the temperature inside clothing and build a fundamental data base.

Metabolism showed a decreasing tendency and weight loss showed an increasing tendency in the following order: SL, DL and TL. When the $\overline{T}_{cl}$ was higher, the increase of body heat content was lower ($p < .01$, Table 2). These may be because the increase of clothing layers affects $\overline{T}_{cl}$ and the increased $\overline{T}_{cl}$ affects the increase of skin temperature again; therefore, weight loss is considered to increase. The increase of body heat content decreased as the $\overline{T}_{cl}$ increased is regarded as thermoregulation of increased heat loss by rising skin temperature by oneself to relieve heat stress.

The thermal sensation was "cold" for single-layered clothing and "neutral" for more layering. Thermal comfort and tolerance in single-layered clothing with 1.51clo were "slightly uncomfortable" and "slightly difficult to tolerate", respectively and were both comfortable in more than 1.91clo of I_{cl} ($p < .01$, Table 2). Participants answered that a higher $\overline{T}_{cl}$ was the warmer they felt and a lower $\overline{T}_{cl}$ was the cooler they felt ($p < .01$, Table 5). This suggests clothing microclimate functions as one of the thermal environments that affect thermal sensation. The predictability of thermal sensation using physiological responses (such as skin temperature and $\overline{T}_{b}$) has been highlighted in previous studies (Jung & Tokura, 1993; Katsuura *et al.*, 1998; Nielson & Nielson, 1984). A relationship between thermal sensation and $\overline{T}_{cl}$ could be inferred from this study.

CONCLUSIONS

This study proves that clothing microclimate, physiological responses and subjective sensation are related; in addition, a mathematical model was developed to predict I_{cl} using the mean temperature inside clothing that indicated a linear relationship. Consequently, temperature inside clothing may be predictive for clothing thermal insulation to some degree. This study is significant in that it investigated the relationship of clothing microclimate and physiological responses. The results of this study are based on limited subjects, limited ambient temperature of 15°C, limited clothing design, limited fabrics and limited layers. Studies that predict or estimate the index (such as I_{cl}) were generally conducted on a large scale. The sample number in this study was not large; however, it is important in that it showed the possible use of temperature inside clothing to predict I_{cl}. Further studies are needed to generalize the result.

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