Development of human thermoregulation model JOS applicable to different types of human body, sex and age

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ABSTRACT
The numerical thermoregulation model JOS was developed. In this model, the influences of body size, sex and age on thermoregulation were reflected on physiological parameters of the thermoregulation model. The whole body model has 17 body segments, each consisting of two layers for core and skin. In addition, it is possible to alter its height, weight, sex, age, body fat percentage, basal metabolic rate and cardiac index. In the limbs of this model, the detailed vascular system was considered, including deep artery and vein, superficial vein and arteriovenous anastomoses (AVA). Under steady state and transient conditions, the validity of the calculation results was confirmed by comparing with the subjective experiments of females and the elderly. This model is able to predict fairly well for the skin temperature distribution, especially in the limbs under cold environments. Moreover, under transient condition, the simulation is also closer to the subjective experiment.

INDEX TERMS
Thermal comfort; Thermoregulation; Modelling; Calculation; Aging

INTRODUCTION
PMV (Predicted Mean Vote) and SET* is suitable and useful to evaluate steady-state thermal comfort under uniform environmental conditions. However, both indices modelled the human body as the uniform heating element, and clothing as the uniform heat resistance on human body surface. As people are often exposed to very non-uniform thermal environments such as car cabin, task air-conditioning space, and outdoors, models with detailed body shape such as the Stolwijk model (Stolwijk,1971) and 65MN (Tanabe *et al.*, 2002) are used for evaluation of such complex environments. Though these models are constructed by the body configuration of a standard adult male, females, children or the elderly are not taken into account. It is said that thermoregulatory reaction of women is more sensitive to cold environments than men (Kuroshima, 1981), and the thermoregulation ability of the elderly declines and tends to be affected by thermal environment more easily than younger people. Moreover, the delay in thermoregulatory reactions is often observed (Kawashima, 1994). The conventional thermoregulation models are not suitable for woman and the elderly. Therefore, a new thermoregulation model applicable to woman and the elderly needs to be developed; and in this study, the JOS (Thermoregulation Model Jointed Circulation System) is developed.

OUTLINE OF JOS
The whole body is divided into 17 body segments (head, neck, chest, back, left shoulder, right shoulder, left arm, right arm, left hand, right hand, left thigh, right thigh, left leg, right leg, left foot and right foot). The subscript '*i*' (1–17) represents the segment number in the following equations. Individual body segment consists of core and skin layers. This layer division is expressed with the subscript '*j*' (1–2). As blood flow is simplified as the heat exchange between local tissues and the central blood compartment in the Stolwijk model and 65MN, differences in predicted skin temperature compared to subjective experiments tend to be larger

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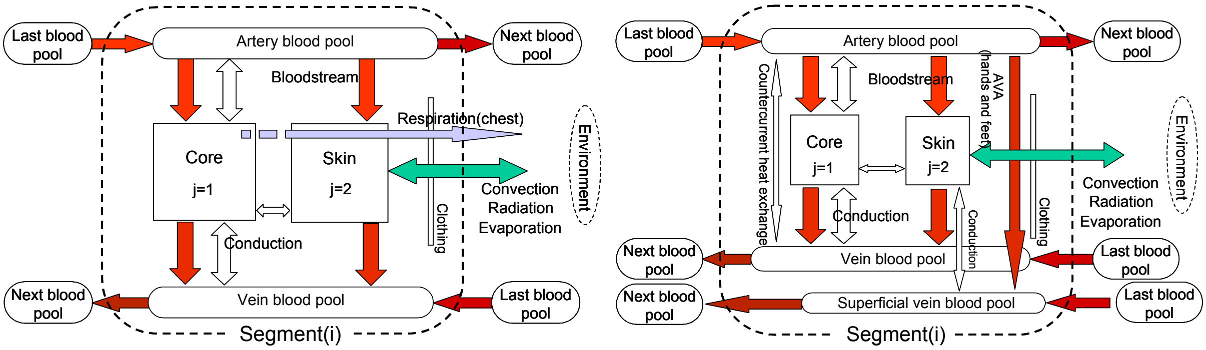
in the limbs under cold environments. In the JOS, a vascular system is modelled into deep artery and vein blood pools, superficial vein blood pools and arteriovenous anastomoses (AVA), in addition to the central blood compartment. AVA is located at each segment of hand and foot. It is known that the course of blood flow is different affected by thermal environments. Under cold environments, AVA is kept closed and blood flows through capillaries and tissues into deep veins. On the other hand, a part of blood flows through AVA, not capillaries and tissues, into deep veins under warm environments. Since AVA opens under warm environments and increases quantity of blood flow in the superficial vein, the influence on heat emission to the environment is large. The skin surface and the environment exchange heat by convection, radiation, evaporation and respiration. The heat loss by respiration is regarded to occur only at the core layer of the chest segment. The conceptual figure of heat exchange in the JOS is illustrated in Figure 1. In order to examine the validity of this model, the calculation results of mean skin temperature and skin wettedness calculated by a standard man of JOS are compared in Figure 2. The results show the predicted mean skin temperatures of JOS and the two-node model are almost identical.



<Except limbs> <Limbs>

Figure 1 Conceptual figure of heat exchange in the JOS.

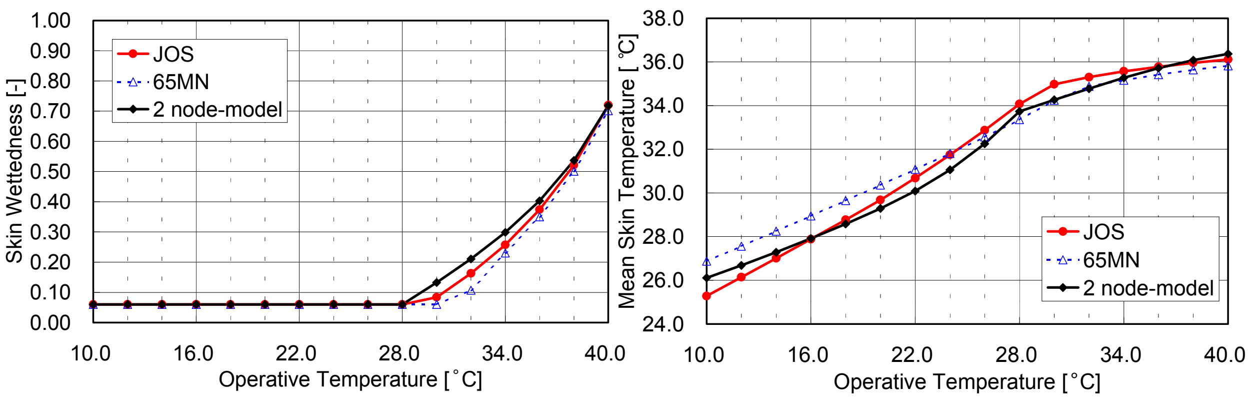


Figure 2 Skin wettedness and mean skin temperature.

ALTERATION OF PARAMETERS

Body Surface Area and Weight

The body surface area of this model is calculated by Dubois's equation. In the Stolwijk model and 65MN, the standard man represents the body surface area of 1.87 m^2 ($=A_{Dust}$) and the body weight of 74.430 kg ($=Wt_{st}$). The body surface area and body weight of each segment is based on the Stolwijk model, shown in Table 1. $A_{Du}(i)$ (m^2) and $Wt_{st}(i)$ (kg) of each body segment of the standard man are shown in Table 1. The following coefficients were defined in modelling the altered body:

$$Adura = A_{Du}/A_{Dust} \qquad (1)$$

$Wtra = Wt/Wt_{st}$ (2)

where *Adura* (–) is the ratio of the altered body surface area A_{Du} (m^2) to that of the standard man. *Wtra* (–) is the ratio of the altered body weight *Wt* (kg) to that of the standard man.

Thermal Conductance

Thermal conductance is altered by body fat percentage, *Adura* and *Wtra*. The value of the standard man is shown in Table 2. The segment of head and neck is modelled into a sphere and other body segments are modelled into circular cylinders, so heat conductance is derived from the formula for heat conduction. The ratio of lateral area in cylinder or surface area of sphere is assumed to that of the body surface area, the ratio of volume in the cylinder or sphere assumed to that of weight.

$$TC(1\text{–}2, j) = TC(1\text{–}2, j)_{st} \cdot Wtra/Adura \quad (3)$$

$$TC(3\text{–}17, j) = TC(3\text{–}17, j)_{st} \cdot (Adura)^2/Wtra \quad (4)$$

where $TC(i, j)$ (W/°C) is the thermal conductance between core and skin. The coefficient applied is the same one between artery blood pool and core layer, vein blood pool and core layer, artery blood pool and vein blood pool, or superficial vein blood pool and skin layer.

Basal Metabolic Rate

Differences in basal metabolic rate exist due to national–geographic differences, sex and age. Basal metabolic rate for different groups is derived from the literature review (Nakayama, 1987) and given in Table 3.

Table 1 $A_{Dust}(i)$ (m^2) and $Wt_{st}(i)$ (kg)

i	*Segment(i)*	$A_{Dust}(i)$	$Wt_{st}(i)$
1	Head	0.110	3.176
2	Neck	0.029	0.844
3	Chest	0.175	12.400
4	Back	0.161	11.030
5	Pelvis	0.221	17.570
6	L-Shoulder	0.096	2.163
7	L-Hand	0.063	1.373
8	L-Arm	0.050	0.335
9	R-Shoulder	0.096	2.163
10	R-Arm	0.063	1.373
11	R-Hand	0.050	0.335
12	L-Thigh	0.209	7.013
13	L-Leg	0.112	3.343
14	L-Foot	0.056	0.480
15	R-Thigh	0.209	7.013
16	R-Leg	0.112	3.343
17	R-Foot	0.056	0.480
-	Total	1.870	74.434

Table 2 Thermal conductance (W/°C)

i	*Segment(i)*	~12.5	12.5~17.5	17.5~22.5	22.5~27.5	27.5~
1	Head	3.500	3.422	3.348	3.276	3.206
2	Neck	0.930	0.909	0.889	0.870	0.852
3	Chest	1.879	1.785	1.698	1.618	1.542
4	Back	1.729	1.643	1.563	1.488	1.419
5	Pelvis	2.370	2.251	2.142	2.040	1.945
6	L-Shoulder	1.557	1.501	1.448	1.396	1.346
7	L-Hand	1.018	0.982	0.947	0.913	0.880
8	L-Arm	2.210	2.183	2.156	2.130	1.945
9	R-Shoulder	1.557	1.501	1.448	1.396	1.346
10	R-Arm	1.018	0.982	0.947	0.913	0.880
11	R-Hand	2.210	2.183	2.156	2.130	1.945
12	L-Thigh	2.565	2.468	2.375	2.285	2.198
13	L-Leg	1.378	1.326	1.276	1.227	1.181
14	L-Foot	3.404	3.370	3.337	3.304	3.271
15	R-Thigh	2.565	2.468	2.375	2.285	2.198
16	R-Leg	1.378	1.326	1.276	1.227	1.181
17	R-Foot	3.404	3.370	3.337	3.304	3.271

Age	Western		Japanese	
	Male	Female	Male	Female
20	44.9	41.1	42.9	39.0
25	43.6	40.9	42.1	38.5
30	42.8	40.8	41.1	37.3
35	42.4	40.7		
40	42.2	40.6	40.0	36.6
45	42.1	40.1		
50	41.6	39.4	39.1	36.1
55	41.2	38.7		
60	40.6	38.0	37.9	35.5
65	40.0	37.4		
70	39.3	36.9	36.3	34.9
75	38.6	36.4		
80	38.4	35.9	34.8	34.5

Basal Blood Flow

Basal blood flow is calculated by the cardiac index and body surface area in Eqn (5):

$$BFB = CI \cdot 60 \cdot A_{Du} \cdot R_{CIage} \quad (5)$$

where *BFB* (l/h) is the basal blood flow, *CI* (l/min/m^2) is the cardiac index and R_{CIage} is the coefficient on the decline by aging.

Heat Capacity

It is assumed that heat capacity is calculated by Eqns (6) and (7):

$$Cs(i, j) = Cs(i, j)_{st} \cdot Wtra \quad (6)$$

$$Cb(i, j) = Cb(i, j)_{st} \cdot BFBallra \quad (7)$$

where *Cs* (W h/°C) is the heat capacity of body segment, core layer or skin layer. *Cb* (W h/°C) is the heat capacity of blood pools and the central blood compartment. *BFBallra* (–) is the ratio of basal blood flow to the standard man.

Heat Transfer Coefficients

In this model, the convective and radiant heat transfer coefficients are equal to the values of the standard man, derived from the thermal manikin experiment (Ichihara, 1997).

THERMOREGULATORY SYSTEM

The thermoregulatory system is constituted of four control processes: sweating, shivering, vasodilation and vasoconstriction. Each process is depended on sensor signals, consisted of three terms, head core signal, skin signal and term related with both (Stolwijk, 1971). As humans become older, thermoregulatory ability declines, so these signals have to be multiplied by diminishable coefficient.

$$SW = SW_{st} \cdot Adura \cdot R_{swa} \quad (8)$$
$$SV = SV_{st} \cdot Adura \cdot R_{sva} \quad (9)$$
$$DL = DL_{st} \cdot Adura \cdot R_{Dla} \quad (10)$$
$$ST = ST_{st} \cdot R_{Sta} \quad (11)$$

where *SW*, *SV*, *DL* and *ST* are the signal of perspiration, shivering, vasodilation and vasoconstriction, respectively. R_{swa}, R_{sva}, R_{Dla} and R_{Sta} are the diminishable coefficient caused by aging, respectively.

Set-Point Temperature

The set-point temperature in the thermoregulation is derived from the calculation, which the model is exposed under the condition on PMV = ±0 [$t_a = t_r = 28.8$ (°C), $v = 0.1$ (m/s), rh = 50 (%), 0.00 (clo), 1.0 (met)], and no thermoregulation occurs. The psychological neutral is set to the physiological neutral.

Blood Flow in AVA and Superficial Vein

AVA blood flow is calculated by Eqns (13)–(15) (Takemori, 1995):

$$F_i = V_i f/100 \cdot Wtra \cdot BFBallra \cdot O_i \quad (13)$$
$$O_i = 0.265(T_{sk} - (T_{set} - 0.43)) + 0.953(T_{bcr} - (T_{bcrn} - 0.1905)) + 0.9126 \quad (14)$$
$$O_i = 0.265(T_{sk} - (T_{set} - 0.43)) + 0.953(T_{bcr} - (T_{bcrn} - 0.1905)) + 0.9126 \quad (15)$$

where F_i (ml/min) is the quantity of blood flow in AVA and superficial vein at the segment. V_i (cm^3) is the volume of the segment. f (ml/min 100 ml tissue) is the maximum quantity of blood flow at skin: 30 (ml/min 100 ml tissue). O_i is the openness percentage of AVA. T_{sk} is the mean skin temperature; T_{set} is the mean of set-point temperature at whole body skin; T_{bcr} is the deep body temperature; T_{bcrn} is the mean of set-point temperature at the trunk (chest, back and pelvis).

COMPARISON WITH THE SUBJECTIVE EXPERIMENTS

Results predicted by JOS were compared with the subjective experiments in the literature to examine the validity of the model. In each simulation, the body fat percentage, 25%, and the cardiac index, 3.2 ml/min/m^2, are set to the average of Japanese (Kawashima, 1994).

Steady State Conditions

The subjects were 27 Japanese females, 19–20 years of age, average height is 154.87 cm and average weight is 50.05 kg (Tamura, 1983). The conditions of experiment and simulation are shown in Table 4.

Results

The mean skin temperature is shown in Figure 3 and the skin temperature distribution in Figure 4. Compared with the data of a standard man, the results of calculation of JOS assumed woman are closer to the subjective experiment, especially the skin temperature in the limbs under the thermal condition of 22°C.

Table 4 The condition of the experiment

	Initial condition	Experimental condition
Exposure time[min.]	60	120
Air temperature(ta)[℃] / MRT(tr)[℃]	28.5 (ta=tr)	22,25,28,31, 34 (ta=tr)
Air velocity[m/s]	0.25	0.15
Relative humidity[%]	50	50
Clothing insulation[clo]	0.00	0.00
Metabolic rate[W/m^2]	39.37	39.37

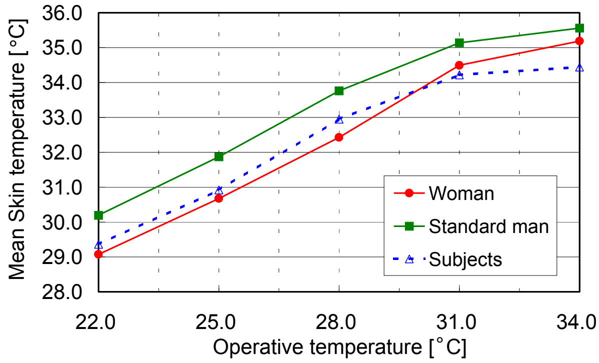


Figure 3 Mean skin temperature.

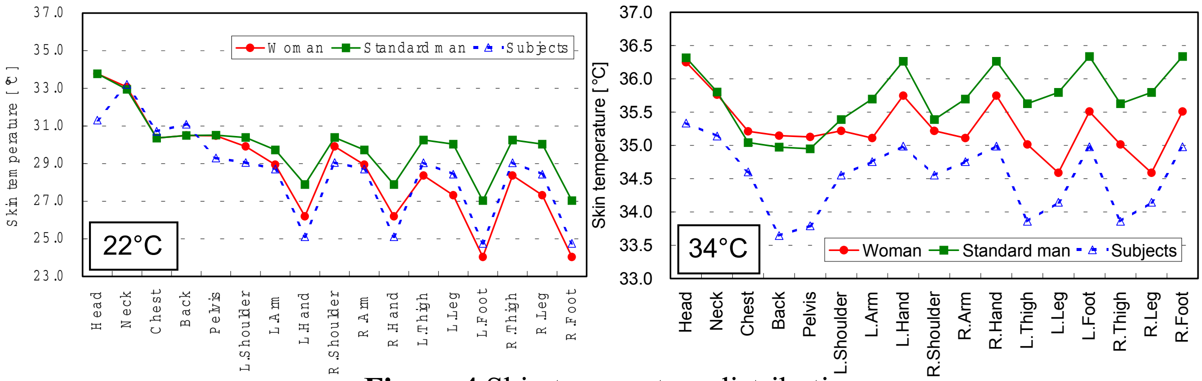


Figure 4 Skin temperature distribution.

Transient Conditions

The subjects were all Japanese females (9 aged and 12 young) (Tochihara, 1993). The condition of experiment and simulation is shown in Table 5 and the physical body data of subjects is shown in Table 6. Clothing insulation is 0.63 clo and the subjects wore no gloves. Finger skin temperature was compared with the skin temperature on the left hand of JOS.

Table 5 The condition of the experiments

	Initial condition	Experimental condition
Exposure time[min.]	60(before), 47(after)	49
Air temperature(ta)[℃] / MRT(tr)[℃]	25(ta=tr)	35(ta=tr)
Air velocity[m/s]	0.2	0.2
Relative humidity[%]	60	60
Clothing insulation[clo]	0.63	0.63
Metabolic rate[met]	1.0	1.0

Table 6 The physical body data of the subjects

Average	Aged (n=9)	Young (n=12)
Age	67.8	22.1
Height[cm]	148.7	157.8
Weight[kg]	50.6	50.6

Results

The variation of skin temperature is shown in Figure 5. Compared with the physiological data of subjective experiments and the calculation of simulation, the mean skin temperature and finger skin temperature are predicted more precisely than the simulation of a standard man. By considering the decline by aging in thermoregulation, the delay of response to the change of thermal condition could be reproduced. The different tendency of change in mean skin temperature is guessed that the clothing is modelled into thermal resistance and not taken account in absorption of moisture. The calculation result of left hand by JOS is corresponding to the finger skin temperature of subjects well.

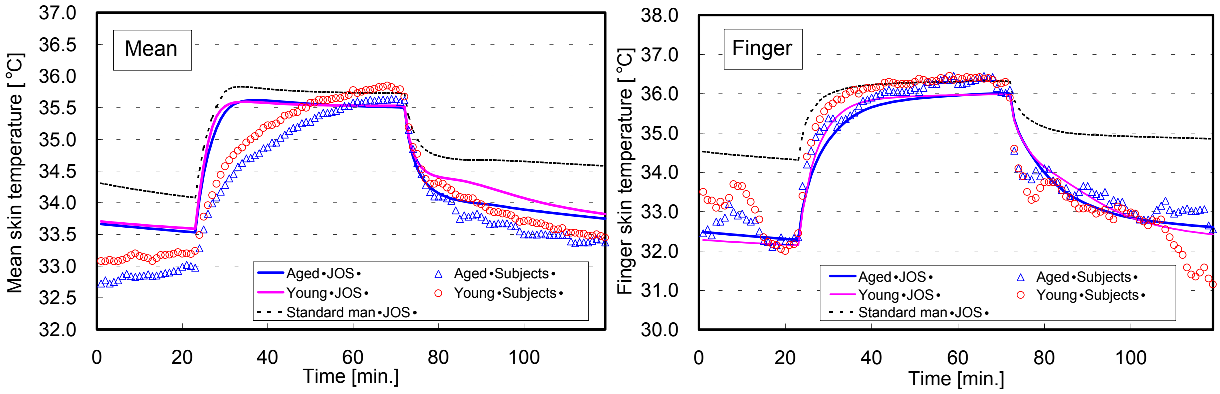


Figure 5 The change of skin temperature.

CONCLUSIONS

The thermoregulation model JOS was developed based on the Stolwijk model. By altering the parameters in the thermoregulation model and by comparing with the subjective experiments, the precision of calculations has improved not only near thermal neutrality but also under cold and warm conditions. This model was confirmed to predict fairly well for skin temperature distribution intended for women and elderly people.

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