Development of a human body thermo-physiological model considering the effect of gravity on blood

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In general, blood flow in the human body is significantly impacted by gravity; thereby resulting in thermo-physiological effect. In the present study, we modeled and formulated the effect of gravity on blood flow for each body part, depending on the body posture. We added the gravity term to the segmented two-node model; whereby skin temperature was calculated. This value agrees well with the results of the human subject experiment.

Keywords: postural changes, thermal comfort, blood flow, gravity, thermo-physiological model
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1. Introduction

Conventional comfort assessment has considered six elements of the thermal environment: air temperature, radiant temperature, airflow, humidity, amount of clothing and metabolic rate.[1] However, considering that the rate of blood flow changes as the posture of the human body changes, there exists a possible need to consider "posture" as the seventh element of the thermal environment. Therefore, we hypothesized that the gravitational effect caused by posture change may also affect the skin temperature. The purpose of this study is to verify this hypothesis through experiments, to formulate the blood flow change owing to gravity, and finally to develop a simulator that can evaluate thermal comfort considering the effect of gravity.

2. Computational theory

2.1 Development of 2-node blood pressure model (2NBPM)

The conventional two-node model (2 NM) developed by Gagge[2] as a thermal comfort evaluation method does not consider the effect of gravity. Thus, we developed a new 2NBPM based on 2 NM that can consider the effects of gravity and blood pressure. This model considers that the positional relationship between both the core layer and skin layer changes with posture and defines it as the "posture angle". The posture angle is the position of the skin layer when viewed from the core layer, where counterclockwise is positive($0° \leqq \theta \leqq 360°$). The deep layer and the skin layer are considered to be connected by blood vessels, as in 2 NM. This blood vessel is defined as a "virtual blood vessel," which is a single conduit that includes all arterioles and capillaries in the real human body. Fig. 1 demonstrates the developed 2NBPM and the definition of posture angleθ.

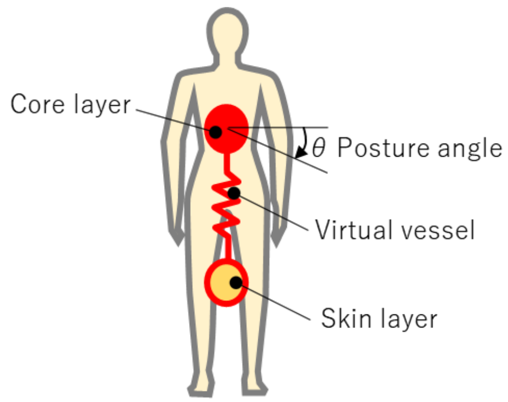

Figure. 1- Definition of posture angle θ in the 2NBPM

2.2 Development of a Segmented Two-node Blood Pressure Model

The segmented two-node model developed by Kohri et al[3] and Okabe et al. [4] divides the human body into 22 parts, and the model calculates skin temperature by solving the heat balance between the common core layer and the skin layer of each part. In this study, we introduce the gravitational effect described in the previous section into the segmented two-node model and further introduce the concept of “standard posture”. Many existing thermo-physiological models and thermal environment indices assume sitting posture or standing posture. In this study, all existing models were considered to be taking the standard posture. Therefore, the blood flow rate between the core and skin layers during standard posture is consistent with the conventional 2 NM and segmented two-node models. Fig. 2 illustrates the definitions of the standard posture angle and site height.

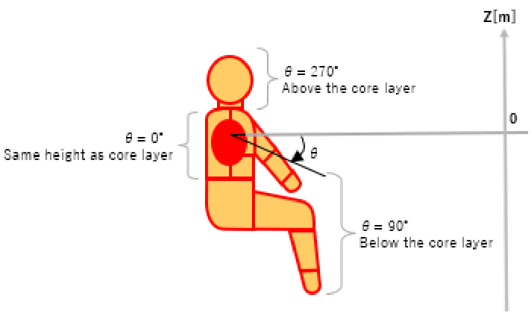

Figure. 2-Definition of Standard Posture angle θ and seating height z

The force applied to the blood flowing through the virtual blood vessel is called the total driving force(F_i), and the ratio to the total driving force $F_{g,i}$ in the standard posture is defined as the change rate of blood flow $r_{b,l,i}$. i indicates the number of each body part. The total driving force and the rate of change in blood flow are expressed by the following equations:

$$F_i = \left(p_0 + \frac{1}{2}\rho v^2\right) \cdot \pi r^2 + m_i g sin\theta_i - \rho g z_i \cdot \pi r^2 \quad (1)$$

$$F_{g,i} = \left(p_0 + \frac{1}{2}\rho v^2\right) \cdot \pi r^2 + m_i g sin\theta_{g,i} - \rho g z_{g,i} \cdot \pi r^2 \quad (2)$$

$$r_{bl,i} = \frac{F_{g,i}}{F_i} \quad (3)$$

m_i is the weight of blood flowing to each site, z_i is the site height with respect to the heart during standard posture and $z_{g,i}$ is the site height with respect to the heart during posture change. p_0 is the blood pressure in the heart, v is the virtual blood flow velocity, and r is the virtual vessel diameter. In the model, we adopted a mean blood pressure of 13.3 kPa, a blood flow velocity of 0.6 m/s in the ascending aorta, and a vessel diameter of 0.035 m in a man[5]. The first term on the right-hand side of equations (1) and (2) is the force that pumps blood from the depth to each part of the body, the second term on the right-hand side is the gravity on the blood, and the third term on the right-hand side is the hydrostatic pressure with respect to the depth. In addition, in the conventional segmented two-node model, each human body part is directly connected to the core layer, but in this model, each part is connected in series from the core layer. For example, when you raise your hand, blood flow is assumed to be in the order of the upper arm, forearm, and hand. Therefore, by multiplying the rate of change in blood flow at the upstream site by the rate of change in blood flow at the downstream site, the blood flow rate changes more significantly at the downstream site. If the rate of change in blood flow at the upstream site is $r_{bl,i}$ and the rate of change in blood flow at the downstream site is $r_{bl,j}$, the rate of change in blood flow at the downstream site can be expressed by the following equation:

$$r^*_{bl,j} = r_{bl,i} \times r_{bl,j} \quad (4)$$

$r^*_{bl,j}$ is the rate of change in blood flow at the downstream site after serialization. In the conventional segmented two-node model, the constant D_{bl} that distributes the blood flow to each site is defined experimentally. In the segmented two-node blood pressure model, the rate of change in blood flow is multiplied by this distribution rate to achieve the change in blood flow in each region.

$$D'_{bl,i} = r^*_{bl,j} \times D_{bl,i} \quad \mathbf{(5)}$$

However, because the distribution rate D_{bl} is defined by the body surface area ratio of each body part, the calculation in the above equation is not consistent. Therefore, we redefined the blood flow distribution ratio by normalizing it to the body surface area ratio.

$$D''_{bl,i} = D'_{bl,i} \times \frac{\sum D_{bl,i}}{\sum D'_{bl,i}} \quad (6)$$

Therefore, the blood volume can be changed by multiplying the redefined distribution rate by the blood flow rate at each site.

$$V'_{bl,i} = D''_{bl,i} \times V_{bl,i} \quad (7)$$

In this way, the effects of attitude angle and gravity can be considered for the conventional segmented two-node model by calculating the blood flow.

3. Validation

3.1 Examination (1) Comparison of fingertip skin temperature when the upper arm is raised

We conducted a simple subject experiment with four subjects to validate the developed variance two-node blood pressure model. The experimental conditions are presented in Table 1.

Tab. 1-Experimental condition

Environment	Air temperature	24.5 °C
	Radiant temperature	24.5 °C
	Airflow velocity	0.1 m/s
	Relative humidity	50 %
Human	Metabolic rate	1 met as standing
	Amount of clothing	0.7 clo

In the experiment, thermocouples were attached to the fingertips of the right and left hands to measure the skin temperature. Fig. 3 shows the skin temperature differences at the fingertips of the four subjects and their averages.

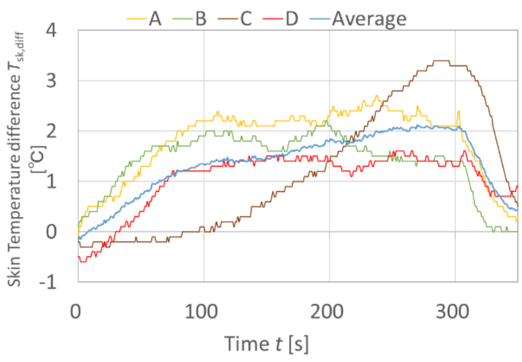

Fig. 3-Skin-temperature difference between left and right fingertips in four subjects

Figure 3 shows the 300 seconds after the right hand is raised. Focusing on the difference in skin temperature between the left and right sides of the body when 300 s elapsed after the right hand was raised. The largest difference in skin temperature between the left and right was 3.4 °C for subject C. The smallest difference in skin temperature was 1.3 °C for subject D. We confirmed that skin temperature changes owing to the effect of gravity, although it varied from subject to subject. Next, we illustrate a comparison of the results of simulations under the same conditions as the experiments using the developed two-node blood pressure model in Fig. 4. Figure 4 shows the 300 seconds after the right hand is raised. In the initial state, there was no difference in skin temperature between the left and right hands, but immediately after the right hand was raised, the temperature of the left hand increased, and at the 300-second elapsed time, the temperature difference between the left and right hands reached 2.1 °C. This agrees with the average value of 2.0 °C for the four subjects. The temperature of the left hand was higher than that of the right hand immediately after the right hand was raised.

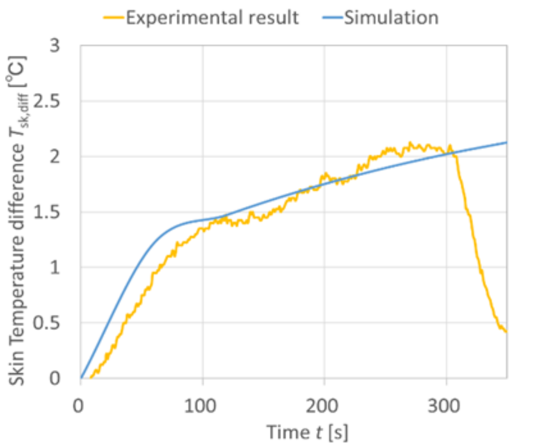

Fig. 4-Comparison of average experimental results with simulation results

3.2 Examination (2) Examination of the effects of whole body posture changes

Next, we conducted experiments and simulations in the upraised posture (Case 1) and supine posture (Case 2) to compare skin temperature changes and analyze the effects on blood flow changes and SET* in the simulations. In the experiment, seven subjects engaged in a sitting position for 30 min and then maintained the changed posture for 10 min, and their skin temperatures before and after the change were compared. The skin temperature was measured on the left palm. Table 2 summarises the posture angles and site heights in Case1 and Case2.

3.2.1 Blood flow and skin surface temperature

Fig. 5 illustrates the changes in blood flow and skin temperature in the upper arm, forearm, and hand in Case 1, and Fig. 6 illustrates the changes in blood flow and skin temperature in each body part in Case 2. In the simulation of Case 1, the blood flow decreased in the upper arm, forearm, and hand; the skin temperature decreased by 0.31 °C in the upper arm and 0.12 °C in the forearm. The skin temperature of the hand in the subject experiment decreased by 1.0 °C, whereas in the simulation, it decreased by 0.17 °C. Case 2 confirmed that blood flow in the upper body, especially in the head, increased in the simulation, while blood flow in the lower body decreased. The skin temperature decreased by a maximum of 0.54 °C in the feet. The simulation shows a decrease of about 0.086 °C in the hands and 0.54 °C in the feet, compared with a decrease of about 0.55 °C in the hands and 0.4 °C in the feet in the subject experiments.

Tab. 2- Posture angle and site height in Case1 and Case2

Part	Case 1		Case 2	
	Posture angle θ [deg]	Height of part z [m]	Posture angle θ [deg]	Height of part z [m]
Head	270	0.52	0	0
Neck	270	0.282	0	0
Chest	0	0	270	0
Back	0	0	90	0
Abdomen	90	0	270	0
Waist	90	-0.24	0	0
Upper arm (L / R)	270	0.521	0	0
Forearm (L / R)	270	0.772	0	0
Hand (L / R)	270	0.962	0	0
Thigh_Fr (L / R)	90	-0.716	0	0
Thigh_Bk (L / R)	90	-0.716	0	0
Leg_Fr (L / R)	90	-1.111	0	0
Leg_Bk (L / R)	90	-1.111	0	0
Foot (L / R)	90	-1.194	0	0

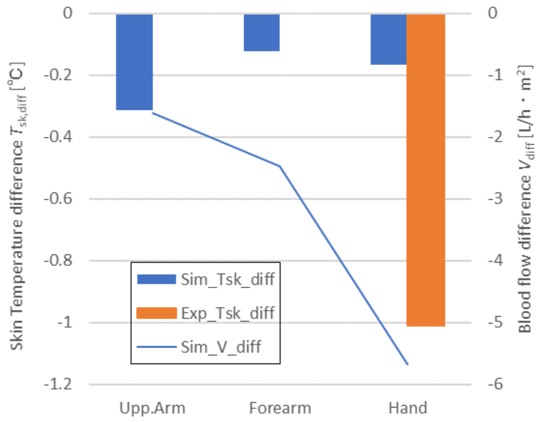

Fig. 5- Amount of change in blood flow and skin temperature in Case1

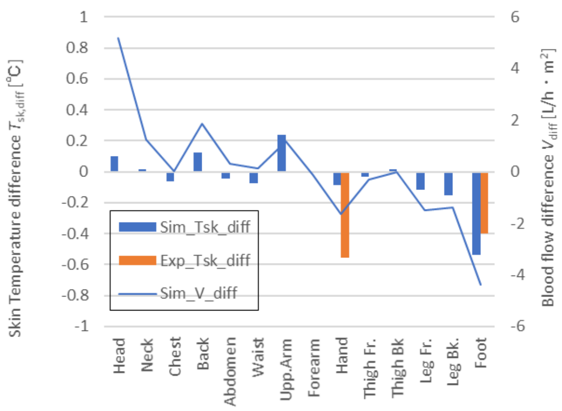

Fig. 6- Amount of change in blood flow and skin temperature in Case2

By introducing the rate of change in blood flow into the model, the skin temperature decreased in the area where blood flow decreased in the simulation. Compared with the experiment, the amount of change in the model was different for the reproduction of the skin temperature change by changing the posture angle; therefore, further improvement is necessary.

3.2.2 Blood flow response rate

Figs. 7 and 9 illustrate the rate of change of blood flow in the hand between simulation and experiment in Cases 1 and 2. In Case 1, when comparing the speed of response of blood flow changes between simulation and experiment, the experimental results illustrate a faster increase. Therefore, we extended the calculation time of the simulation, and the result is illustrated in Fig. 8. Fig. 8 illustrates that the blood flow rate changed at about 1800 seconds after the postural change. In Case 2, when comparing the speed of response of blood flow changes between simulation and experiment, the experimental results increased faster, as in Case 1.

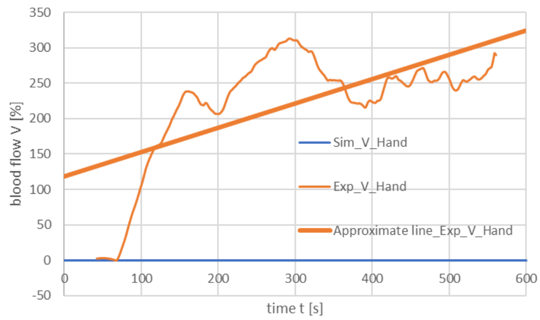

Fig.7- Blood flow changes in the hand in Csae1

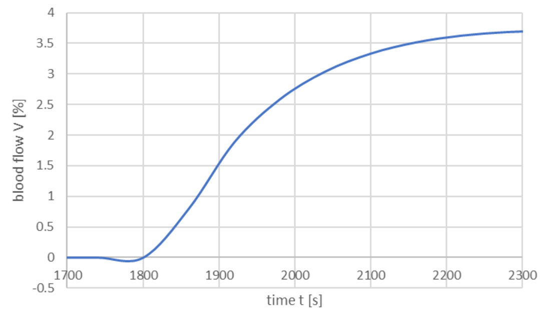

Fig.8- Simulation results of blood flow changes in the hand in Case1

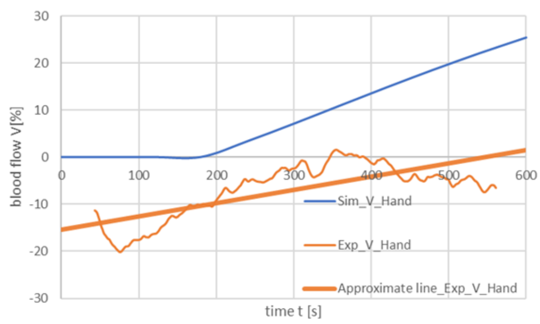

Fig.9- Blood flow changes in the hand in Case2

The simulation illustrates a slower response time to blood flow changes than the experiment. Therefore, future improvements are needed.

3.2.3 Change in SET from standard posture*

Fig. 10 and 11 illustrate the change in SET* from the standard posture in Cases 1 and 2. In addition to the aforementioned difference in skin temperature, a slight difference in SET* was observed owing to the effect of posture. In particular, a difference of 0.25 °C was observed for the upper arm in Case 1, and a difference of 0.68 °C was observed for the head in Case 2. This difference is considered to be perceived by the human body. Therefore, the gravitational effect owing to the difference in posture is considered to affect the warm and cold sensations of the human body.

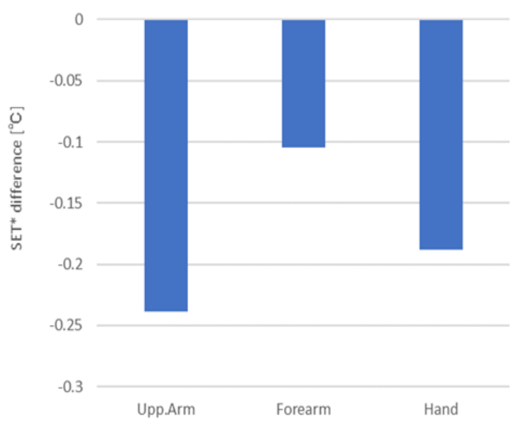

Fig. 10- Amount of change in SET* in Case1

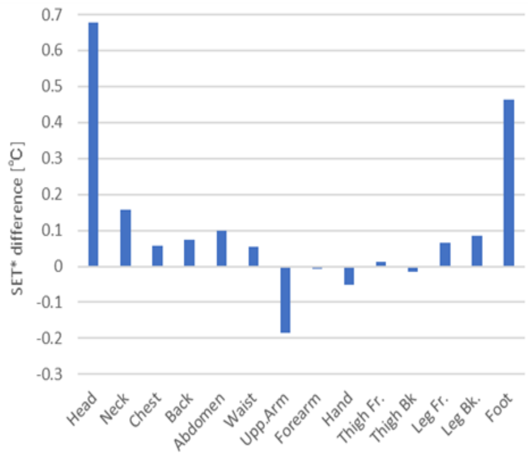

Fig. 11- Amount of change in SET* in Case2

4. Conclusion

In this study, we developed a thermos-physiological model of the human body to consider the effect of gravity on blood flow on thermal comfort. The effects of posture on blood flow, skin temperature, and SET* were clarified through experiments and numerical simulations with subjects in different postures.

1) By treating the core skin as a one-dimensional blood vessel and considering the total driving force acting on the blood, the blood flow rate determined by the conventional thermal regulation was formulated to be affected by gravity.
2) A model that incorporates a blood pressure model into a segmented two-node model with partitions and changes the direction of gravity action was developed.
3) In the experiment with subjects, the difference between the skin temperature of the raised fingertips of the right hand and that of the lowered fingertips of the left hand ranged from 1.3 °C to 3.4 °C, depending on the subject, and we confirmed that the skin temperature could change owing to gravity. This result agrees with the simulation results of the proposed model.
4) When both hands were raised, the skin temperature of the upper arms decreased by 0.31 °C, and the SET* decreased by 0.24 °C. In the supine position, skin temperature decreased by 0.54 °C in the feet, and SET* increased by 0.68 °C in the head and 0.46 °C in the feet.

In the future, we will increase the number of subjects in the experiment and measure the skin temperature and blood flow at 22 body parts. We will also increase the number of studies under different posture conditions and compare the experimental and simulation results to improve the accuracy of the model.

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Data sharing not applicable to this article as no datasets were generated or analysed during the current study.