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ScienceDirect

Building and Environment 43 (2008) 2142–2153

BUILDING AND ENVIRONMENT

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Radiative and convective heat transfer coefficients of the human body in natural convection

Yoshihito Kurazumi[a,*], Tadahiro Tsuchikawa[b,1], Jin Ishii[a,2], Kenta Fukagawa[a,3], Yoshiaki Yamato[c,4], Naoki Matsubara[d,5]

[a]Department of Socio-environmental Design, Faculty of Engineering, Hiroshima International University, 5-1-1, Hirokosingai, Kure, Hiroshima 737 0112, Japan

[b]School of Human Science and Environment, University of Hyogo, 1-1-12, Hon-cho, Shinzaike, Himeji, Hyogo 670 0092, Japan

[c]Department of Architecture and Structural Engineering, Kure College of Technology, 2-2-11, Aga-minami, Kure, Hiroshima 737 8506, Japan

[d]Department of Environmental Design, Kyoto Prefectural University Nakaragi-cho, Shimogamo, Sakyo-ku, Kyoto 606 8522, Japan

Received 6 April 2007; received in revised form 17 December 2007; accepted 20 December 2007

Abstract

The purpose of this study was to investigate the convective and radiative heat transfer coefficients of the human body, while focusing on the convective heat transfer area of the human body. Thermal sensors directly measuring the total heat flux and radiative heat flux were employed. The mannequin was placed in seven postures as follows: standing (exposed to the atmosphere, floor contact); chair sitting (exposed to the atmosphere, contact with seat, chair back, and floor); cross-legged sitting (floor contact); legs-out sitting (floor contact); and supine (floor contact). The radiative heat transfer coefficient was determined for each posture, and empirical formulas were proposed for the convective heat transfer coefficient of the entire human body under natural convection, driven by the difference between the air temperature and mean skin temperature corrected using the convective heat transfer area.

Keywords: Natural convection; Convective heat transfer coefficient; Radiative heat transfer coefficient; Heat transfer area; Posture; Human body

1. Introduction

The convective heat transfer coefficient and convective heat transfer area of the human body must be determined in order to calculate the convective heat exchange between the body and the environment. The studies on measurement of convective heat transfer between the body and contacting surfaces have not been reported.

The arms may be in contact with the sides and the thighs may be in contact with each other in standard postures. The standing posture leaves the body open to rather vigorous convective processes in the surrounding air. Even sitting positions can expose the body to convective flows, if the contacting areas are assumed to be very small, as most ordinary postures expose more body surface area to air currents than they shield, as demonstrated by the relatively area of contact between the feet and the floor in sitting and standing postures (non-convective heat transfer area). The calculation formulas taken into account these non-convective heat transfer areas have not been established, however. It is simple to assume that the standing and chair sitting positions expose "all" the body surface area, and this is probably why research has concentrated on these postures.

Most studies on convective heat exchange from the human body have focused on the convective heat transfer coefficient. Previous studies [1–40] have determined this

*Corresponding author. Tel.: +81 823 73 8237; fax: +81 823 73 8352.
E-mail addresses: kurazumi@it.hirokoku-u.ac.jp (Y. Kurazumi), tad@hept.himeji-tech.ac.jp (T. Tsuchikawa), j-ishii@it.hirokoku-u.ac.jp (J. Ishii), k-fukaga@it.hirokoku-u.ac.jp (K. Fukagawa), yamato@kure-nct.ac.jp (Y. Yamato), n_mats@kpu.ac.jp (N. Matsubara).
[1]Tel.: +81 792 92 9378; fax: +81 792 93 5710.
[2]Tel.: +81 823 73 8238; fax: +81 823 73 8352.
[3]Tel.: +81 823 73 8246; fax: +81 823 73 8352.
[4]Tel.: +81 823 73 8956; fax: +81 823 73 8956.
[5]Tel.: +81 75 703 5426; fax: +81 75 703 5426.

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doi:10.1016/j.buildenv.2007.12.012

coefficient by measuring local coefficients and then calculating the ratio of that area to the entire body surface area. If one considers the results given above, however, such calculations include non-convective heat transfer area, and are thus of questionable accuracy. According to the principles of heat transfer, it is necessary to use the convective heat transfer area to more accurately calculate the convective heat transfer coefficient. In fact, only a handful of studies have taken into account the local heat transfer area of the human body.

Previous research reports have also estimated total heat transfer from the body using physiological measurements and heat flow sensors, as well as standard formulas, and then used the radiated heat to calculate the convective heat transfer coefficient of the body. However, the angle factors (configuration factors) for the local body are necessary to calculate radiative heat transfer. These have not been found, and the suggested estimates for their values are very questionable.

Some researchers have focused on experimental rather than theoretical formulas. Some have used simple heat emitting devices or assemblies to model the convective heat transfer coefficient of the human body [1–5,41,42], some have used real subjects to investigate the heat balance of the human body [6–22,43], others have used thermal mannequins [10,23–37], and some have used the mass and heat transport properties of naphthalene [38–40].

The figures and formulas for convective heat transfer coefficient established in the above reports differ with experimental procedures and theoretical calculations. The body has a complex shape, and it stands to reason that measured values would vary in validity and accuracy when calculating the heat transfer coefficient, both for body parts and for the entire body. Furthermore, most of the above studies used standing or sitting postures to measure the convective heat transfer coefficient. As mentioned previously, researchers tend to select simpler postures for which the entire body surface area contributes to the convective processes.

These experiments have sometimes used different wind speeds to create conditions of forced convection, or used temperature differences between the air, skin, and floor to create conditions of natural convection. The experimental formula is based on the driving force behind the convection expressed as a function. Such figures and calculations have differed depending on the experimental methods and computational logic used. This is because the shape of the human body is complex, and there may be some variation in the validity and effective accuracy of the selected measurements used to calculate the heat transfer coefficient.

Much research has been carried out since Winslow et al. [6] published their partitional calorimetry method, and since Hardy and DuBios [8] published their direct calorimetry method for measuring the heat exchange between the human body and its surrounding environment through convection. However, these experiments assumed that convective heat exchange took place at a uniform rate across the whole body surface.

Starting with Nielsen and Pedersen [10] later experiments used models of the human body, and measured forced convection wind speeds in small discrete areas. These measurements were considered representative of natural convection, and convective heat transfer coefficients were thus calculated. All of these experimental methods worked on the assumption that convective heat exchange was diffused equally across the surface of the human body.

On the other hand, Lee et al. [24] applied Colin and Houdas' conception [11] of the influence of natural convection across the whole body to limited areas of the human body surface, and proposed a convective heat transfer coefficient based on a mixed air flow model incorporating rising airflow due to natural convection together with the forced convection currents. Experiments designed to estimate the heat transfer coefficient at the location of such mixed air flows have also assumed that convective heat exchange takes place uniformly across the locations into which the surface of the object has been divided, with the exception of surfaces that are in contact with the floor and physically unable to permit the passage of air.

In addition, Tanabe and Hasebe [25] and Kuwabara et al. [33] considered that in forced convection experiments using moderate wind speeds, airflow direction had a great impact on convective heat exchange on limited areas of the human body's surface. In the areas with the exception of surfaces in contact with the floor and physically unable to permit the passage of air, there are heat exchanges, irrespective of whether or not they were facing the direction of the air current. However, even these experiments which aimed to find the heat transfer coefficient of limited areas of the human body's surface due to forced convection, they are assumed that all the parts of the surface hold uniform convective heat exchange.

It is, therefore, apparent that to determine the convective heat transfer coefficient for a particular direction of air flow or at a particular point is difficult, and that even those studies purporting to measure the coefficient at one particular point assume a uniform rate of heat exchange across the whole surface of the object under investigation. In other words, prior studies have been founded on the assumption that even under airflows with varying properties, convective heat exchange occurs evenly across the whole surface of the human body.

Most researchers have used a convective heat transfer area ratio of 1.0 for the convective heat transfer area for calculations of convective heat transfer area in the standing and chair sitting postures. According to Refs. [44,45], however, Kurazumi et al. took measurements and found that 10–20% of the body surface area did *not* contribute to the convective heat transfer surface.

It is commonly thought that the body's radiative heat transfer coefficient is calculated in the same way as the convective heat transfer coefficient and heat balance, but very few reports have given specific values for it, and there are no published reports of direct measurements of the radiative heat transfer coefficient. The only postures studied have been standing and chair sitting. Stolwijk [41], de Dear et al. [27], Ichihara et al. [28], and Ishii [46] have reported concrete values for the radiative heat transfer coefficient in the standing and chair sitting postures. Stolwijk [41], de Dear et al. [27], Ichihara et al. [28] used a human model to measure heat balance, Mochida et al. [2] used a human model to calculate heat balance, and Ishii [46] used real subjects to measure the heat balance of the human body. The configuration factors between the body parts and space were calculated using the Stefan–Bolzmann law.

Thus, there has been progress in research on the entire body's convective heat transfer coefficient in the standing and sitting postures, but publications on other postures are rare. In addition, it is rare for calculations of the convective heat transfer coefficient of the entire body to take actual account of the body's local convective heat transfer area.

In this study, postures in real spaces were considered, in which the influence of heat conduction through contacts between the body and the floor could not be neglected, while focusing on convective heat transfer area. These were the basic postures of standing, chair sitting, cross-legged sitting, legs-out sitting, and supine. The convective heat transfer coefficients of the entire body were measured using a thermal mannequin, and the goal was to develop empirical formulas for the convective heat transfer coefficients in each posture, with an accurate account of the convective heat transfer area. An additional goal was to measure the radiative heat transfer coefficients of the body. On the assumption of ordinary, steady-state convective air flow in the living space, we also attempted to establish the convective heat transfer coefficient of the body under steady-state conditions.

2. Calculation of convective heat transfer coefficient

It was decided to employ a thermal mannequin in a steady-state thermal environment in order to measure the radiative heat transfer and total local heat transfer with a radiant flux sensor and a heat flux sensor, respectively. The area of each sensor was $3.142 \times 10^{-4}\,\mathrm{m}^2$, but in comparison to the total surface area of the thermal mannequin (described in more detail below), this area is quite small and can be considered as a point.

The local convective heat transfer coefficient h_{ci} and local radiative heat transfer coefficient h_{ri} for body part i can be calculated from the measured local radiative heat flux R_{i} for body part i and the total heat flux Q_{i} for body part i, using the following equations:

$$h_{\mathrm{i}} = Q_{\mathrm{i}}/(T_{\mathrm{si}} - T_{\mathrm{a}}), \quad (1)$$

$$h_{\mathrm{ri}} = R_{\mathrm{i}}/(T_{\mathrm{si}} - \mathrm{MRT_i}) = R_i/(T_{\mathrm{si}} - T_{\mathrm{a}}), \quad (2)$$

$$h_{\mathrm{ci}} = h_{\mathrm{i}} - h_{\mathrm{ri}}, \quad (3)$$

where h_{i} is the local heat transfer coefficient for body part i [W/(m^2 K)], h_{ri} the local radiative heat transfer coefficient for body part i [W/(m^2 K)], h_{ci} the local convective heat transfer coefficient for body part i [W/(m^2 K)], Q_{i} the total heat flux for body part i [W/m^2] (quantity indicated by heat flux sensor), R_{i} the local radiative heat flux for body part i [W/m^2], T_{si} the local surface temperature of body part i [K], T_{a} the local air temperature of surrounding body part i [K], and $\mathrm{MRT_i}$ the local mean radiant temperature between a body part i and surrounding plane [K].

Finally, the radiative heat transfer coefficient h_{r} and the convective heat transfer coefficient h_{c} for entire body can be calculated using the following equations:

$$h_{\mathrm{r}} = f_{\mathrm{rad}} \sum_i h_{\mathrm{ri}} \cdot w_{\mathrm{radi}}, \quad (4)$$

$$h_{\mathrm{c}} = f_{\mathrm{conv}} \sum_i h_{\mathrm{ci}} \cdot w_{\mathrm{convi}}, \quad (5)$$

where h_{r} is the radiative heat transfer coefficient for the entire body [W/(m^2 K)], h_{c} the convective heat transfer coefficient for entire body [W/(m^2 K)], f_{rad} the radiative heat transfer area ratio [N.D.], f_{conv} the convective heat transfer area ratio [N.D.], w_{radi} the radiative heat transfer area coefficient for body part i [N.D.] (weighting coefficient for calculating radiative heat transfer coefficient), and w_{convi} the convective heat transfer area coefficient for body part i [N.D.] (weighting coefficient for calculating convective heat transfer coefficient).

Radiative heat transfer area ratio for body part i f_{radi} can be calculated using the following equation:

$$f_{\mathrm{rad}} = A_{\mathrm{rad}}/A_{\mathrm{s}}, \quad (6)$$

where A_{rad} is the radiative heat transfer area for entire body [m^2], and A_{s} the total body surface area for the human body [m^2].

Convective heat transfer area for body part i f_{convi} can be calculated using the following equation:

$$f_{\mathrm{conv}} = A_{\mathrm{conv}}/A_{\mathrm{s}}, \quad (7)$$

where A_{convi} is the convective heat transfer area for entire body [m^2].

Radiative heat transfer area coefficient for body part i w_{radi} can be calculated using the following equation:

$$w_{\mathrm{radi}} = A_{\mathrm{radi}}/A_{\mathrm{rads}}, \quad (8)$$

where A_{radi} is the radiative heat transfer area for body part i [m^2], and A_{rads} the radiative heat transfer area for entire body [m^2].

Convective heat transfer area coefficient for body part i w_{convi} can be calculated using the following equation:

$$w_{\mathrm{convi}} = A_{\mathrm{convi}}/A_{\mathrm{convs}}, \quad (9)$$

where A_{convi} is the convective heat transfer area for body part i [m^2], and A_{convs} is the convective heat transfer area for entire body [m^2].

3. Schemes for experiment

3.1. Experimental apparatus and settings

The experiment was performed in the artificial climate chamber (Espec Corp., TBRR-9A4GX) shown in Fig. 1. A thin cloth-walled booth was set up as an artificial climate chamber, providing steady-state conditions where the air temperature was about the same as the cloth-wall surface temperature. The heat capacity of the cloth-wall was low, and thus we assumed the surface temperature was balanced with the air temperature.

A thermal mannequin (Kyoto Electronics Manufacturing Co., Ltd., THM-117S/217S) with movable joints at the shoulders, hips and knees was used for the experiment. It was divided into 17 regions: head, chest, back, abdomen, lower back, upper arms, lower arms, hands, thighs, shins, and feet. The heat generation and the surface temperature on each part could be controlled. The surface temperature of each part was maintained at a constant 33 °C.

Measurements were carried out with the mannequin in the seven postures shown in Fig. 2: standing (exposed to the atmosphere; floor contact); chair sitting (exposed; contact with seat, chair back, and floor); cross-legged sitting (floor contact); legs-out sitting (floor contact); and supine (floor contact).

The mannequin was supported in the standing (exposed) posture by hanging it so that its feet were about 0.2 m above the floor, in order to avoid contact between adjacent area surfaces, leaving them completely open to air currents. In the standing (floor contact) posture, it was supported by hanging again, but this time, with heat insulation attached in firm contact with the bottom of its feet. To support the mannequin in the chair sitting (exposed) posture, it was placed in a frame that exposed all body surfaces, except those in mutual contact, to air circulation. It was seated in the artificial climate chamber about 0.2 m above the floor. For the chair sitting (contact with seat, chair back, and floor) observation, the seat and back of the chair were made of heat insulation and heat insulation was placed beneath the mannequin's feet. The mannequin was placed so that its contacting surfaces were in full contact with the seat, back, and floor. For the cross-legged sitting (floor contact), legs-out sitting (floor contact) and supine (floor

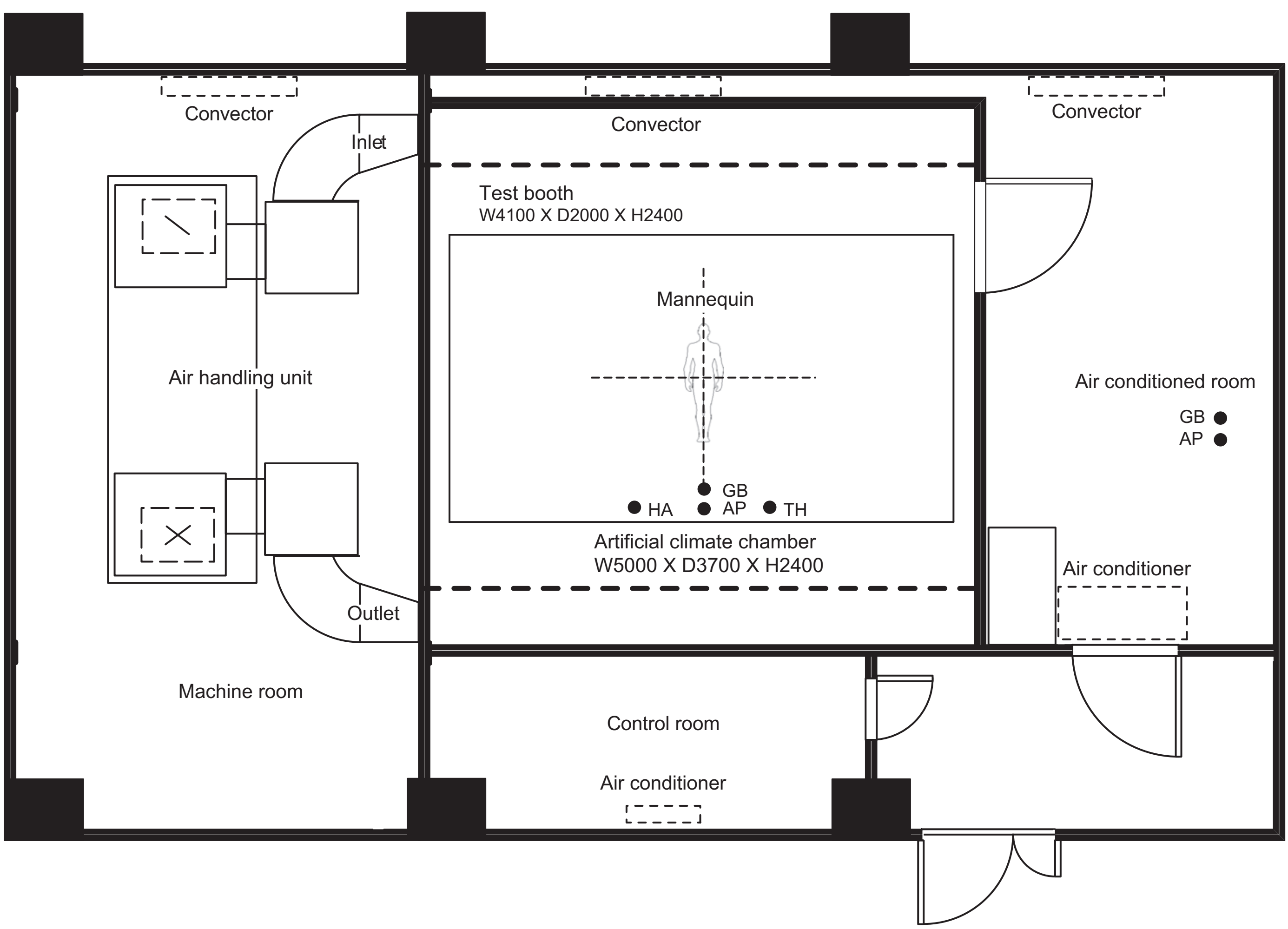

Fig. 1. Plan of experimental setup where thermal mannequin is exposed to thermal conditions. GB: globe thermometer; AP: aspirated psychrometer; HA: hot-sphere anemometer; and TH: air temperature in height.

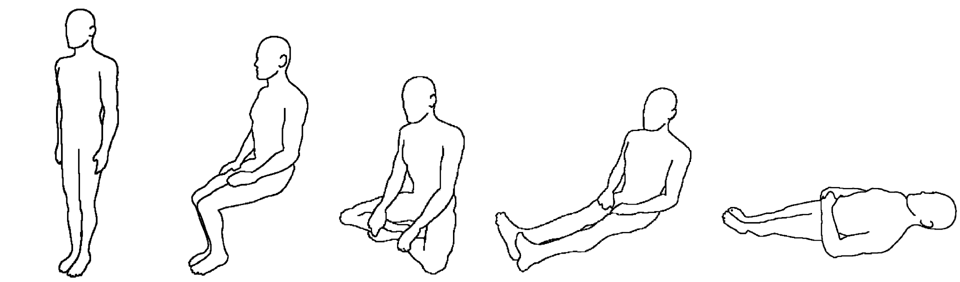

Fig. 2. Experimental postures. Stnd-exp is the standing (exposed) position without the area of contact between the body and the floor. Stnd-cod is the standing (floor contact) position with the area of contact between the body and the floor. Chair-exp is the chair sitting (exposed) position without the area of contact between the body and the chair and the area of contact between the body and the floor. Chair-cod is the chair sitting (contact with seat, chair back, and floor) position with the area of contact between the body and the chair and the area of contact between the body and the floor. Cross is the cross-legged sitting (floor contact) position with the area of contact between the body and the floor. Leg-out is the leg-out sitting (floor contact) position with the area of contact between the body and the floor. Supine is the supine (floor contact) position with the area of contact between the body and the floor.

Table 1
Experimental conditions

Air temp. (°C): T_a	Air velocity (m/s): V_a	Relative humidity (%): RH	Wall temp. (°C): T_w	Ceiling temp. (°C): T_c	Floor temp. (°C): T_f
16.0 18.0 20.0 22.0 24.0 26.0	<0.2	50	$=T_a$	$=T_a$	$=T_a$

contact) positions, a false floor of heat insulating sheet was constructed 0.8 m above the floor in the artificial climate chamber and the mannequin was seated facing toward or away from the thermal sensors. The heat insulation used for the floor and chair components was 50 mm extruded polystyrene foam sheets (Dow Kakoh K.K., Styrofoam, with a coefficient of thermal conductivity of 0.040 W/(m K)).

The thermal environmental conditions were set at 26 °C or less, at which the surface temperature of the thermal mannequin could be controlled accurately, as the thermal mannequin did not possess a heat loss mechanism, and was only cooled via natural heat loss. Table 1 shows the conditions in the thermal environment, which was made as uniform as possible. The air and wall temperatures were equalized at six levels; 16, 18, 20, 22, 24, and 26 °C. A gentle airflow was established at 0.2 m/s or lower, and the humidity was maintained at 50% RH.

3.2. Items for measurement

The local radiative heat transfer and local total heat transfer of the thermal mannequin were measured with a radiant flux meter (Captec Entreprise, broad-band RF series, 0.25 mm thick, sensitivity 0.875–1.48 mV/(W/m^2) and response time, 50 ms) and a thermal flux sensor (Captec Entreprise, HF series, 0.4 mm thick, sensitivity 1.69–2.10 mV/(W/m^2), response time, 200 ms, one side painted black). These sensors were placed close to the mannequin and the measured values were employed in the calculations. Both sensors were about 20 mm in diameter, and were relatively thin disks that could be flexed into a convex shape, and that were judged to have no meaningful effect on the convective flow conditions or temperature field near the mannequin. They contained T-type thermocouples whose output was taken as the mannequin surface temperature.

Toy and Cox [47] and Ishii et al. [22] have shown that the convective heat transfer coefficient varies with circumference position around the trunk, upper and lower limbs, and other locations of the body. The reliability of such measurements can be expected to increase at more data are gathered, but as the sensors and their supporting structures are inevitably a disturbing factor and the number of sensors is limited, it was, therefore, decided to take measurements at three typical circumference positions that are easily measured with the available equipment. Fig. 3 shows the skin temperature and heat flow measurement locations. There were a total of 22 locations on 11 body parts, on the left side of the mannequin: head (forehead and occipital pole); chest (breast); back (scapular spine); abdomen (navel); lower

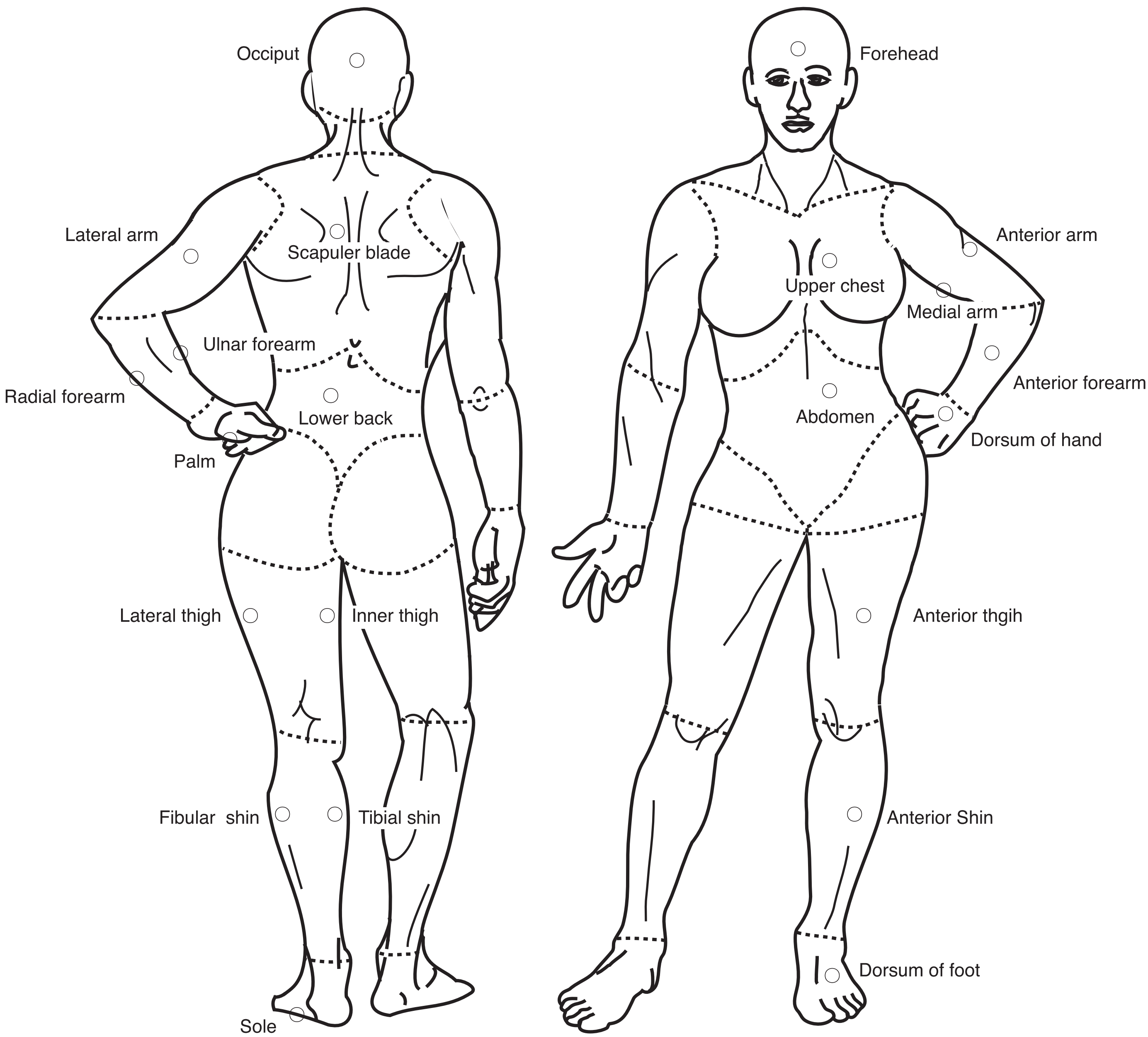

Fig. 3. Measuring points of skin temperature and heat flow rate. ○: measuring spot.

back (iliac crest); upper arms (three points at 120° intervals around the arm, starting at the outermost line); forearms (three points at 120° intervals, starting at the outermost line); hands (back, palm); thigh (three points at 120° intervals, starting at the front line); lower leg (three points at 120° intervals, starting at the front line); and foot (instep, sole). Measurements were taken at 15-s intervals.

The weighting coefficients involved with the convective heat transfer areas listed in Table 2 were used to calculate the total heat transfer, the radiative and convective heat transfer coefficients for the entire body and mean skin temperature. As mentioned above, the conventional approach has treated all portions of the surface of body parts as equally exposed to convective flows, except for those that must always be physically blocked, such as the soles of the feet. The local differences between upstream and downstream exposure to such flows were neglected. In other words, it has been assumed that all of the surfaces of the human body have the same convective heat transfer characteristics, irrespective of differences in the characteristics of the actual airflows. In body parts where multiple measurements were taken, equal weights were assigned and the results of measurements were averaged to calculate the thermal transfer coefficient.

The air temperature, relative humidity, vertical distribution of air temperature, air flow velocities and temperatures of all room interior surfaces were monitored in order to have a full record of environmental parameters.

Air temperature and relative humidity were measured using an Assmann aspiration psychrometer placed ahead

Table 2
Weighting coefficients for calculating mean skin temperature and heat transfer coefficients

Region	Stnd-exp	Stnd-cod	Chair-exp	Chair-cod	Cross	Leg-out	Supine
Head	0.084	0.085	0.086	0.093	0.095	0.088	0.091
U-arm	0.091	0.092	0.096	0.104	0.107	0.099	0.095
L-arm	0.061	0.061	0.062	0.067	0.066	0.064	0.065
Hand	0.039	0.040	0.037	0.040	0.040	0.039	0.032
Trunk	0.274	0.277	0.275	0.275	0.312	0.285	0.252
Thigh	0.248	0.251	0.238	0.208	0.228	0.217	0.246
Foot	0.141	0.143	0.145	0.156	0.107	0.136	0.141
Leg	0.062	0.051	0.060	0.057	0.045	0.072	0.078

Weighting coefficient [N.D.] is the local heat transfer area of a region area of the body to the heat transfer area of entire body.

Table 3
Heat transfer area ratios for calculating heat transfer coefficients

Area ratio	Stnd-exp	Stnd-cod	Chair-exp	Chair-cod	Cross	Leg-out	Supine
Radiation	0.786	0.773	0.741	0.732	0.606	0.686	0.708
Convection	0.954	0.948	0.918	0.860	0.843	0.906	0.844

Radiative heat transfer area ratio [N.D.] is the radiative heat transfer area to the total body surface area of the human body. Convective heat transfer area ratio [N.D.] is the convective heat transfer area to the total body surface area of the human body.

of the mannequin (Fig. 1). The height was set at a position of the mannequin's abdomen. The height for the standing (exposed to the atmosphere, floor contact), chair sitting (exposed to the atmosphere; contact with seat, chair back, and floor), cross-legged sitting (floor contact), legs-out sitting (floor contact), and supine (floor contact) positions were at 120, 80, 100, 100, and 90 cm above the floor. Air flow velocity was measured using a non-directional hot bulb-type anemometer. The vertical air temperature profile was also taken, and the temperatures of all room wall surfaces were taken with T-type thermocouples (0.3 mm dia.) at 15-s intervals. The vertical temperature profile was determined from measurements at the floor surface, at 10, 60, 110, and 170 cm above the floor, and the ceiling surface.

3.3. Experimental procedure

The thermal mannequin was placed in each posture, and predetermined thermal environmental conditions were established. The electrical power to each part of the mannequin was controlled to maintain surface temperature at 33 °C. After the heat transfer between the thermal mannequin and the thermal environment reached equilibrium, the mannequin was exposed to steady-state conditions for at least 45 min. The final 15 min of data for environmental thermal conditions, mannequin surface temperatures, radiative heat transfer, and total heat transfer were used for analysis.

In order to obtain a radiative heat transfer coefficient for the entire body, it is essential to include the heat transfer area for each posture. However, despite the many reports on measurements of the radiative heat transfer area of the human body in standing and sitting positions, very few reports address other postures. With regard to convective heat transfer areas, at this writing, the measurements by Kurazumi et al. [44,45] are the only reports in existence. The heat transfer coefficients were calculated, incorporating the radiative heat transfer area ratio [48] and convective heat transfer area ratio [45] for each posture shown in Table 3. The mean local heat transfer coefficient for each body part was calculated by employing the weighting coefficients for convective heat transfer area given in Table 2.

There have been many reports on the emissivity of the human body [49–76]. These differ somewhat with regard to the waveband observed, but coefficients typically range between 0.99 and 0.95.

Hardy [77], Hendler et al. [61] and Rapp and Gagge [78] estimated the emissivity of the body using the coefficient of reflectivity of electromagnetic waves. Of particular interest is the report by Hendler et al. [61], who found that the color-dependent reflectivity of electromagnetic waves of length 2 μm and above was 1.7%, suggesting an emissivity of 0.983. Huang and Tokugawa [76] recently described a non-contact measuring method using an infrared camera and found a value of 0.964 for the emissivity of the human body. They found no variations among body parts or experimental subjects.

These measurements were carried out under steady-state conditions. As the temperature gradient at the surface of the skin varies with changes in blood flow and other factors; however, it is difficult to accurately set the temperature for the heat source. Many researchers have used thermal radiometers to compare the radiated heats from the skin surface and a perfect black body. Because the two radiative heat transfer coefficients are almost equal, however, small measurement errors can be magnified into large errors in estimates of radiated heat. It has also been pointed out that the skin's emissivity is different under moist conditions.

This study employed a new method for measuring heat transfer from the body and attempted to extend the boundaries of knowledge by examining the convective heat transfer coefficients in previously unexamined postures. The conventional figure of 0.98 [79] was used for the emissivity of the human body when evaluating the radiative heat exchange between the human body and the environment.

4. Experimental results and discussion

The air temperatures remained within $\pm 0.1\,^{\circ}\mathrm{C}$ during the experiments. The RH stayed within $\pm 10\%$. The air temperatures were nearly equal at the heights measured, from 10 to 170 cm above the floor in the test area. The vertical air temperature distribution was within the set value (about $\pm 0.1\,^{\circ}\mathrm{C}$). The air current speed was stable, remaining within 0.1 m/s throughout the experiments.

Thus, the thermal environment was approximately uniform in all of the experiments. As the dry-bulb temperature was uniform within $0.1\,^{\circ}\mathrm{C}$ in the vertical range corresponding to the height of the mannequin, that value was used for the potential difference in calculating the convective heat transfer.

As mentioned above, it was assumed that the thin cloth surface temperature was about the same as the air temperature, and thus we assumed the surface temperature was balanced with the air temperature. In other words, the mean radiant temperature was equal to the air temperature. Consequently, that value was used for the potential difference in calculating the radiative heat transfer.

For each posture, Fig. 4 shows the relationships between the radiative and convective heat transfer coefficients, and differences between the mean skin temperature corrected using the convective heat transfer area and the air temperature.

Each radiative heat transfer coefficient tended to decrease slightly with the difference between air temperature and skin temperature, corrected for the convective heat transfer area, in all postures. These coefficients were greatest in the standing (exposed) and least in the cross-legged sitting (floor contact) postures.

Normally, they substitute the emissivity and the heat transfer area ratio of the human body for the linear equation [79] and are calculated. This reason is that there are no experimental values. However, as the radiative heat transfer area of other postures differs greatly when compared with standing and chair sitting, it is essential to include the handling of the human body's radiative heat transfer area when using a linear equation. The posture with the highest radiative heat transfer area was standing posture and the lowest was cross-legged sitting posture [48,80]. Postures in which the lower extremities are close to the trunk gave lower radiative heat transfer area than other postures. This can be attributed to large radiation

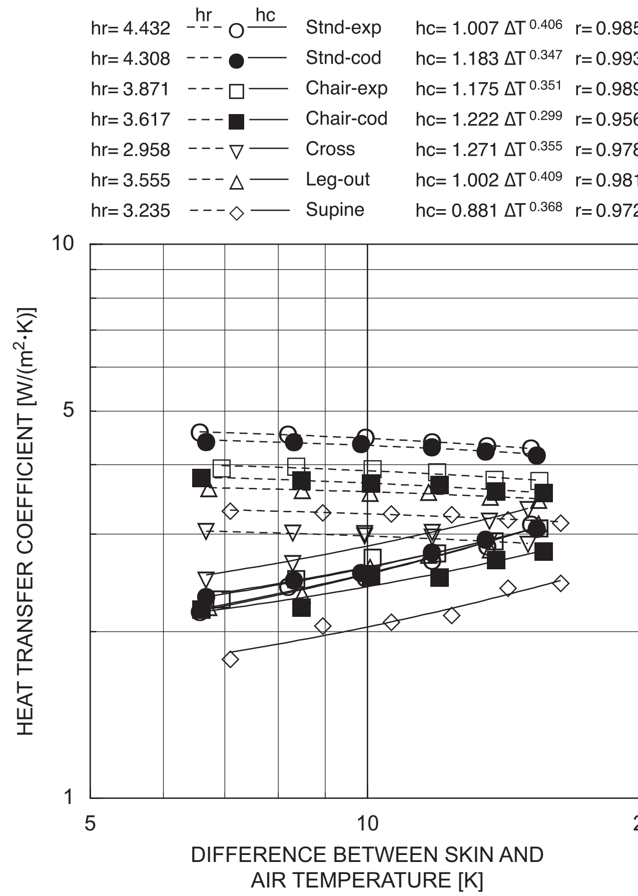

Fig. 4. Relation between heat transfer coefficients for the whole body and difference between skin and air temperature. h_r: radiative heat transfer coefficient [W/(m^2 K)]. h_c: convective heat transfer coefficient [W/(m^2 K)]. ΔT: difference between heat transfer area—corrected mean skin temperature and air temperature [K].

interchange and conductive heat transfer between the different parts of the body.

These were the results of the adjustment to the radiative heat transfer area ratios [48,80]. Comparing the results among standing (exposed), standing (floor contact), and supine (floor contact), which had similar support conditions, the supine posture had a much lower radiative heat transfer coefficient. The physical contact between the body and floor had a large impact on heat transfer.

The coefficient of the regression equations for the radiative heat transfer coefficient in each posture was tested with ANOVA for significance. Probability values (p) of >0.05 were found for every part, and so the derived slopes could not be considered valid. Therefore, the local radiative heat transfer coefficient for each posture can be expressed as the mean. The highest mean coefficient was that of the standing (exposed) posture, at 4.432 W/(m^2 K), and the lowest, that of the cross-legged sitting posture, at 2.958 W/(m^2 K).

Radiative heat transfer coefficients were directly measured in this study, and so comparisons can only be made in a loose manner. The values for the standing posture found by Stolwijk [41] and Mochida [2] are lower than those found using linearized equations [79,81]. The present results were similar to those of Ichihara et al. [28], which were 4.2 W/(m^2 K). In the present study, lower results were found for chair sitting than those found by deDear et al. [27] and Ichihara et al. [28], the results are similar to those found by Ishii [46] (3.9 W/(m^2 K)), who attempted to account for the distribution of coefficients. There are no data with which to compare our results for the cross-legged sitting, legs-out sitting, or supine postures, but the present results seem to reflect the influence of radiative heat transfer area ratio and distribution of surface area among the body parts.

Each convective heat transfer coefficient tended to increase with the difference between air and skin temperatures, corrected for the convective heat transfer area, in all postures. When the air temperature is low, the body's skin temperature also deceases, and the body regulates its temperature to reduce heat loss. However, it was not possible to take this into consideration within the scope of this research, as the skin temperature was maintained at 33 °C. The results indicated in Fig. 4 show how the convective heat transfer coefficient grows larger as the temperature difference between the air and skin temperatures increases. In cases where the body's aforementioned physiological response comes in the form of a drop in skin temperature, the difference between the air and skin temperatures shrinks. The velocity of ascending air currents may also decrease physically due to differences in temperature in the body's surroundings. Consequently, as it is believed that the convective heat transfer coefficient also shrinks, it has been conjectured that movement commensurate with the change in the temperature difference occurs along the regression line.

The regression equations for the convective heat transfer coefficients (h_c [W/(m^2 K)]) for natural convection, driven by the difference between the mean skin temperature corrected using the convective heat transfer area and the air temperature, are given below:

standing (exposed to atmosphere)

$$h_c = 1.007\Delta T^{0.406}, \tag{4'}$$

standing (floor contact)

$$h_c = 1.183\Delta T^{0.347}, \tag{5'}$$

chair sitting (exposed to atmosphere)

$$h_c = 1.175\Delta T^{0.351}, \tag{6'}$$

chair sitting (contact with seat, chair back and floor)

$$h_c = 1.222\Delta T^{0.299}, \tag{7'}$$

cross-legged sitting (floor contact)

$$h_c = 1.271\Delta T^{0.355}, \tag{8'}$$

legs-out sitting (floor contact)

$$h_c = 1.002\Delta T^{0.409}, \tag{9'}$$

supine (floor contact)

$$h_c = 0.881\Delta T^{0.368}, \tag{10'}$$

where h_c is the convective heat transfer coefficient [W/(m^2 K)], and ΔT the difference between mean skin temperature corrected using convective heat transfer area and air temperature [K].

The value is the highest for cross-legged sitting and lowest for supine. In the standing and sitting postures, the convective heat transfer coefficients without the contact of the floor or chair surfaces are larger than the coefficients with the contact of the floor or chair surfaces.

Fig. 5 compares the figures for the convective heat transfer coefficients in the postures examined in this study and in previous studies. The present figures were nearly the same as those found by Omoto and Mochida [5] and much lower than those published by Nielsen and Pedersen [10], but showed nearly the same dependence on the difference between mean skin temperature and air temperature. In contrast, the present figures were slightly lower than those of Nishi and Gagge [38] but showed a distinctly different trend in the dependence on temperature difference. In the chair sitting posture, the present findings were nearly the same as those of Ishigaki et al. [18] and lower than those of Nielsen and Pedersen [10] and Omoto and Mochida [5], while showing nearly the same dependency on difference between mean skin temperature and air temperature. On the other hand, the present findings were lower than the results of Mitchell et al. [13] and Ishii et al. [22], and showed differing dependencies on temperature difference.

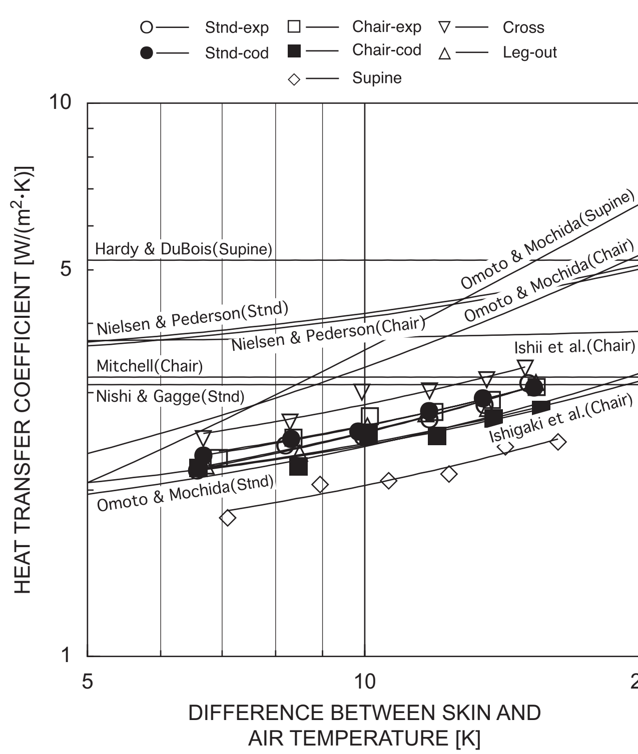

Fig. 5. Comparison of convective heat transfer coefficients of the human body in previous studies.

In the supine posture, the present findings were remarkably lower than the results presented by Omoto and Mochida [5] and Hardy and DuBois [8].

The results of other studies must also be noted. Choi et al. [19] found the convective heat transfer coefficient for a person seated cross-legged on a heated floor, driven by the difference between the mean skin temperature and the operative temperature. Under the floor heating space, the potential for the difference in temperature is influenced by the floor surface temperature. Thus, the difference is not the temperature between a body's skin temperature and its air temperature but the temperature between a body's skin temperature and its equivalent temperature, the operative temperature. Consequently, this cannot be directly compared with the present study. There are no studies addressing the legs-out sitting posture. Overall, the present results are lower than those found in previous studies. When examining heat transfer, the convective heat transfer coefficient is expressed through an exponential function that relates to the difference in temperature between skin temperature and the surrounding atmospheric temperature when there are natural convection currents. Therefore, a temperature difference-dependent tendency is seen. However, the impact of setting constant values from a practical point of view appears to affect this temperature difference-dependent tendency. There is also speculation over whether the human body model used in the experiment was able to simulate the shape of the human body, and it is believed that its posture exerted an influence. Complex postures and differences in human body shape have an effect on disturbing air currents, while the length of the buoyant direction has an impact on the development of air currents. With regard to this point, it is necessary to perform an investigation by measuring the air current distribution surrounding the body. Büttner [43] has proposed an equation for the convective heat transfer area, which takes into account the convective heat transfer coefficient during forced counterflow, but also showed that this equation underestimates the coefficient during ordinary forced counterflow. The difference from previous studies in the presently determined values is probably due to two factors: these values were obtained in a procedure involving direct measurements, in contrast to previous methods for calculating radiative heat loss; and a convective heat transfer area ratio was used, similarly to Büttner [43].

5. Summary

A thermal mannequin was used to carry out measurements of heat transfer coefficients of the whole human body under natural convection in seven postures as follows: standing (exposed to the atmosphere, floor contact); chair sitting (exposed to the atmosphere; contact with seat, chair back, and floor); cross-legged sitting (floor contact); legs-out sitting (floor contact); and supine (floor contact). The convective heat transfer area was a key parameter in this study. The radiative heat transfer coefficients were evaluated in these postures. New empirical formulas were proposed for the convective heat transfer coefficients of the human body in different postures, incorporating the convective heat transfer areas.

Acknowledgments

We would like to express our sincerest gratitude to the individuals who assisted us in taking measurements and conducting the experiment in the present study.

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