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Evaluation of Hand and Finger Heat Loss with a Heated Hand Model

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Abstract. A heated full-scale hand model has been used to determine indirectly hand and finger heat losses of human subjects exposed to four ambient cold conditions (0, 4, 10 and 16°C, air velocity ≈0.3 m/s). Heat transfer coefficients determined with the hand model, were used to calculate heat flux based on measured skin to ambient temperature gradients. The responses of eight subjects from a previous study were used for the analysis. The measurements were carried out in a small climate chamber which was cooled by evaporating liquid carbon dioxide. The thermal hand was put into the chamber in a vertical position with the thumb up. The surface temperature of the thermal hand was controlled at 21, 25, 28, 31 and 34°C under each of the four ambient cold conditions, in order to investigate possible temperature dependence of the calculated combined convective and radiate heat transfer coefficient (h_{CR}). The value of h_{CR} varied between approximately 9–13 W/m^2°C for fingers and palm and back of hand, respectively. Calculated heat losses showed significant individual variation, corresponding to the maintained skin to ambient temperature gradient. Individual values from about 50 to more than 300 W/m^2 were calculated. Several subjects showed CIVD and heat fluxes associated with this phenomenon were sometimes doubled. The measurement results showed realistic and comparable with literature date. The advantages of the thermal hand model can be counted as easy to use; directly measures the heat loss; highly reproducible and no interruption. It appears that a heated hand model provides a useful methods for analysis and quantification of hand heat loss.

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Keywords: Cold, finger, hand, thermal hand, heat loss

Introduction

The heat flow from a small surface such as hand and fingers, has been measured with heat flux sensors (Daanen and Ducharme, 1991), or flexible heat flow devices (Gin et al., 1980; Nicholls 1924). The weak point of these methods is that the thermal insulation of the sensing device of the heat flux sensor will reduce heat flow by an amount that will vary with the underlying insulation of the body tissue. The electrical output of the disc is not proportional to the heat loss that takes place through adjacent skin not covered by the device. The still convective heat transfer coefficient (h_C) was studied by Danielsson (1990) using a heat flux sensor. A complicated calibration process was performed. Still, some error due to the influence from radiation could not be avoided. Also, the results would be much dependent on the location of the sensor. Very little data are published for hand heat exchange in air.

The present study used a heated full scale hand model to indirectly measure the heat loss from the human hand.

Method

In air the heat loss from hand and fingers to the cold environment is mainly through radiation and convection. The rate of heat loss can be calculated by $Q=h_{CR} \cdot \Delta T$, where h_{CR} is the combined heat transfer coefficient for heat loss by convection and radiation (Monteith 1973; Monteith and Mount, 1974) and ΔT is the temperature gradient between the skin surface and the air.

A heated full scale thermal hand (Nilsson et al., 1992) was used in the experiment. The plastic hand model is casted in a model prepared from a standard porcelain hand model used for manufacturing rubber gloves (Rosenthal, Germany). The hand surface is divided into seven zones: thumb, index, middle, ring and little fingers, palm and back of the hand. Each zone is densely covered by resistance wires with a varnish layer on top. Hand is heated from a DC-power transformer.

Heat input is sufficient to maintain a mean hand surface temperature at any level in the range 20 to 35°C at a chamber temperature (T_{ch}), which is at least 20°C lower. Surface temperature (T_{surf}) of each zone of the thermal hand is measured and controlled at defined levels under defined environmental conditions. Local deviations from the controlled mean T_{sur} do not exceed ± 0.1°C. A personal computer served as a regulation and acquisition unit for the system.

The technical specification and function of the thermal hand follows the European Standard EN 511. The technique allows highly reproducible measurements of hand heat loss under a variety of environmental conditions and sets of heat transfer coefficients can be derived for fingers and other parts of the hand.

The thermal hand allows the indirect determination of the combined heat transfer coefficient for convection and radiation (h_{CR}) (Equation 1). When the power consumption has equilibrated, the power input to the hand is measured. This is equal to the heat loss by convection and radiation. The accuracy of the power measurement is ± 2% of the average power for the test period. A regulation program measures T_{surf}. The resultant heat transfer coefficient for zone i of the hand including the boundary air layer is calculated by

$$h_{CRi} = \frac{Q_i}{T_{surfi} - T_{ch}} \qquad (1)$$

i is the zone number i of the thermal hand.
Q_i is the heat loss of zone i, in W/m^2.
h_{CRi} is the heat transfer coefficient of zone i, in W/m^{2}K.

The h_{CR} for the whole hand was calculated from the sum of heat losses from the finger zones, palm and back of hand divided by the temperature gradient (same for all zones).

The experiment for measuring the heat transfer coefficient from the thermal hand and the heat loss from human hands under different cold air conditions was carried out in a small climate chamber. The small chamber measured 770 × 400 × 400 mm. The temperature inside the chamber was controlled and varied with a pre-fabricated control system (AES model RW-1100). The air was cooled by liquid carbon dioxide evaporation in the chamber. The gas injection was controlled by a valve through a thermistor and a regulation circuit. The air and the wall temperatures inside the small chamber were tested on 19 points in preliminary experiments for each experimental condition. Air temperature in the chamber could be maintained with a precision of ± 1°C. The air in the chamber was slowly circulated with a fan and air velocity in the operating zone of the hands was less than 0.3 m/s. The temperature on the walls of the chamber was very close to the temperature of the air (± 1°C).

The thermal hand was put into a small chamber in the vertical position with the thumb up. The chamber temperatures (T_{ch}) were controlled at 0, 4, 10 and 16°C. The thermal hand surface temperatures were controlled at 21, 25, 28, 31 and 34°C for each T_{ch} condition. The power input to the hand was measured every 10 seconds. The test under each combined conditions (T_{surf} and T_{ch}) was taken twice and the differences between the two measurement were less than ± 0.1 W/m^2. During thermal hand measurement, the chamber air temperature was measured at 2 points around the thermal hand simultaneously with the measurement of heat input to the thermal hand and surface temperature on the thermal hand. The average of the two air temperature measurements were taken as T_{ch}. The power input (Q_i) to the hand was averaged for 10 minutes after equilibrium. The Q_i and the T_{ch} were then applied in the Equation (1) to calculate the h_{CRi} of each zone of the thermal hand.

Subject data for the determination of hand finger heat losses were obtained from the investigation reported by Chen et al. (1996). Eight volunteers (4 male and 4 female) participated in the experiments. They were average 38 years of age (from 23 to 48 years). During the experiment, subject sat on an adjustable chair with thermally comfortable clothing. The left hand was put into the small camber and kept vertically with the thumb up (the same position as thermal hand). The wrist of the hand was supported to reduce fatigue during 60 minutes of cold air exposure. The right hand and the rest of the body were in room temperature (20 to 22°C). The air temperature inside the small chamber was controlled. Each subject was exposed once to each T_{ch} condition for one hour.

Skin temperature (T_{sk}) was measured at the base, middle and tip of the index finger (palm side), at the middle phalanx of each finger (palm side) and at the center of palm and back of the hand. The T_{ch} was measured at two points around the hand, as the same as in the thermal hand study. The skin temperatures and the chamber temperatures were monitored with Fenwal thermistors, which were calibrated with a precision of ± 0.2°C. Skin temperatures were recorded every minute by the acquisition system.

The surface area of the thermal hand was measured by putting tape on the surface, then take off the tape, weigh it and compare it with the weight of tape plaster with a known surface area. The precision of the measurement was ± 1 cm^2. It was assumed that the index finger of the subjects could be considered as a cylinder. The circumferences were measured on the proximal flexion crease of the index finger. The length of the index finger was measured from the tip to the proximal flexion crease of the finger. All the dimension measurements were made with a soft ruler with a precision of ± 1 mm. The volume of the finger was measured by immersing the index finger into a water container filled up to the proximal flexion crease of the finger. Each measurement was taken three times in three days. The surface area of the index finger was calculated by Equation (2). The accuracy of the finger area measurement was ± 0.5 cm^2.

$$A = \frac{C_p + C_t}{2} \cdot L + \frac{C^2{}_t}{4 \cdot \pi} \qquad (2)$$

A: is the skin surface area of the index finger of the subjects.
C_p: is the circumference measured on the proximal flexion crease of index finger.
C_t: is the circumference at the tip of index finger. It was calculated from the measurement of finger volume.
L: is the length of the index finger.

The heat loss of the hand of the human subject was calculated by Equation 3 according to the heat transfer coefficient (h_{CR}) from thermal hand experiments. In this calculation, the finger was assumed as a cylinder in which it had a well-proportioned T_{sk} gradient with the highest on the base of the finger and lowest on the tip of the finger. The T_{sk} measurement on the middle phalanx of the fingers could represent the average T_{sk} of the whole finger cylinder. h_{CRi} was calculated from equation 1 for the different T_{ch} conditions.

$$Q_I = (T_{skI} - T_{ch}) \cdot h_{CRi} \quad (3)$$

I is the different parts of the human subjects' hands respectively to the same part of thermal hand i.

The total heat loss from the index finger (P) was then calculated by multiplying Q_{ii} with the surface area (A) (Equation 2) of the index finger. The heat loss per volume (q) of the index finger was calculated by using P divided by the measured volume of index finger.

During data analysis, three groups were classified according to the T_{sk} reaction patterns (Fig. 1) of the human subjects during the cold air exposure: CIVD group, in which the cold induced vasodilatation (Lewis 1930); Steady state group (SS) in which the T_{sk} reached a steady state, and unstable group (USS), in which the subjects T_{sk} did not reach a steady state. In CIVD group, the T_{sk} used for calculating the heat loss was taken separately at the highest crest point and the lowest trough point of the recorded curve. The time when crest T_{sk} and trough T_{sk} appeared was considered when average lowest and highest T_{sk} of the hand appeared on individual's cooling curve. In SS group, the average T_{sk} of different section of the hand in the last 10 minutes of exposure was considered. In USS group, the T_{sk} of the last 2 minutes of the cold exposure was used.

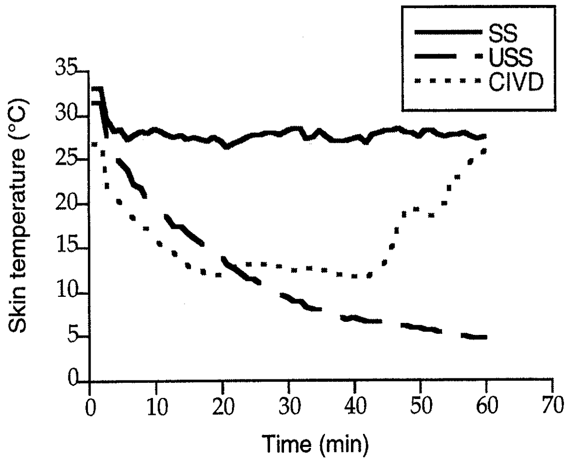

Fig. 1 Three typical skin temperature records from the index finger representing the groups of CIVD, SS and USS.

Results

The morphological measurements of the index finger of the 8 subjects gave the average length of 7.5 ± 0.7 cm, the circumference on the base of 6.9 ± 0.7 cm, and the volume of (1.97 ± 0.54) × 10^{-5} m^3. The calculated surface area of the finger was (4.32 ± 0.67) × 10^{-3} m^2.

The combined heat transfer coefficient (h_{CR}) for each zone of the thermal hand was significantly effected by the chamber temperature ($P<0.001$) (using multiple analysis of variance). The surface temperature on the thermal hand did not have significant effect on h_{CR} when considering each zone separately, but had a significant effect when taking the measurement from all the zones together as the same data pool (using multiple analysis of variance). Table 1 shows h_{CR} value under each chamber temperature condition.

There are significant differences ($P<0.001$) for the combined heat transfer coefficient between each zones of the thermal hand under the same chamber air temperature condition. Fig. 2 shows the results. Each bar shows the high, average and low values with 95% confidence intervals. The data for each bar comes from 10 measurements. The h_{CR} value for the whole hand were between 10–11 W/m^2°C.

The grouping situation according to the T_{sk} responses pattern during the cold exposure is shown in Table 2.

Fig. 3 shows the calculated heat loss for crest and trough of CIVD group. The data was taken as the average of the four subjects. The heat loss was calculated from Equation 3, where the h_{CRi} was taken according to the corresponding finger and T_{ch} condition from Table 1.

The results of calculated heat loss of SS group and USS group are shown in Fig. 4 and Fig. 5. The data for the SS group was taken as the average of 8 subjects. Each bar represented the lowest, average and highest values in the group. A similar representation as in Fig. 5 is used.

The total heat loss of the index finger (P) and the heat loss per surface area and per volume (q) of the tissue of the index fingers were calculated. The data in CIVD group

Table 1 The combined heat transfer coefficient of different zones of thermal hand under the different temperature conditions. in W/m^{2}K

Tch	Thumb	Index	Middle	Ring	Little	Palm	Back
0°C	9.5 ± 0.7	10.7 ± 0.9	12.2 ± 0.8	10.9 ± 0.6	12.8 ± 0.5	11.7 ± 0.9	11.2 ± 1.0
4°C	8.8 ± 0.7	10.2 ± 1.2	11.1 ± 1.0	10.0 ± 0.9	11.6 ± 0.9	10.7 ± 0.9	10.4 ± 0.7
10°C	9.2 ± 0.6	10.2 ± 1.1	11.4 ± 0.9	10.2 ± 0.9	12.2 ± 0.4	10.9 ± 1.5	10.8 ± 0.9
16°C	8.6 ± 1.0	9.0 ± 1.8	10.6 ± 1.1	6.9 ± 1.2	12.3 ± 1.1	9.5 ± 3.2	10.6 ± 0.5
Average	9.0 ± 0.8	10.0 ± 1.4	11.3 ± 1.1	10.2 ± 1.0	12.2 ± 0.9	10.7 ± 1.9	10.7 ± 0.8

Table 2 The cases in each of the group during the data analysis

Grouping	0°C	4°C	10°C	16°C
CIVD	4	4	0	0
SS	1	1	8	8
USS	3	3	0	0
Total	8	8	8	8

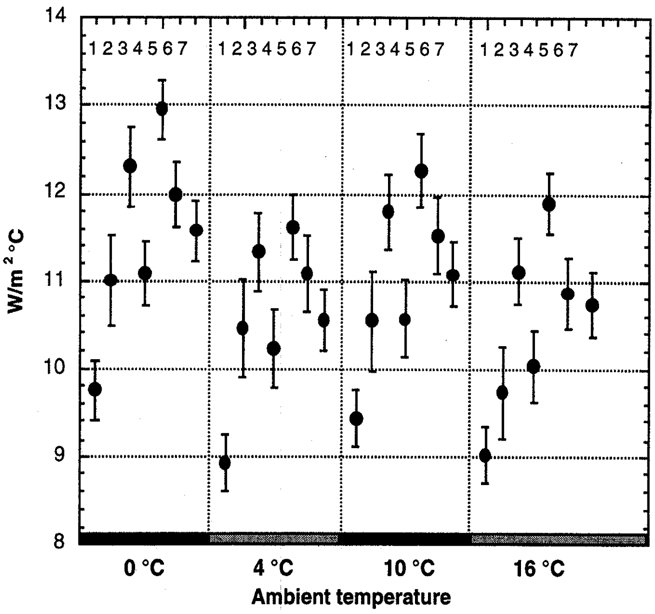

Fig. 2 Mean values and the 95% confidence intervals for the combined heat transfer coefficient. The numbers represent: (1) thumb, (2) index (3) long (4) ring (5) little finger, (6) palm of the hand, and (7) back of the hand.

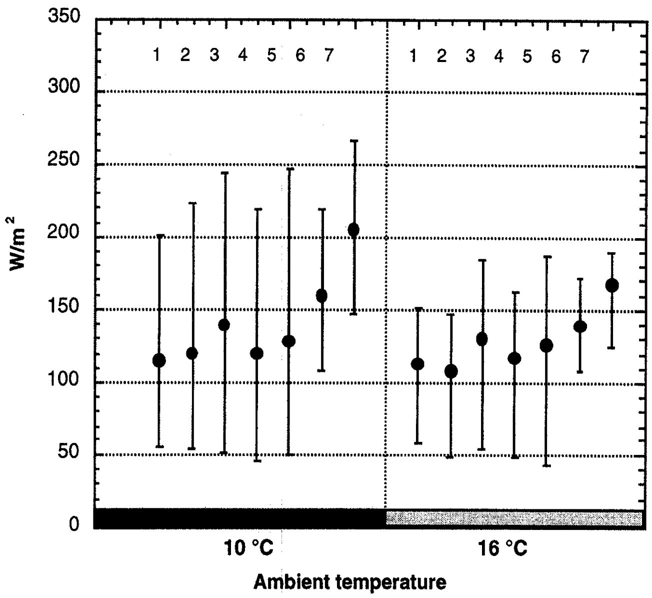

Fig. 4 Heat loss (Q W/m²) of SS group. For explanation of numbers, see Fig. 2.

is shown in Table 3, and the data range of SS and USS group is shown in Table 4.

Discussion

The thermal hand used here was designed for the purpose of measuring the thermal insulation of gloves (Nilsson et al. 1992). The finger diameter of the thermal hand was slightly smaller than that of the subjects. Since the heat transfer coefficient of each zone of the thermal

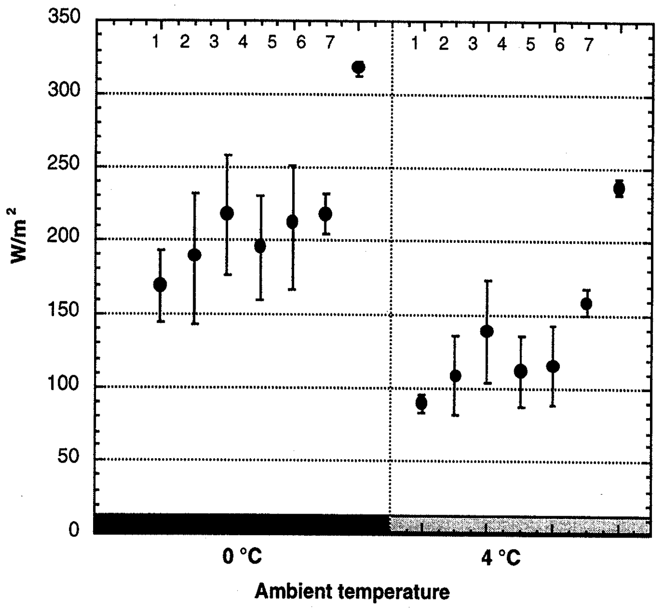

Fig. 3 Heat loss (Q W/m²) of different parts of the hand in CIVD group. For explanation of numbers, see Fig. 2.

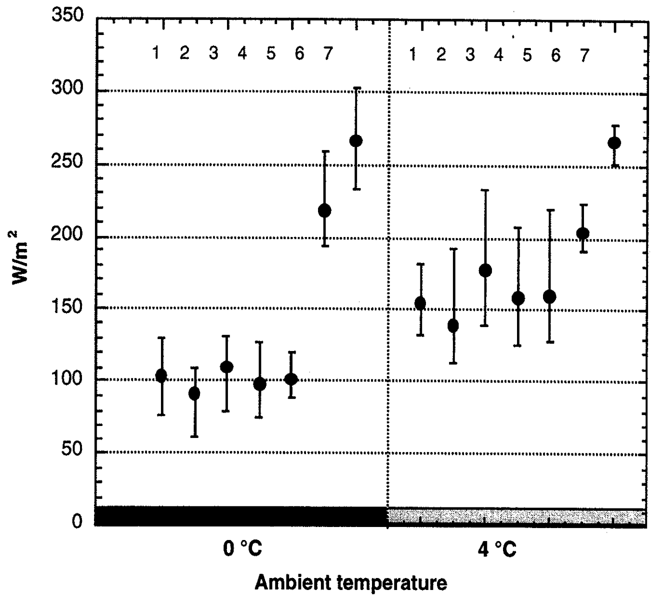

Fig. 5 Heat loss (Q W/m²) of USS group. For explanation of numbers, see Fig. 2.

Table 3 The heat loss P (W) and heat loss per volume q (W/m^3) of whole index finger in CIVD group

Tch	P trough (W)	P crest (W)	q trough ($\times 10^4$) (W/m^3)	q crest ($\times 10^4$) (W/m^3)
0°C	0.62 ± 0.19	0.99 ± 0.28	3.65 ± 1.07	5.79 ± 1.4
4°C	0.34 ± 0.06	0.57 ± 0.17	2.11 ± 0.38	3.52 ± 0.83

Table 4 The heat loss P (W) and heat loss per volume q (W/m^3) of whole index finger in SS group and USS group under different T_{ch} condition

Tch	Heat Loss P in (W)			Heat Loss q, ($\times 10^4$) in (W/m^3)		
	Average	Highest	Lowest	Average	Highest	Lowest
0°C, USS	0.49 ± 0.17	0.68	0.34	2.19 ± 0.71	2.89	1.47
4°C, USS	0.72 ± 0.24	0.95	0.47	3.22 ± 1.20	4.60	2.44
10°C, SS	0.57 ± 0.34	1.10	0.22	2.80 ± 1.48	5.32	1.42
16°C, SS	0.52 ± 0.23	0.86	0.19	2.54 ± 0.76	3.50	1.27

hand was calculated by Equation (1), in which the heat loss Q_i of each zone was presented in Watts per square meter of the surface area, the size differences between the thermal hand and human subject's hand should have small influence. The calculated heat loss from the human hand was always done using the individual anatomical characteristics of the subject.

The heat transfer coefficient from Equation 1 is a combined heat transfer coefficient ($h_{CR} = h_C + h_R$), where h_C is the convective heat transfer coefficient and h_R is the radiation heat transfer coefficient. The value of h_R can be calculated using the Stefan-Boltzmann law. The free convective heat transfer coefficient can then be calculated. There are some radiation effects from each other of the fingers and other part of the hand. This is usually difficult to determine. More detailed analysis are required to quantify separately the radiation and convection components. For the present purpose, a combined heat transfer coefficient will be the best way to describe the rate of heat loss.

Multiple ANOVA test on h_{CR} value shows significant differences between the zones of the thermal hand ($P<0.01$). There is a certain pattern of the h_{CR} value (see Fig. 2). This ordering might be due to the position of the hand in the chamber. The thermal hand was placed on a vertical position with the thumb up. Thus heat lost from the little finger by natural convection will affect the ring finger, by reducing its heat loss. Similarly, the lower heat loss from the ring finger has less impact on the long finger, that in turns will heat the index finger. This is the likely explanation for the ordering pattern seen in Fig. 2. The thumb is influenced by natural convection from both palm and back of the hand, reducing its heat loss and, hence, the calculated coefficient. Also differences in curvature should affect the values of the coefficient.

Since the thermal hand was placed in the same position as the hand of the subjects, the influences of the neighbor fingers to heat transfer should be similar for subjects and the thermal hand. Hence, the h_{CR} value was highest for the little finger (close to bottom in the chamber) and lowest for the thumb (facing upwards).

The differences in heat loss between vasodilatation phase (crest T_{sk} phase) and vasoconstriction phase (trough T_{sk} phase) in fingers are more pronounced than in the palm and back of the hand. In the SS group, there are no significant differences in heat loss between 10°C and 16°C condition, but individual differences in 10°C are larger than in 16°C condition (Fig. 4). In the USS group, The heat loss from fingers in 4°C is significantly higher ($P>0.01$) than in 0°C (see Fig. 5).

The values for h_{CR} of the fingers and hand are slightly higher than values given by Shitzer et al. (1994) and Nishi and Gagge (1970). This is probably due to the higher air velocity in our chamber (about 0.3 m/s) and the previously mentioned "position" effect. In both cases the measured values will be lower than under wind-still conditions and with the hand in e.q. a "fingertips down posture". On the other they are slightly lower than finger values given by Goldman (1994).

Shitzer and coworkers have proposed models to estimate the endurance times of the digits exposed to cold. Blood perfusion effects are either lumped into a volumetric heat generation term (Shitzer et al., 1991) or calculated separately (Shitzer et al., 1995). From the assumptions, the volumetric heat-generation rate was 1.5×10^4 to 2.9×10^4 W/m^3. In the present study, the q value of the index finger varied from 1.27×10^4 to 5.8×10^4 W/m^3 (see Table 3 and 4) when the finger was exposed to the cold air from 0°C to 16°C.

The predicted temperature of the finger tip at "maximal vasoconstriction" according to Shitzer et al. (1995) follows closely the measured temperature of subject A (see Fig. 6). However, the tip and middle finger temperature of subject A levels off and seem to equilibrate around 3–4°C. This may indicate a slightly higher blood flow to the finger (and heat input), but the temperature has not equilibrated at 60 min and may well fall further down to 1–2°C. The prediction with Goldman's model gives another cooling curve and a slightly higher end

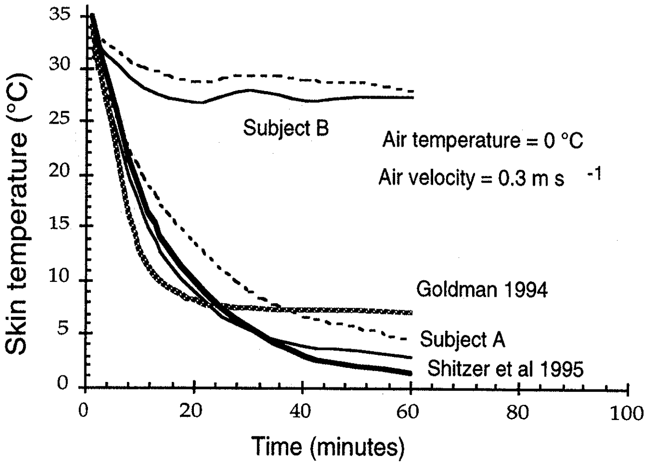

Fig. 6 Comparison of predicted values (Shitzer et al., 1995; Goldman, 1994) for digit skin temperature and measured values for two different types of responses of the naked finger at 0°C. The predictions apply to "worst case" with low blood flow (low heat flow) to the finger. The solid lines refer to finger tip and the broken line to middle finger site. (See also text for explanation).

temperature. For the "warm" subject both models predict a similar warm response, albeit Goldman's model predicts a small increase in temperature. Both methods seems to reasonably agree with the measured responses. This should indicate that the heat loss measurements are realistic. The critical values that can explain most of the differences are heat input and insulation around the finger. The values in the prediction models may not compare directly with the experimental conditions. More analysis are required for the detailed validation of the models.

In conclusion the measured heat fluxes appear to be realistic and comparable with literature data. There are several advantages using a thermal hand model: 1. It is easy to use; 2. It directly measures the heat loss; 3. It can be used in extreme conditions when human experimentation would not be justified; 4. There is no interruption of surface air flow due to sensor placement; 5. It is highly reproducible and repeatable. Due to the influence of neighbor fingers, it is important that values be determined for hand positions similar to that of the human hand. This becomes even more important when air motion increases or the hand is moved. These conditions were not studied in the present investigation.

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