THERMAL INSULATION PROVIDED BY CHAIRS

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ABSTRACT

The insulation provided by seven different chairs was measured using an articulated, thermal manikin in an environmental chamber. The manikin was tested nude and while wearing several different indoor clothing ensembles. Data were collected with the manikin sitting in the different chairs and standing. Results indicated that clothing insulation decreased when the manikin was sitting (in a net chair) as opposed to standing. However, when the manikin sat in real chairs, the insulation value increased 0.1 to 0.3 clo. The amount of the increase was related to the amount of chair surface area in contact with the body. In addition, the I_{clu} *clo values for chair insulation can be added to* I_{clu} *values for garments to determine the intrinsic insulation around a person for use in thermal comfort models.*

INTRODUCTION

ASHRAE Standard 55-1992 and ISO Standard 7730 provide models for predicting the thermal comfort of people in indoor environments (ASHRAE 1992; ISO 1984). These standards show the effects of environmental factors (air temperature, relative humidity, mean radiant temperature, and air velocity) and personal factors (clothing insulation and activity) on people's satisfaction with the thermal environment. Tables of intrinsic clothing insulation values for ensembles (I_{cl}) are provided for the user to incorporate into the "comfort equation." In addition, tables of effective garment insulation values (I_{clu}) are included so the user can add up the clo values of individual garments to get the I_{cl} value for an ensemble. Additional clo values are also listed in ISO Standard 9920 (ISO 1992). However, these values are based on data from standing manikins (McCullough et al. 1985). In real-life situations, people spend a lot of time sitting in chairs. Does the chair provide additional insulation to the occupant? Does the clothing insulation change in the seated position as opposed to the standing position?

All of the studies that provided the baseline data for Fanger's PMV-PPD index (Fanger 1982), Gagge's ET* (Gagge et al. 1971), and the comfort research at a U.S. university (Nevins et al. 1966) used a 0.6-clo standard uniform. This insulation was measured on a standing thermal manikin. These comfort studies were performed with subjects dressed in the standard uniform and seated in a net chair; it was assumed that the thermal insulation was still 0.6 clo.

Olesen et al. (1982) reported that intrinsic clothing insulation values decreased 8% to 18% when a manikin was wearing one of three ensembles and sitting in a net chair. The decrease was probably due to the change in posture and the resulting change in insulation at the boundary level (I_a) and compression of clothing layers. The authors acknowledged that the decrease in clothing insulation would probably be compensated for by the insulation provided by a real chair. They did not, however, evaluate chairs.

Havenith et al. (1990) investigated the effect of posture on clothing insulation using human subjects sitting on wooden stools. They reported a 4% to 18% decrease in total insulation and a 13% to 36% decrease in intrinsic insulation for three ensembles.

Rohles and Krohn (1982) studied the effect of chair type on the thermal comfort of human subjects. Although they did not find any significant differences in the subjects' thermal sensations at 26°C, the subjects felt more comfortable in cloth-covered chairs as opposed to vinyl-covered ones.

The purpose of this study was to measure the insulation provided by seven different types of chairs with the use of an articulated, thermal manikin. The manikin was tested nude and while wearing several different indoor clothing ensembles. Data were collected with the manikin standing and sitting in the different chairs. The amount of chair surface area in contact with the body and the thickness of the chairs were independent variables used to predict changes in insulation around the body due to sitting in different types of chairs.

METHODOLOGY

Chairs

The chairs were selected to represent the designs commonly found in office environments. The amount of body surface area in contact with the chair varied across the design types. In addition, the types of materials used to construct the chairs (e.g., wood, metal, foam plus fabric)

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TABLE 1
Chair Information

Chair Type	Surface Area in Contact with Body (cm^2)	Fraction of Total Contact Area	Chair Thickness by Part (cm)	Area-weighted Thickness (cm)
1. No Chair (net)	0	0	0	0
2. Wooden Stool	494	—	—	3.6
Back	0	0	0	
Seat	494	1.0	3.6	
Arms	0	0	0	
3. Metal Folding Chair	1254	—	—	0.1
Back	395	0.31	0.1	
Seat	859	0.69	0.1	
Arms	0	0	0	
4. Computer Chair	1828	—	—	4.51
Back	682	0.37	2.8	
Seat	1146	0.63	5.5	
Arms	0	0	0	
5. Carrel Chair	2183	—	—	7.26
Back	879	0.40	5.5	
Seat	1284	0.59	8.5	
Arms	20	0.01	3.5	
6. Desk Chair	2697	—	—	8.64
Back	1344	0.50	9.5	
Seat	1274	0.47	8.0	
Arms	79	0.03	4.3	
7. Executive Chair	3399	—	—	11.67
Back	1818	0.53	11.8	
Seat	1423	0.42	12.0	
Arms	158	0.05	7.5	

and their thicknesses varied. Descriptions of the chairs are given in Table 1. A net chair was included to simulate the manikin sitting in no chair at all. In this way, the effect of posture could be examined separate from the insulation added by the chair. Sketches of the chairs are given in Figure 1.

The amount of body surface in contact with the back, seat, and arms of each chair was determined by either tracing around the manikin's contact areas on the chair with chalk or pushing pins into the chair cushions. Then clear film was placed over the chalk or pin outline and pinned to the chair. The marked outline was traced with a pen and these areas of the film were cut out and weighed on a balance. By comparing the weight of a known area of the film to the weight of the traced areas, the total area in contact with the chair was calculated.

The thickness of the back, seat, and arms of the chairs was roughly determined using a ruler. These values were different on each chair part. Therefore, each thickness measurement was multiplied by the fraction of the total chair area that was in contact with the body (Table 1). These area-weighted values were then summed for use in the regression analysis.

Clothing

The clothing ensembles selected for study are described in Table 2. A heavy business suit was included (1.1 clo) to represent winter clothing. A short-sleeved shirt and trousers ensemble (0.6 clo) was included to represent summer clothing. These two ensembles and the nude condition were tested with the manikin sitting in all seven chairs and standing. In addition, two women's ensembles—one with a long-sleeved blouse and a straight skirt and one with a long-sleeved blouse and a pleated skirt—were tested with the net chair and the executive chair. This was done to demonstrate that some skirts actually cover more body surface area when a woman is seated than when she is standing, and this additional coverage increases the insulation value. The women's ensembles had I_{cl} values of about 0.6 clo (like the trouser ensemble), but they had coverage on the arms instead of the lower legs.

Manikin Procedures

An articulated thermal manikin (Fred) was used for measuring the insulation provided by each ensemble and

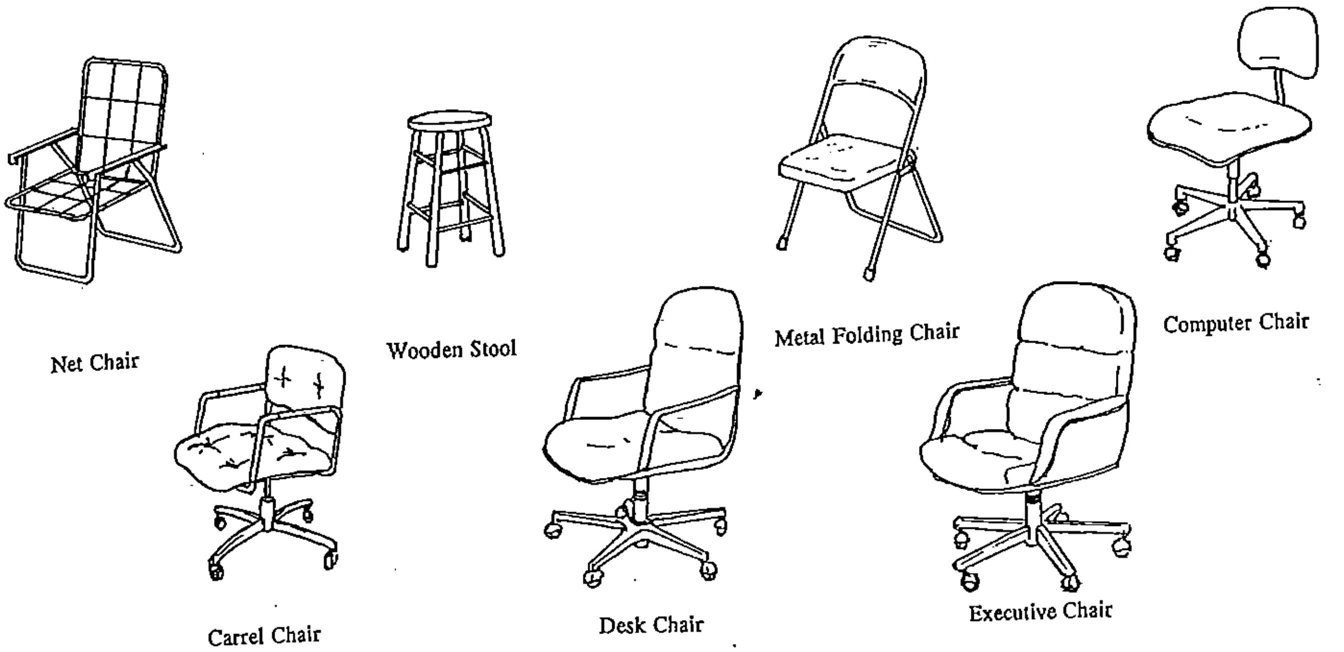

Figure 1 *Chair designs.*

TABLE 2
Description of Clothing Ensembles

Ensemble Description	Clothing Area Factor f_{cl}	Standing Insulation (clo) I_T	Standing Insulation (clo) I_{cl}
0. *Nude* (I_a)	—	0.65	—
1. *Heavy Business Suit* briefs, t-shirt long-sleeved dress shirt, shirt collar necktie, belt suit jacket, single-breasted long dress trousers calf-length dress socks hard-soled street shoes	1.32	1.60	1.11
2. *Shirt and Trousers* briefs short-sleeved shirt, shirt collar long trousers, thin calf-length dress socks hard-soled street shoes	1.15	1.14	0.57
3. *Blouse and Straight Skirt* panties long-sleeved shirt, shirt collar straight skirt, knee length pantyhose hard-soled street shoes	1.29	1.10	0.60
4. *Blouse and Pleated Skirt* panties long-sleeved blouse, shirt collar pleated skirt, knee length pantyhose hard-soled street shoes	1.33	1.13	0.64

chair. Fred is a full-sized male manikin, 179.1 cm tall with 19 electrically separated segments—18 of which are in operation at one time. The heating and measurement wires are located near the surface of the manikin. Heating wires are embedded in the plastic foam, evenly distributed over the surface of each segment, with a resistance giving a maximum heating effect of 300 W/m^2 at full voltage. External to the layer of heating wires and electrically insulated from them is a metallic layer that serves to spread the heat and create an even surface temperature. External to this layer and electrically insulated from it are wires with a known thermal coefficient for measurement of the body surface or skin temperature. Measurement and control of the heat supply for each section is achieved by using a digital process computer system. The temperature readings and power input values for each segment are area-weighted when calculating the total insulation value.

Fred hangs from a hook attached to a metal stand. A handle at the back of the stand is used to raise and lower the hook (and the manikin) for dressing and seating him. The power and temperature cables attach to Fred's neck in the back.

To determine the insulation value of the clothing ensembles and chairs, the manikin tests were conducted in an environmental chamber according to *ASTM F 1291-90, Standard Test Method for Measuring the Thermal Insulation of Clothing Using a Heated Manikin* (ASTM 1992). The air temperature in the chamber was controlled at 22° ±0.5°C; it was measured with a matrix of four thermistors from the manikin's head to its feet. Air velocity was maintained at less than 0.15 m/s. A dew-point temperature was selected that would give 50% relative humidity and was controlled at 11.1° ±1°C. The mean skin temperature of the manikin was maintained at 33.2° ±.5°C.

Fred was dressed in the ensemble to be tested and placed in a stationary, standing position. The manikin system was considered at steady state when the stability of the power level for each segment from one minute to the next was no more than ±0.2 W and the deviation of the segment surface temperature was no more than ±0.1°C from the setpoint. When the system had been at equilibrium for 60 minutes, a 30-minute standing test was conducted. Then the manikin was seated in a chair and tested. The test was repeated until all chairs had been tested. The resistance of the air layer (I_a) was also measured by conducting the tests on the nude manikin while it was standing and sitting in a net chair. Two replications of the study were conducted.

Total insulation (I_T) was calculated as follows:

$$I_T = \frac{KA_s(T_s - T_a)}{Q} \qquad (1)$$

where

I_T = total thermal insulation of clothing and/or chair plus air layer, clo;
K = constant = 6.45 clo·W/m^2·°C;
T_s = mean skin temperature, °C;
T_a = ambient air temperature, °C;
A_s = manikin surface area, m^2; and
Q = power input, W.

Intrinsic insulation (I_{cl}) was calculated as

$$I_{cl} = I_T - \frac{I_a}{f_{cl}} \qquad (2)$$

where

I_{cl} = intrinsic insulation, clo;
I_T = total thermal insulation of clothing and/or chair plus air layer, clo;
I_a = insulation provided by the air layer around the nude manikin, clo; and
f_{cl} = clothing area factor.

The clothing area factor (f_{cl}) for each ensemble was estimated by finding similar ensembles in previous research data bases (McCullough et al. 1989) (see Table 2).

The insulation of a chair, like the insulation of a garment, can be expressed as effective thermal insulation (I_{clu}). In this way, the garment clo value and the chair clo value can be added to determine the I_{cl} value for a clothing ensemble/chair combination. This was calculated as

$$I_{clu} = I_T - I_a \qquad (3)$$

where I_a is the insulation of the air layer around the nude manikin sitting in a net chair.

Statistical Analysis

The independent variables were the amount of chair surface area in contact with the body and the area-weighted thickness of the chairs. Regression analyses were conducted to predict the difference between sitting insulation values and standing insulation values using I_T and I_{cl} data.

RESULTS AND DISCUSSION

Differences in Sitting and Standing Insulation Values

Insulation data for the nude manikin sitting in different chairs are given in Table 3. When the manikin was sitting in the net chair, the total insulation value was 9% lower than the standing nude condition. Sitting on a wooden stool and metal chair did not provide any additional insulation over that of the standing value. However, the insulation value began to increase significantly when the manikin was sitting in fabric-covered, cushioned chairs (4 through 7).

Table 4 provides similar data on the seven chairs when the heavy business suit (ensemble 1) and the shirt/trouser combination (ensemble 2) were worn. In addition, data for

TABLE 3
Change in Total Insulation Due to Sitting in Different Types of Chairs (Nude Condition)

Chair Type	Total Insulation Sitting I_T (clo)[a]	Difference Between Sitting I_T and Standing I_T (clo)	(%)
1. No Chair (net)	0.59	−0.06	−9.23
2. Wooden Stool	0.60	−0.05	−7.69
3. Metal Chair	0.65	0.00	0.00
4. Computer Chair	0.71	0.06	9.23
5. Carrel Chair	0.72	0.07	10.77
6. Desk Chair	0.75	0.10	15.38
7. Executive Chair	0.76	0.11	16.92

[a]I_T is equal to I_a for the standing nude condition (0.65 clo) and the sitting nude condition *without* a chair (0.59 clo), where insulation is only provided by the external air layer. However, when the manikin is seated on a chair, I_T includes the insulation provided by the air layer and the chair.

TABLE 4
Change in Insulation Due to Sitting in Different Types of Chairs

Chair Type	Total Insulation Sitting I_T (clo)[a]	Difference Between Sitting I_T and Standing I_T (clo)	(%)	Intrinsic Insulation Sitting I_{cl} (clo)[b]	Difference Between Sitting I_{cl} and Standing I_{cl} (clo)	(%)
Ensemble 1 Business Suit (standing I_T = 1.60, I_{cl} = 1.11 clo)						
1. No Chair (net)	1.38	−0.22	−13.75	0.93	−0.18	−16.22
2. Wooden Stool	1.51	−0.09	−5.63	1.06	−0.05	−4.51
3. Metal Chair	1.48	−0.12	−7.50	1.03	−0.08	−7.21
4. Computer Chair	1.60	0.00	0.00	1.15	0.04	3.60
5. Carrel Chair	1.70	0.10	6.25	1.25	0.14	12.61
6. Desk Chair	1.64	0.04	2.50	1.19	0.08	7.21
7. Executive Chair	1.71	0.11	6.87	1.26	0.15	13.51
Ensemble 2 Shirt and Trousers (standing I_T = 1.14, I_{cl} = 0.57 clo)						
1. No Chair (net)	0.98	−0.16	−14.04	0.47	−0.10	−17.54
2. Wooden Stool	1.09	−0.05	−4.39	0.57	0.00	0.00
3. Metal Chair	1.08	−0.06	−5.26	0.57	0.00	0.00
4. Computer Chair	1.16	0.02	1.75	0.65	0.08	14.04
5. Carrel Chair	1.17	0.03	2.63	0.66	0.09	15.79
6. Desk Chair	1.15	0.01	0.88	0.64	0.07	12.28
7. Executive Chair	1.20	0.06	5.26	0.69	0.12	21.05
Ensemble 3 Blouse and Straight Skirt (standing I_T = 1.10, I_{cl} = 0.60 clo)						
1. No Chair (net)	0.97	−0.13	−11.82	0.51	−0.09	−15.00
7. Executive Chair	1.14	0.04	3.60	0.68	0.08	13.33
Ensemble 4 Blouse and Pleated Skirt (standing I_T = 1.13, I_{cl} = 0.64 clo)						
1. No Chair (net)	1.05	−0.08	−7.08	0.61	−0.03	−4.69
7. Executive Chair	1.22	0.09	7.96	0.78	0.14	21.88

[a]When the manikin is seated on a chair, I_T includes the insulation provided by the air layer, the clothing, and the chair.
[b]I_{cl} sitting was calculated by subtracting the I_a value for the nude manikin seated without a chair (0.59 clo), divided by the f_{cl} value, from I_T sitting. Therefore, the insulation provided by the chair is still included in I_{cl}.

the skirt ensembles (3 and 4) are included for the net chair (1) and the executive chair (7). In all cases, the insulation value decreased when the clothed manikin was sitting in the net chair as compared to the standing posture. Decreases ranged from 7% to 14% for total insulation and 5% to 18% for intrinsic insulation. These findings agree with those of Olesen et al. (1982). When the manikin was sitting on the wooden stool or in the metal folding chair, the insulation either decreased or stayed the same as the standing value. The stool and metal chair provided only a little more insulation than the net chair did, probably because they were made of thin dense materials and the area in contact with the manikin's body was minimal.

The results changed significantly when the manikin was sitting in the thick, cushiony chairs (4 through 7). In all cases, the insulation value *increased*. Specifically, I_T clo values increased up to 8% and I_{cl} values increased up to 22% (above standing values).

The decrease in insulation due to sitting on the net chair (as compared to standing) was less for the pleated skirt as compared to the straight skirt. Likewise, in the executive chair, the increase in insulation was greater for the pleated skirt than for the straight skirt (Table 4). This was because the pleated skirt draped loosely around the thighs and lower legs when the manikin was sitting, and the straight skirt was compressed tightly against the thighs.

Predicting Differences in Sitting and Standing Insulation Values

Linear regression analysis was used to determine if there was a significant relationship between the amount of chair surface area in contact with the body and the area-weighted chair thickness on the change in insulation due to sitting as compared to standing. The manikin wore typical indoor clothing (I_{cl} = 0.6 to 1.1 clo) and sat in seven different chairs for this data set.

The amount of chair surface area in contact with the body explained 79% of the variance in I_T and 77% of the variance in the I_{cl} (Figures 2 and 3). The regression equation for I_{cl} data can be used to estimate the change in a standing manikin's clo value given in a comfort standard if the person wearing the clothing ensemble will be seated in a cushiony chair. The equation is

$$C = 0.0000748 \times CSAC - 0.1 \tag{4}$$

where C is the change in I_{cl} due to the chair (clo) and $CSAC$ is the amount of chair surface area in contact with the body (cm^2). For example, if a person's body covers about 3,300 cm^2 of a chair, then 0.15 clo should be added to the intrinsic insulation value for the clothing ensemble worn (i.e., the standing I_{cl} clo value).

The area-weighted thickness of the chair was less effective in predicting the change in insulation. This variable explained 77% of the variance in I_T data and 75% of the variance in I_{cl}. Since we area-weighted the chair thickness values, the *CSAC* variable is hidden in the thickness variable. Therefore, we do not recommend the use of this relationship. The amount of chair surface area in contact with the body is the primary factor related to the additional insulation provided by the chair.

Additional Insulation Provided by Chairs as Compared to No Chair

The I_{cl} value for an ensemble is used in models to calculate an index for the thermal environment or thermal sensations of people (PMV-PPD, ET*). These models wrongly assume that the thermal insulation value for a sedentary person dressed in a 0.6-clo standard uniform is 0.6 clo when seated in a net chair; this study indicated that the value is actually lower (i.e., 0.5 clo). In addition, people generally sit in real chairs, not net chairs. Therefore, the empirical relationship between the heat balance of persons and their subjective responses should be re-examined in these comfort models.

The added insulation of a real chair compared to a net chair is shown in Table 5 for four different ensembles and the nude manikin. The values for the nude manikin are analogous to I_{clu} chair clo values and can be added to the I_{clu} values listed for garments in standards (ASHRAE 1992; ISO 1984, 1992). Based on the values in Table 5, it is seen that the added insulation also depends on the type of clothing used. When an indoor ensemble with a high thermal insulation (ensemble 1) is worn, the increase in insulation due to a chair is larger. This increase in insulation from a chair will have a significant effect on the preferred temperature of sedentary persons. A 0.1-clo increase in insulation will have the same effect as a 0.8°C increase in operative temperature for normal indoor clothing ensembles, 0.5 to 1.0 clo, and at normal office activities, 1.3 met. The executive chair will, on average (ensembles 1 and 2), add 0.27 clo to the insulation, which is equivalent to a 2°C higher operative temperature.

This added insulation of chairs may be used to compensate for the reduced activity levels of sedentary persons compared to standing persons so the two groups can work under the same temperature conditions and be comfortable. Some field studies in offices (Schiller et al. 1988) have reported lower preferred room temperatures than predicted. In these studies it was assumed that the thermal insulation for sedentary people could be calculated from the insulation values measured on standing thermal manikins. The present results show, however, that it is necessary to add an effective insulation value for the chair on the order of 0.1 to 0.3 clo. That would change the preferred operative temperature 0.8° to 2.5°C. This may partially explain why some field studies find a lower preferred operative temperature than predicted.

The weight of the manikin used in the present investigation is less than that of a normal person. That means a normal person seated in a chair will "sink" deeper into the

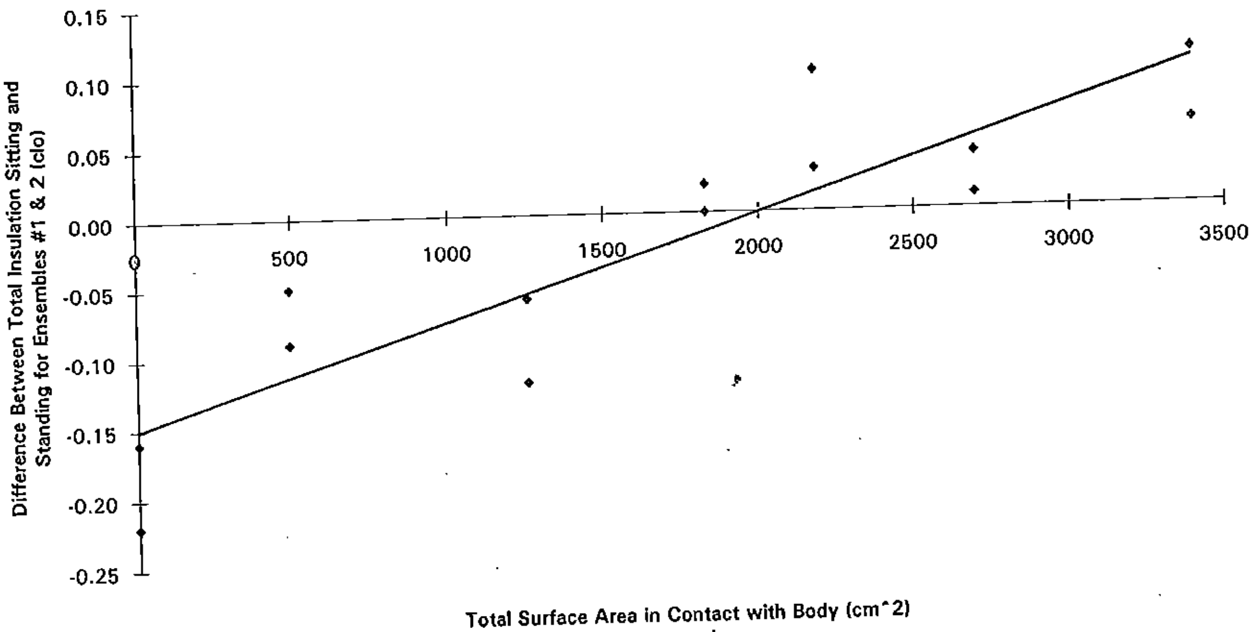

Figure 2 *The relationship between the amount of chair surface area in contact with the body and the change in total insulation.*

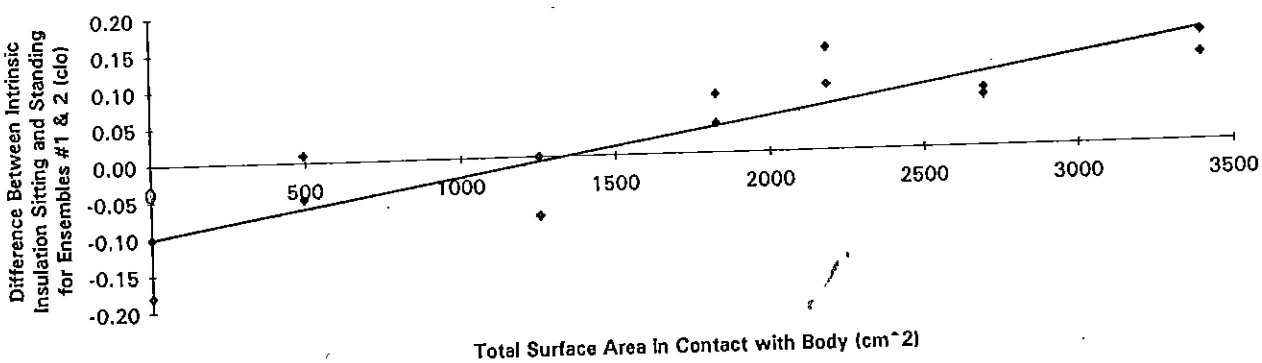

Figure 3 *The relationship between the amount of chair surface area in contact with the body and the change in intrinsic insulation.*

TABLE 5
Added Insulation of Chairs Relative to No Chair

Chair Type	Insulation Change (clo)[a]				
	Nude[b]	Ensemble 1	Ensemble 2	Ensemble 3	Ensemble 4
2. Wooden Stool	0.01	0.13	0.11	—	—
3. Metal Chair	0.06	0.10	0.10	—	—
4. Computer Chair	0.12	0.22	0.18	—	—
5. Carrel Chair	0.13	0.32	0.19	—	—
6. Desk Chair	0.16	0.26	0.17	—	—
7. Executive Chair	0.17	0.33	0.22	0.17	0.17

[a]The difference between the insulation value in a chair vs. no chair (i.e., the net chair 1) is the same whether I_T or I_{cl} is used.
[b]The additional insulation provided by each chair when the manikin was nude is equivalent to a garment I_{clu} value and it can be treated accordingly in summation equations for ensembles.

cushion than the thermal manikin. In addition, a person's body tissue will "spread out" when seated, whereas the rigid manikin will not. Consequently, the insulation provided by chairs as measured by the manikin is probably on the lower end of possible values as compared to the effect on a seated human being.

CONCLUSIONS

When a person is in the seated position as compared to the standing position, the insulation value is lower because the insulation provided by the air layer around the body is reduced due to posture and the air trapped in clothing layers is reduced due to compression. When a person is seated on a chair, the chair provides additional insulation to the body. Thus, the added insulation of a chair compared to a net chair should be taken into account when using existing models to predict the preferred temperature or thermal sensation of people. The insulation (I_{clu} value) for typical office chairs is in the range of 0.1 to 0.3 clo and can be added to garment I_{clu} values in standards. The difference between standing clothing insulation values (in standard tables) and actual clothing insulation values while sitting in a chair can also be predicted from the amount of chair surface area in contact with the body.

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DISCUSSION

Mark Y. Ackerman, University of Alberta, Edmonton, Canada: What range of clo values is obtained in a repeated test of the same garment? If the mannequin is dressed, measured, undressed, dressed, and retested, how much scatter is evident?

E.A. McCullough: When the insulation value of indoor clothing is being measured with a manikin in the standing or seated position, the variability is usually no greater than ±0.03 clo between replications. The manikin is always dressed and undressed between replications. If the clothing was not changed, the clo value would stay the same or change by 0.01 clo.