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Pain, thermal sensation and cooling rates of hands while touching cold materials

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Summary. Hand cooling and resulting comfort and pain were studied in 12 subjects, while touching six different materials (polyurethane foam, wood, nylon, rustproof steel, aluminium, and temperature-controlled metal) which were initially at ambient temperature. This was done for three ambient temperatures (−10°, 0° and 10° C), after pre-exposure exercise or rest, with bare hands or while wearing gloves. The observed cooling curves were analysed as Newtonian cooling curves. The observed time constants appeared to be significantly related to the materials' contact coefficients, the presence of hand protection, the preceding activity, and the interaction between contact coefficient and the presence of hand protection. These parameters also allowed a good description of the time constant ($r^2 = 0.8$) of the related cooling curves. Thermal and pain sensation could be described in terms of the local skin temperature, ambient temperature and hand protection. Equal pain and thermal levels were associated with lower temperatures of the back of the hand than of the contact side. The slightly painful condition was associated with a skin temperature of 16° C for the back and 19° C for the palm of the hand. The pain level appeared to be inversely related to cooling speed. Skin freezing occurred at higher skin temperatures when touching cold objects than when exposed to cold air as a result of reduced supercooling. The regression equations determined allowed calculations to be made of safety limits for hand cooling while in contact with a wide range of materials.

Key words: Cold sensation - Skin temperature - Cold injury - Contact

Introduction

Contact between the hands and cold surfaces is part of the daily occupation of many people. Examples are accidental touching of, for example, cold machines, walls or pipelines, or contacts which are the direct result of handling tools or materials in a cold environment. The contact with cold objects can cause hand cooling and lead to discomfort and, in more extreme cases, to pain and freezing injury (Enander 1982, 1984). Further, cold exposure can have a detrimental effect on manual performance due to reduced sensitivity (Mackworth 1953; Morton and Provins 1960) and reduced dexterity (Fox 1967) and thus it may lead to reduced safety.

Previous studies have related to sensory aspects and performance, many of which were reviewed by Enander in 1984, and dealt with hands of resting subjects cooled in air, often with the rest of the body in a comfortable environment. Studies regarding skin freezing (Wilson and Goldman 1970; Molnar et al. 1972, 1973) only exposed the middle phalanx of one finger to cold air. However, most of these authors were well aware of the influence of the temperature of the unexposed parts of the body on the sensation and the cooling rates of the exposed parts. This influence is due to the sensory integration of the inputs from all parts of the body, and to heat input from the unexposed parts to the exposed parts caused by blood flow and heat conduction, respectively. As, in realistic situations, a person is usually completely exposed to the climate, in this study an attempt was made to investigate the rate of hand cooling and comfort sensations of subjects while their complete (clothed) bodies were exposed to the test climate. To investigate the effect of a different central input (i.e. body core temperature) on the system (blood flow-peripheral vasoconstriction) the test was performed after a preceding exercise or rest period in the same environment. Further, the test was not done for hands exposed to air only but while they were touching different materials with a range of thermal properties, and finally, the test was done with both men and women to obtain a sample more representative of the working population. The results should enable predictions to be made of the hand cooling rate while touching cold objects, as well as to add to the available data on comfort and pain in relation to the hand skin temperature. Since the tests also

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include extreme discomfort, the data may in due course be used in the development of safety standards.

Methods

Subjects and protocol. A group of 12 subjects (6 men and 6 women, age 18–27 years) without any history of peripheral vascular disease, cold injury or cold acclimation participated in the study after giving their informed consent. After a rest period in a neutral climate they entered the climatic chamber, and they either rested there for 30 min or performed exercise (stepping up and down on a stool at a variable intensity aiming at a total increase in their rectal temperature of 0.4° C (regulated through feedback of the core temperature)) for the same 30-min period. They were allowed to adjust the amount of clothing they wore for their personal comfort. After this initial 30-min period they sat down in a plastic chair with their elbows on armrests and took in each hand a large cylinder (length 30 cm, diameter 4 cm) made of one of the test materials and which was at room temperature. To prevent differences in hand grip force (and subsequent blood flow differences) because of the differences in the mass of the different materials, all cylinders were suspended by a cable. The subjects rested with their elbows on armrests and they had, therefore, only to apply enough force to compensate for the mass of their own forearm. The experiment was stopped after 30 min of contact, if the subjects could no longer tolerate the discomfort, or if a skin temperature below 5° C was measured, whichever came first. The latter was used as a safety criterion to avoid frostbite.

The experiment was repeated for each subject with all combinations of the following parameters:

1. Ambient temperature. Three ambient and thus also initial material temperatures were used: – 10, 0 and 10° C (relative humidity 40%–60%, wind speed less than 0.2 $m \cdot s^{-1}$
2. Rest or exercise in these climates for 30 min before the contact was made
3. With or without gloves. All experiments were done both with bare hands and while wearing gloves. The glove used was a thin work glove made of leather and fabric
4. Six different materials. The materials are listed in Table 1. The thermos-tube was a thin-walled aluminium cylinder rapidly perfused by a temperature-controlled water-glycol mixture. It was set at a temperature equal to the environment and created a strong heat sink.

The order of the separate sessions with the various combinations of the parameters was balanced among the subjects and sessions were spread out over a period of 4 weeks to prevent sequence and menstrual cycle effects. Left and right hands were treated as being equal, so that each subject experienced a certain combination of parameters only with one hand. To minimize lateral influencing of one hand to the other due to differences in cooling rate, the pairs of cylinders being held by the subjects were nearly matched for contact coefficients. Thus widely different combinations, like the foam cylinder in one hand and the temperature regulated cylinder in the other were never used. In between separate exposures, the subjects rested and were fully rewarmed outside of the climatic chamber.

The six contact materials were selected to provide a range of thermal properties. To describe these properties the contact coefficient or thermal penetration coefficient (b) was used (BSI 1978; Yoshida et al. 1989), which is defined as:

$$b = \sqrt{c \cdot \rho \cdot \lambda} \quad (J \cdot m^{-2} \cdot s^{-1/2} \cdot {}^\circ C^{-1}) \tag{1}$$

where c is specific heat ($J \cdot g^{-1} \cdot {}^\circ C^{-1}$), ρ is density ($g \cdot m^{-3}$), and λ is heat conductivity ($W \cdot m^{-1} \cdot {}^\circ C^{-1}$). The contact coefficients of the materials are listed in Table 1.

Measurements. The following temperatures were monitored during the experiment: rectal temperature (T_{re}, skin temperature (T_{sk}) (abdomen, big toe, two lower arms and hands), two contact temperatures (distal phalanx of the middle finger and the palm of the hand between the abductor and flexor pollicis brevis) as well as four other hand temperatures (on the index finger at the side of the middle finger, on the ring finger at the side of the little finger, on the dorsal side of the distal phalanx of the thumb, and on the back of the hand). Contact temperatures were measured by thermocouples (copper-constantan) taped to the skin, the others by thermistors (Yellow Springs Instruments, 700 series, Yellow Springs Instruments Co., Ohio, USA). All measurements were collected by a Fluke 2400b intelligent front end system (John Fluke MFG. Co. Inc., Everett, Wagdrop, USA), averaged over 1-min intervals and stored on a Digital PDP11/23 computer (Digital equipment Corp. Maynard, Mass., USA).

Mean T_{sk} was calculated as weighted average of the T_{sk} on the abdomen, the lower arms and the toe. Body heat storage was calculated as Storage $= 3.48\,[0.7\,(37.0 - T_{re}) + 0.3\,(33.0 - T_{sk})]$, mean contact temperature was calculated as the average of the two contact temperatures and the hand temperature on the dorsal side as the average of the four noncontact hand temperatures.

Temperature and pain sensations of the subjects were recorded for all subjects directly after touching the materials and just before ending the session. The subjects were asked to give these judgements (using the list in Table 2) for both hands separately and also to discriminate between the contact side of the hand and the back of the hand.

Characteristics of the hands of the subjects are given in Table 3. The hand volumes were determined by submerging the hands in water up to the processus styloideus. The contact surface area was determined in a dark room by wrapping a cylinder in photographic paper, letting the subject hold it in the same way as during the experiment, and then exposing it to light. After this had been developed, the contact area was measured by planimetry.

Analysis. From the measurements of the different hand (contact) temperatures, a cooling curve was obtained. In cases of the occurrence of cold induced vasodilatation (CIVD), the curves were ana-

Table 1. Materials used for the cylinders and their contact coefficients

Material	Contact coefficient ($J \cdot m^{-2} \cdot s^{-1/2} \cdot {}^\circ C^{-1}$)
Polyurethane-foam	100
Wood (mahogany)	256
Aquilon (nylon-6)	1545
Stainless steel	13335
Aluminium	21739
Thermos-tube (estimate)	40000

Table 2. List of scores which were used to determine the subjects temperature (a) and pain sensation (b) (translated into English from Dutch)

(a)	2	Comfortably warm	(b)	6	No pain at all
	1			7	
	0	Neutral		8	Slightly painful
	– 1			9	
	– 2	Comfortably cool		10	Rather painful
	– 3			11	
	– 4	Uncomfortably cool		12	Painful
	– 5			13	
	– 6	Cold		14	Very painful
	– 7			15	
	– 8	Very cold		16	Unbearably painful
	– 9				
	–10	Extremely cold			

Table 3. Contact surface areas and volumes of the subjects' hands. Values are means of both hands

Subject	Sex	Contact surface area (cm^2)	Hand volume (cm^3)
1	Men	47.3	360
2	Men	54.3	343
3	Women	40.1	260
4	Women	46.4	285
5	Women	53.2	372
6	Men	41.2	356
7	Women	30.6	312
8	Women	30.1	297
9	Men	43.8	350
10	Women	51.4	340
11	Men	55.8	405
12	Men	57.2	375
Average:		45.9	338

lysed only up to the point of the start of CIVD. Each individual cooling curve was subsequently analysed as being a Newtonian cooling curve (Molnar 1971; Molnar et al. 1972) using the method of least squares approximation. These curves which relate the cooling of a solid inanimate body to the temperature of the environment can be described as:

$$T(t) = T_a + \Delta T \cdot e^{-t/\tau} \quad (°C) \tag{2}$$

where $T(t)$ is the temperature of the object at time t, T_a is the temperature of the environment, ΔT is the start temperature minus environmental temperature, t is time, τ is the time constant of the cooling process.

However, as the hand is not inanimate, it has been shown that it does not cool down to the temperature of the environment, but remains at a slightly higher temperature (Molnar et al. 1972). This is due to the remaining heat input by the blood flow, even when the hand is cold. This equilibrium temperature was estimated for a hand in air (dry heat transfer coefficient = $9\ Wm^{-2} \cdot °C^{-1}$) with a blood inflow of $0.5\ ml\ 100\ ml^{-1} \cdot min^{-1}$, a volume of 340 ml, a surface area of $0.05\ m^2$, a temperature difference of incoming and outflowing blood of $37°C - T_{hand}$ and an effectivity ratio of the counter current heat exchange of 0.6 (Raman and Vanhuyse 1975). Calculating the heat balance for the hand results in an equation for the equilibrium temperature (T_{eq}) for the hand of:

$$T_{eq} = 5.0 + 0.86\, T_a \quad (°C) \tag{3}$$

resulting in the equation for the cooling curve of:

$$T(t) = T_{eq} + (T_{start} - T_{eq}) \cdot e^{-t/\tau} \quad (°C) \tag{4}$$

The hypothesis was that the time constant τ, which resulted from this analysis, reflected, besides anatomical properties of the hand, also the presence of insulation (glove) and the physical properties of the contact material.

A special case in the analysis of the cooling curves occurred when the hands did not cool down, but remained stable or even increased in temperature. For these cases the model given by Eq. 2 was in principle not a valid one. However, for safety standards, for which these data may be used, the cases where no cooling occurred implied safety. The presence of the resulting infinitely high time constants in these data had some implications for the treatment of the data. Taking straight averages of the time constants of all subjects for a certain situation, including these high values would have produced invalid results. For this reason, instead of averages the median value for each situation was determined, to represent the test population's cooling response. It was aimed at a *safety* time constant rather than at a *representative* time constant for the group. Usually for this type of approach the 95th percentile has been used, but as the number of subjects in this experiment was too low for a valid 95th percentile, the value of the lower hinge (75th percentile) was used instead.

The data were analysed using analyses of variance with post hoc tests for differences between separate effect levels. The relationships between the time constants and the independent parameters as well as their interactions (in case the analyses of variance showed significance) were analysed by multiple regression analysis. Also the subjective perceptions of pain and comfort were analysed by multiple regression analysis. For the statistical analysis the software package SYSTAT (Systat Inc., Evanston, IL, USA) was used. For significance, P values below 0.05 were accepted.

Results

Exercise

The attempt to create different levels of central input during the cooling process by pre-exposure rest versus exercise was effective. On average, the preceding exercise raised T_{re} from 37.15 to 37.58° C and T_{sk} from 31.21 to 31.55° C. This resulted in an average increase in hand temperatures of 4.5° C.

Temperatures

Unless mentioned differently, all data in this section refer to the values at the end of the exposure. Analyses of variance for the different hand temperatures and T_{re} showed that the main effects (material, T_a, exercise, gloves and subject) were all significant ($P<0.001$), except for the effect of material type on the temperature of the back of the hand and on T_{re}.

Averaged for all conditions, the presence of a glove increased hand contact temperature by 4° C relative to the bare hand, exercise increased it by approximately 5° C relative to the preceding rest period, and an T_a increase from −10° C to 10° C resulted in an increase in hand contact temperature of approximately 8° C.

Post-hoc analysis showed that the difference in hand temperatures between some materials was not significant. Stainless steel and aluminium were only distinguishable in the coldest situations (bare hands, low T_a, rest), which was also the case for polyurethane foam and wood, and for wood and nylon. Several interactions between main effects were observed. For average hand temperature, with gloves and exercise, the difference between the two most extreme materials was reduced from approximately 13° C in the coldest condition, to almost 0° C in the warmer climates. This is due to interactions between material, exercise, glove and temperature.

There was also a significant subject effect. There was a tendency for the subjects with the slimmest hands to have the lowest hand temperatures. Average hand temperature differed by about 5° C between the coldest and the warmest subjects. There also was a significant sex effect. The women had slightly lower peripheral temperatures (0.1 to 1.5° C), but higher T_{re} and abdomen T_{sk} (0.15 and 0.25° C).

During the whole session, the average temperature of the back of the hand was lower than the temperature of the contact side, except while in contact with the materi-

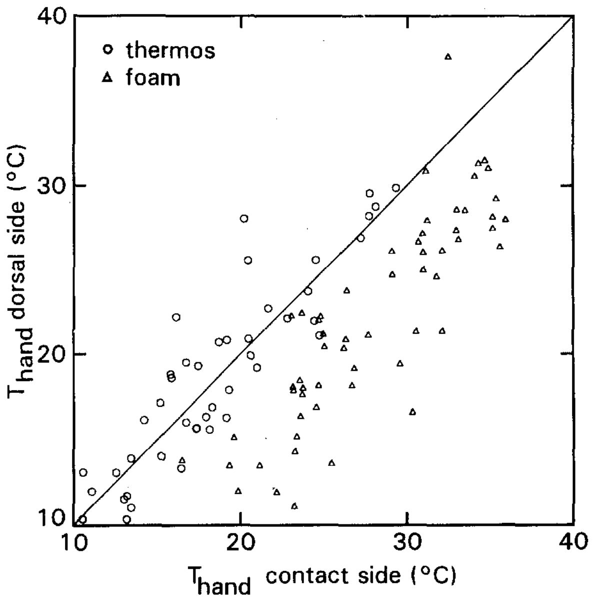

Fig. 1. Relationship between the temperature (T_{hand}) of the dorsal side and the contact side of the hand, averaged over the period of contact with the foam cylinder and the thermos cylinder

als with a high contact coefficient, where the temperature of both sides became approximately equal (Fig. 1). The thumb temperature was always the lowest hand temperature.

Cooling curves

Examples of the hand cooling curves obtained averaged for all subjects are presented in Fig. 2. The curves shown are given for those points where at least 9 of the 12 subjects were still holding the cylinders. The thermos-tube with its high heat sink resulted in the steepest cooling curves, reaching the safety criterion within 5 to 10 min for bare hands at $-10°$ C in some subjects. In combinations of the coldest climate with preceding rest, five occurrence of frostnip were observed while holding the thermos-tube and the aluminium cylinder, although the safety criterion for the measured contact temperature of 5° C was not exceeded. Apparently there were local cold spots with lower temperatures than measured by the contact thermocouples. For this reason, the safety criterion while holding the thermos tube was raised to 10° C. The calculated time constants of the observed individual cooling curves ranged from 5.5 min to infinity, reflecting the wide range of conditions.

In Fig. 3, the relationship between the inverse of the time constant K ($=1/\tau$) (median over all subjects) and the natural logarithm of the contact coefficient is presented for the combinations of preceding exercise and rest, both with and without gloves for the T_a of $-10°$ C. Clearly visible is the large effect of the glove, as well as the effect of exercise and the contact material. These effects are present for all temperatures and a strong temperature effect is present also. There are also interactions between material and glove, temperature and glove

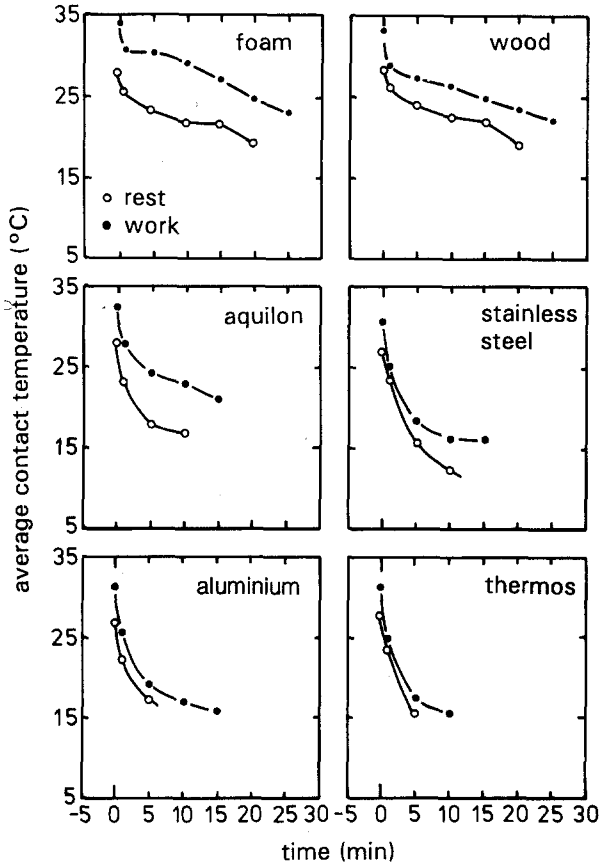

Fig. 2. Average hand cooling curves while touching the cylinder of six materials at an ambient temperature of $-10°$ C with and without preceding exercise (curves end when two subjects have ended contact)

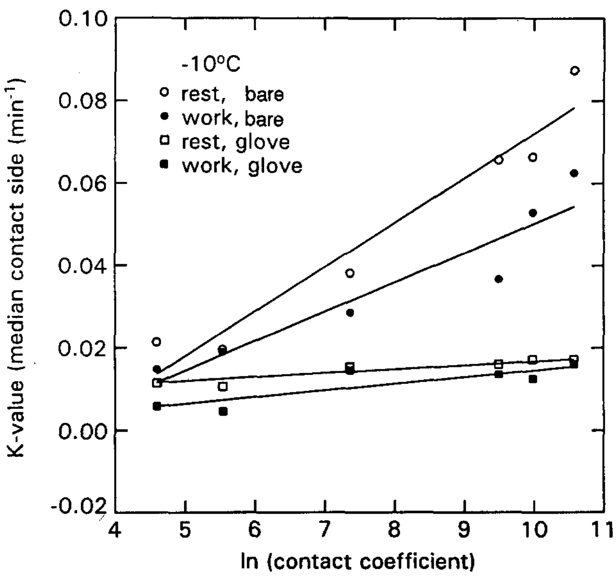

Fig. 3. Median values for K ($=1/\tau$) in relation to the natural logarithm of the contact coefficient of the test cylinders for $-10°$ C, with two exercise and two hand protection conditions

and exercise and glove. The interaction between T_a and material is only significant for the bare hands. For the warmer environments with the lower contact coefficients, and with the glove, the K values approach zero, which is the same as an infinite time constant, i.e. no cooling at all.

The stepwise regression analysis of the K value (the K value was used instead of the τ in this analysis, as the latter has a nonlinear relationship with the independent parameters, which could make the analysis unnecessarily complicated) on the independent parameters (contact coefficient of materials, glove, exercise, T_a and their interactions) resulted in the following equations:

For the median of the group:
without gloves:

$$K = 10^{-3} \cdot [-12.8 + 7.2 \cdot \ln(b) - 9.9 \cdot \text{exercise} - 0.69 \cdot T_a] \quad (\text{min}^{-1}) \quad (r = 0.92) \tag{5a}$$

with gloves:

$$K = 10^{-3} \cdot [14.0 + 1.5 \cdot \ln(b) - 9.9 \cdot \text{exercise} - 0.69 \cdot T_a] \quad (\text{min}^{-1}) \quad (r = 0.92) \tag{5b}$$

For the lower hinge (75th percentile):
wihout glove:

$$K = 10^{-3} \cdot [-12.8 + 9.3 \cdot \ln(b) - 9.2 \cdot \text{exercise} - 0.68 \cdot T_a] \quad (\text{min}^{-1}) \quad (r = 0.94) \tag{6a}$$

with glove:

$$K = 10^{-3} \cdot [14.8 + 1.6 \cdot \ln(b) - 9.2 \cdot \text{exercise} - 0.68 \cdot T_a] \quad (\text{min}^{-1}) \quad (r = 0.94) \tag{6b}$$

where ln(b) is the natural logarithm of contact coefficient b; exercise is the preceding rest or exercise: rest = 1, exercise = 2; T_a is the ambient temperature (also initial material temperature).

All main effects are present in the equations as well as one interaction [glove·ln(b)]. For reasons of clarity, the original equation has been separated into one with the glove and one without the glove, resulting in the disappearance of the interaction term. Adding the other interactions did not raise the explained variance of the equation significantly. As expected, a higher contact coefficient b caused a higher K (faster cooling), the presence of exercise or a higher T_a caused a lower K (slower cooling), a glove reduced the K value and finally the glove strongly reduced the sensitivity of the K value for the contact coefficient of the contact material (by almost five times).

As the largest safety risk was involved when handling materials with a high contact coefficient, the same analysis has been repeated for the three metals only. This resulted in equations for the median K as follows:

Without gloves:

$$K = 10^{-3} \cdot [-110.4 + 17.4 \cdot \ln(b) - 12.8 \cdot \text{exercise} - 0.86 \cdot T_a \quad (\text{min}^{-1}) \quad (r = 0.92) \tag{7a}$$

With gloves:

$$K = 10^{-3} \cdot [14.6 + 1.8 \cdot \ln(b) - 12.8 \cdot \text{exercise} - 0.86 \cdot T_a) \quad (\text{min}^{-1}) \quad (r = 0.92) \tag{7b}$$

The greatest change was in the magnitude of the glove effect on the sensitivity of the K value for the contact coefficient b (almost a factor ten), which was much higher for the metals only.

Comfort and pain sensations

The onset of pain (score: slightly painful) was observed at contact T_{sk} from 14 to 23° C (average 19° C) and at T_{sk} of the back of the hand from 12 to 20° C (average 16° C). The thermal sensation, comfortably cool, was related to a contact temperature of 25° C and to a dorsal hand temperature of 21° C. The subjective sensation criterion, cold, was reached at temperatures of 16° C and 10° C for the inner and outer side of the hand, respectively. The occurrence of the slightly painful sensation was associated with a thermal comfort score slightly lower than comfortably cool.

Although the subjects were able to judge their subjective temperature sensation for the contact side and the back of the hand separately, they were unable to make this distinction with their pain judgements. Therefore, only a pain sensation for the hand as a whole was given. The subjective temperature scores for both the sides of the hand appeared to be clearly related to the local T_{sk} (Fig. 4). Analyses of variance and subsequent regression analyses also revealed a strong relationship of temperature sensation with the other main parameters in the experiment. No relationship with T_{re} or average T_{sk} was observed. Only the contact side sensation was dependent on body heat storage. Stepwise regression resulted in 95% of the variance being explained with a model including all the significant parameters in the experiment. As this equation was quite unpractical, the analysis was repeated to find an equation describing the temperature sensation (T_{sens}) with a minimum of parameters and an optimal amount of the variance being explained. This resulted in the following equations:

Without gloves:

$$T_{\text{sens contact side}} = -11.7 + 0.417 \cdot T_{\text{contact side}} + 0.082 \cdot T_a \quad (r = 0.95) \tag{8a}$$

With gloves:

$$T_{\text{sens contact side}} = -13.3 + 0.417 \cdot T_{\text{contact side}} + 0.082 \cdot T_a \quad (r = 0.95) \tag{8b}$$

Without gloves:

$$T_{\text{sens dorsal side}} = -7.9 + 0.296 \cdot T_{\text{dorsal side}} + 0.097 \cdot T_a \quad (r = 0.94) \tag{9a}$$

With gloves:

$$T_{\text{sens dorsal side}} = -8.5 + 0.296 \cdot T_{\text{dorsal side}} + 0.097 \cdot T_a \quad (r = 0.94) \tag{9b}$$

showing a slightly higher sensitivity to local T_{sk} for the contact side, a similar sensitivity to T_a and a higher sensitivity to the presence of a glove for the contact side.

Pain sensation had a very strong relationship with T_{sens}, which was very similar for both hand sides. However, the relationship between pain sensation and local

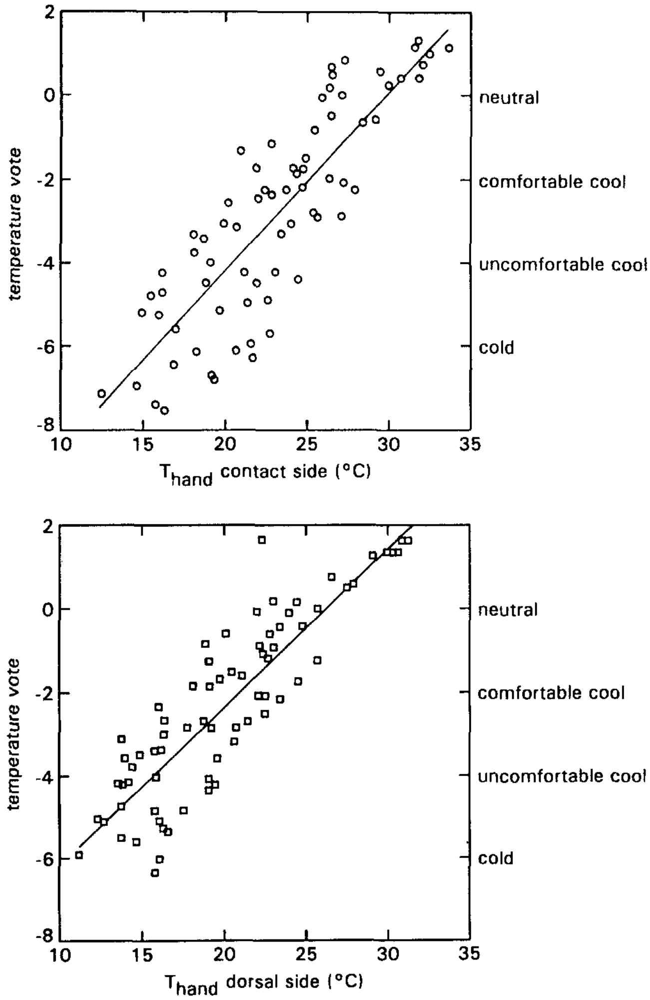

Fig. 4. Relationship between subjective hand temperature vote and actual local skin temperature (T_{hand}) for the contact side and the dorsal hand surface

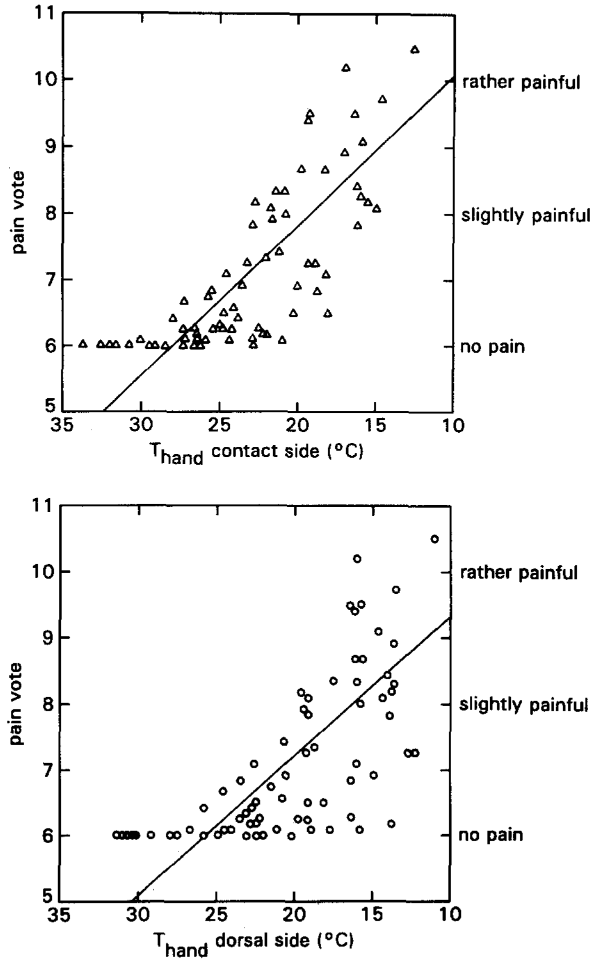

Fig. 5. Relationship between subjective pain sensation and the local hand skin temperature (T_{hand}) for the contact and the dorsal side of the hand

T_{sk} was clearer for the contact temperature than for the temperature of the back of the hand (Fig. 5), although both relationships were significant. Also the other main effects (glove, exercise, contact coefficient, T_{a}) had a significant effect. Stepwise regression resulted in:

Without gloves:

$$\text{pain score} = 12.4 - 0.258 \cdot T_{\mathrm{contact\,side}} - 0.047 \cdot T_{\mathrm{a}} \quad (r = 0.87) \tag{10a}$$

With gloves:

$$\text{pain score} = 13.2 - 0.258 \cdot T_{\mathrm{contact\,side}} - 0.047 \cdot T_{\mathrm{a}} \quad (r = 0.87) \tag{10b}$$

Discussion

Individual variability

Although this study aimed at a generalized description of hand cooling and associated safety risks, some data on the effect of differences among individual subjects have been included in the results. The women appeared to have had lower hand temperatures compared to the men. From Table 3, we can deduce that the women on average had lower contact surface areas and hand volumes than the men (42 vs 50 cm^2 and 311 vs 365 cm^3, respectively). A general tendency for the subjects with the slimmest hands to have the lowest hand temperatures was also observed. As the subjects were not selected to discriminate between the hand size and the sex effect, it was not possible to decide which of these parameters was responsible for the observed differences.

Cooling curves

Cold induced vasodilatation was observed in a small number of the cooling curves. As there was large interindividual variability in the occurrence of CIVD, it was left out of the calculations for the cooling curves, thereby creating an additional safety margin.

Looking at the relationship between the τ (or K) values and the independent parameters in the experiment (exercise, glove, material, T_a), it could be seen that besides the expected main effects, many interactions among the parameters were present. The effect of exercise could be seen as an effect on the central heat input to the hand, whereas the material and the glove affected the heat transfer at the contact surface directly. The effect of the glove was quite large, relative to its small thickness. The presence of a glove showed a strong interaction with the other parameters. A glove reduced the effect of all of them. The interaction between material type and T_a, which was only present for the bare hand, implied that with materials with high contact coefficients the T_a effect was much higher than with materials with low contact coefficients. As the T_a also reflected the starting temperature of the materials, this would also suggest that the starting temperature influenced the time constant depending on the material. The influence of starting temperature on the cooling time constant suggested that cooling was not completely Newtonian, as in cooling of an inanimate body the time constant would be independent of the temperature gradient. Such an effect could have been caused by the heat that was being carried by the blood flow. The blood flow depended on local temperature and would have been reduced more rapidly when touching the coldest materials. This effect would have been of different magnitude for the two sides of the hand since only a part of the hand was in contact with the cylinder and the rest was exposed to air. The different conductivities of air and the cylinders may have resulted in a more complicated cooling curve with two time constants, as the heat loss to the air contributed significantly to the total hand heat loss.

Freezing

Risk of skin freezing was larger when in contact with cold materials with a high contact coefficient, than when exposed to air only - firstly, due to the higher heat outflow from the hand and, secondly, due to the fact that skin in contact will freeze at a higher temperature. Skin in air has been shown to start to freeze at skin surface temperatures below $-10°$ C, due to supercooling of the tissue (Wilson and Goldman 1970; Wilson et al. 1976). It has been observed that skin in contact with cold metal bars starts to freeze at higher T_{sk} ($-2.2°$ C; Lewis and Love 1926). In the current experiments, skin freezing also occurred when the temperature of the freezing spots was much higher than $-10°$ C, as the measured contact temperatures were not yet below 5° C, and as the temperature of at least the surface of the aluminium cylinder (initially $-10°$ C) had increased in time due to heat inflow from the hand.

A possible reason for the higher freezing temperatures during contact was the presence of ice crystals on the cylinders, which could have promoted crystallization on and in the skin, resulting in less supercooling. In general, the actual freezing point of skin has been estimated at approximately $-0.6°$ C (Keatinge and Cannon 1960), with more or less supercooling depending on the circumstances.

Prediction of cooling curves

The model/equation which has been given for the dependence of K on the test parameters can also be used in the prediction of cooling curves for other materials (within the range of contact coefficient values studied in this experiment), based on Eqs. 3, 4 and 5. The starting T_{sk} could be taken from the actual person for which the prediction has to be done, or it could be predicted also from the data obtained in this experiment. Analysis of the starting contact temperatures (T_{start}) resulted in the following equation:

$$T_{start} = 27.9 + 0.05 \cdot T_a + 4.2 \text{ (for preceding exercise)} + 0.34 \text{ (when wearing gloves)} \quad (°\text{C}) \qquad (11)$$

Using this equation and Eqs. 3, 4 and 5 for the prediction of the cooling curves in the conditions of the present experiment resulted in a good correlation with the actually measured data (Fig. 6). For the individual curves, the correlation coefficient was almost the same ($r = 0.93$) but the standard error of the estimate (SEE = 4) was higher than for the group average for each condition ($r = 0.93$, SEE = 1.8). The validity of the cooling prediction for new data and or other materials has yet to be validated.

Thermal and pain sensation

For the occurrence of pain, T_{sk} below 21° C (back of the hand, Enander 1986), 16° C (Chatonnet and Cabanac 1965) and 10° C (Hellström 1965) have been reported. In the present experiment the onset of pain (score: slightly painful) was observed at contact T_{sk} of 14 to 23° C (average 19° C) and at T_{sk} of the back of the hand of 12 to 20° C (average 16° C), which falls well within the range of values in the literature. It was obvious from the data,

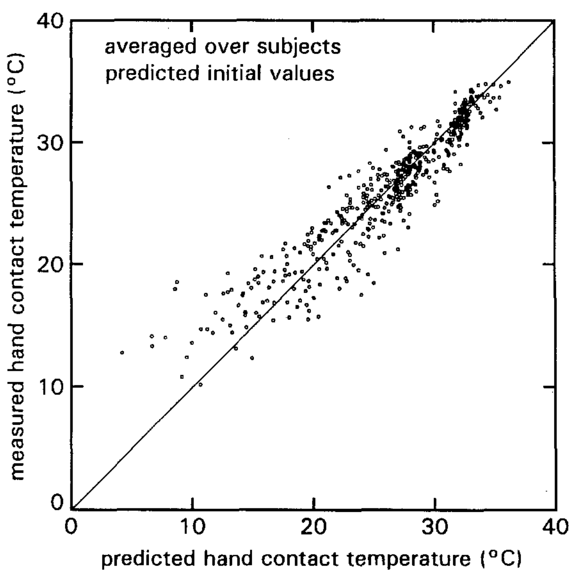

Fig. 6. Relationship between predicted hand contact temperatures and measured hand contact temperatures for the group means in each condition

that when discussing the relationship between pain and T_{sk}, the site of measurement was of major importance.

Reduced hand temperature could lead to reduced comfort and pain as well as to reduced performance and safety. Schiefer et al. (1984) have observed reduced performance when (middle) finger temperature fell below 25° C. Teichner (1957) did not find a significant relationship between hand (little finger) temperature and performance, although he observed a performance reduction with T_a falling below 16° C, and a slight effect of mean T_{sk}. Mackworth (1953) has observed reduced finger sensitivity starting at finger T_{sk} below 25° C with the strongest decrease below 15° C. Morton and Provins (1960) have observed impairments starting at index finger temperatures as low as 6° C, but with considerable individual variations. Some subjects in their experiments showed impaired sensitivity at finger temperatures close to 25° C. The fingers in their experiment were cooled in water, which was different from the other studies which were cooled in air. Overall, the reduction in sensitivity and/or manual performance seems to have occurred most clearly between 15 and 20° C, which coincided with the sensations of slightly painful and uncomfortably cool in the present experiment.

The regression equations relating thermal comfort sensation and pain to the local temperature and T_a explained a large amount of the variance in the data. They showed the obvious effect of local T_{sk} on comfort (positive) and pain (negative). The T_a may have acted through its influence on central body temperature or average T_{sk}, thereby centrally modifying the local sensation.

At first site, the glove effect seemed opposite to expectations. The Eqs. 8, 9 and 10 tell us that at the same local T_{sk} and T_a the subject felt colder and had more pain with a glove. However, with a glove the heat flow to the contact material was lower than without a glove. Thus the cooling would have been slower, which would have resulted in a smaller temperature gradient from skin to deeper tissues while wearing the gloves. Thus with a glove, at equal, T_{sk} the deeper tissues would have been colder than without a glove, which would also have been the case for the temperature at the site of the deeper temperature and pain receptors, resulting in a higher pain level. The fact that pain sensation increased with decreasing cooling speed (at equal skin temperature, Eq. 10) is also supported by the results obtained by Wilson and Goldman (1970) and Molnar et al. (1973) who did not observe pain before the point of frostnip in fast cooling (frostnip within 4 min) of small skin areas. The sensitivity of the equations for comfort and pain was highest for local T_{sk}, with lower and similar influences of T_a and gloves.

Using the relationship between pain and the other parameters in the experiment, it has been possible to calculate exposure times leading to a certain pain level for any given combination of contact material, glove, exercise and T_a (within the range of the experimental conditions). In Fig. 7, the contact times to reach pain levels of slightly painful and rather painful and to reach the safety limit of 5° C contact temperature are presented in relation to the natural logarithm of the contact coefficient for T_a of −10 and 0° C. The values given represent the lower hinge values, which would imply that 75% of the population would cool more slowly, but also that 25% would cool more quickly than this. The reason for taking 75th instead of, for example, 95th percentiles was discussed earlier. These two figures show once more the effects of exercise, glove and T_a: with exercise and

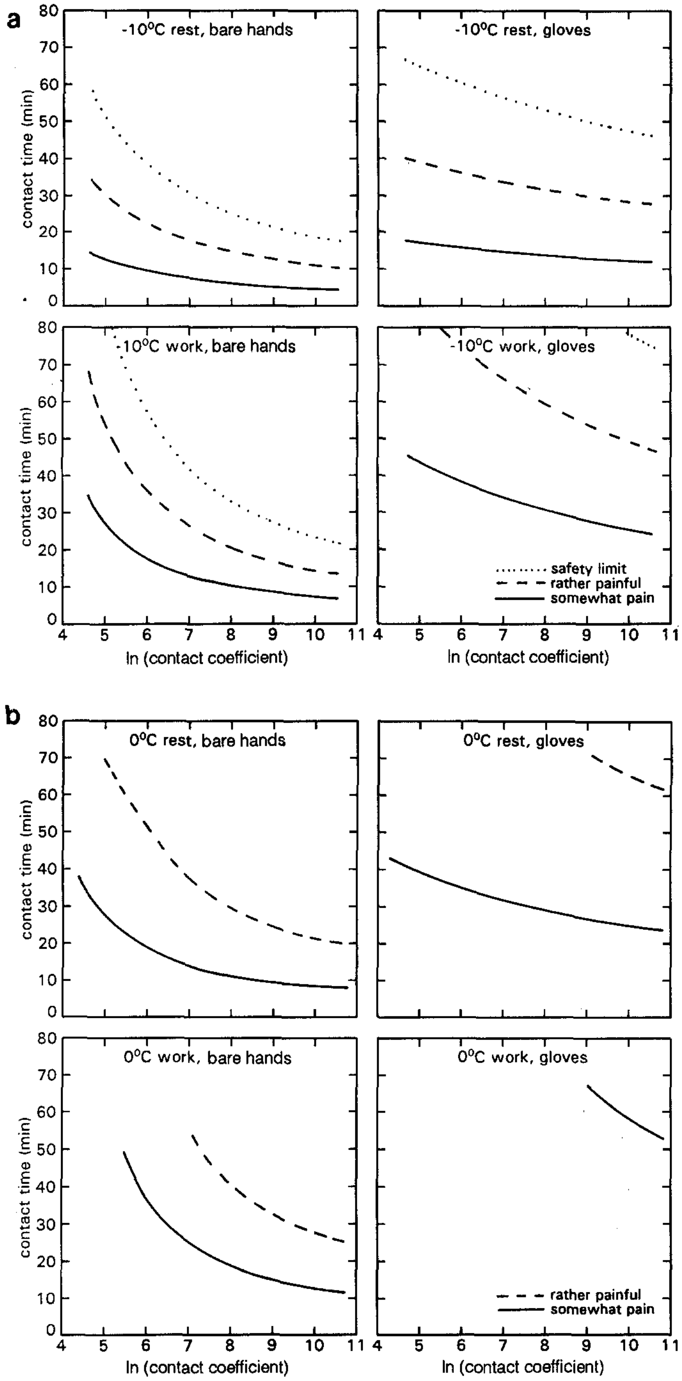

Fig. 7. Contact times before reaching the sensations of slightly painful and rather painful, and the safety criterion of 5° C in relation to the natural logarithm of the materials' contact coefficients for ambient and material temperatures of −10° C (**a**) or 0° C (**b**) with and without the thin work glove and preceding exercise

glove, hardly any safety risk was present at $-10°$ C, and at 0° C no safety risk at all was indicated. The latter is obvious, as with contact material temperatures of 0° C, the hand contact temperature would not descend into freezing conditions; however, rather painful sensations would still be possible.

Conclusions

Hand cooling can be described by Newtonian cooling curves, of which the time constant is a function of the contact material, the T_a, the presence of gloves and exercise. Pain and thermal sensation can be described using local T_{sk}, T_a and the presence of gloves.

When in contact with cold materials the skin tends to freeze at higher temperatures than when exposed only to cold air, due to a reduction in the amount of supercooling. When monitoring hand temperature, the site of measurement is of great importance. At equal pain and thermal levels, the back of the hand was approximately 3° C cooler than the palm of the hand. The amount of pain felt by the subjects appeared to be related to the rate of hand cooling. The lower the rate, the more pain was felt at equal T_{sk}.

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