Temperature limit values for touching cold surfaces with the fingertip

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Temperature limit values for touching cold surfaces with the fingertip


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ABSTRACT.

OBJECTIVES: At the request of the European Commission and in the framework of the European Machinery Directive, research was performed in five different laboratories to develop specifications for surface temperature limit values for the short-term accidental touching of the fingertip with cold surfaces. METHODS: Data was collected in four laboratories with a total of twenty males and twenty females performing a grand total of 1655 exposures. Each touched polished blocks of aluminium, stainless steel, nylon-6 and wood using the distal phalanx of the index finger with a contact force of 1.0, 2.9 and 9.8 N, at surface temperatures from +2 and -40°C for a maximum duration of 120 seconds. Conditions were selected in order to elicit varying rates of skin cooling upon contact. Contact temperature (T_C) of the fingertip was measured over time using a T-type thermocouple. RESULTS: A database obtained from the experiments was collated and analysed to characterise fingertip contact cooling across a range of materials and surface temperatures. The database was subsequently used to develop a predictive model to describe the contact duration required for skin contact temperature to reach the physiological criteria of onset of pain (15°C), onset of numbness (7°C) and onset of frostbite risk (0°C). CONCLUSIONS: The data reflect the strong link between the risk of skin damage and the thermal properties of the material touched. For aluminium and steel, skin temperatures of 0°C occurs within 2 to 6 s at surface temperatures of -15°C. For non-metallic surfaces, onset of numbness occurs within 15 to 65 s of contact at -35°C and onset of cold pain occurs within 5 s of contact at -20°C. The predictive model subsequently developed was a non-linear exponential expression also reflecting the effects of material thermal properties and those of the materials initial temperature. This model provides information for the protection of workers against the risk of cold injury by establishing the temperature limits of cold touchable surfaces for a broad range of materials, and is now proposed as guidance values in a new international standard (ISO/DIS 13732-3, 2005).

Keywords: Cold surfaces, contact temperature, finger touching, machine safety
INTRODUCTION

Contact between bare skin and cold surfaces may occur in industrial settings as well as in everyday activities. This contact may be intentional or accidental and can affect small skin areas such as a fingertip or larger areas such as the palm of the hand. The contact of human skin with a cold surface can cause pain, numbness and risk of skin damage (Daniels, 1956; Havenith et al., 1992; Chen et al., 1994a). Furthermore, the reduction in tactile sensitivity (Provins and Morton, 1960) and manual dexterity (Geng et al. 2000a; Geng 2001; Powell et al. 2002) associated with skin cooling also greatly influences one’s ability to perform the manual tasks routinely required by workers in cold environments in an efficient and safe manner (Enander, 1984; Havenith et al. 1995; Heus et al. 1995). Despite the apparent health and safety risk due to cold contact exposure, and a standard being available to determine temperature limits of hot surfaces in working environments (EN 563:1994; EN13202, 1999), no such standard was available for cold surfaces.

The European Directive on Safety of Machinery requires that touching and handling of cold objects should be safe. Therefore the European Union funded COLDSURF research project was established in 1998 in order to collect data for skin contact with cold surfaces, as the available information in existing literature was sparse or unavailable (Holmér et al., 2003). A first report has been published reporting temperature limits for surfaces involved with long-term (up to 1200 s) gripping contact (Malchaire et al., 2002). The present study reports the results from the second part of the project concerned with the short-term (<120 s) and possibly accidental contact of cold surfaces with a smaller area of the skin, such as the fingertip. The results from both studies have been integrated in a proposal for an international standard for skin contact with cold surfaces (ISO/DIS 13732-3, 2005).
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For the purpose of assessing the cold contact response of the skin-material interface under typical conditions, several principal factors must be considered so that the environmental conditions are appropriately characterised. Surface temperature of contactable solid objects in industry varies greatly and may be as low as -30°C or as high as +10°C (Holmer et al. 2000). Furthermore the thermal properties of the contact material will extend from a low level of conductivity (e.g. wood) to highly conductive surfaces such as metals. Indeed it has been previously reported that metal surfaces, in particular aluminium, present a risk of frostbite within 10 seconds at surface temperatures below -5 °C (Chen et al. 1994a) during three-fingered contact. Another factor to be considered is the level of contact force which has been reported to influence skin cooling rate (Chen, 1994b; Geng et al. 2000b). Forces typically present may be as low as 1 N (fine motor tasks, or accidental contact) up to 10 N (accidentally falling without recovery) (Holmer et al. 2000).

Hand dysfunction and the associated safety risk during occupational practices in the cold increases with decreasing skin temperature. Onset of cold-pain has been reported to occur between 23 and 14°C during cold contact (Havenith et al. 1992). A marked deterioration in tactile discrimination occurs at finger skin temperatures below 8°C with numbness found in one-third of subjects at 7°C (Morton and Provins, 1960). The estimated freezing point of human finger skin is -0.6°C (Keatinge and Evans, 1960), but due to supercooling it may be lower before freezing starts. As the skin surface temperature falls from -4.8 to -7.8°C, the risk of frostbite increases from 5 to 95% (Danielsson, 1996). It is therefore pertinent to investigate the relative risk of different levels of skin cooling that affect the safety of the worker.

The aim of the present study was to develop a predictive model to establish the temperature limits of cold touchable surfaces under conditions representative of those encountered daily in many occupations. This was achieved by, a) collating data to characterise index fingertip
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contact cooling across a broad range of materials, surface temperatures and contact forces; and
b) using this data to empirically model the contact duration required for skin contact
temperature to reach the physiological criteria of the onset of pain (15ºC), numbness (7ºC) and
frostbite risk (0ºC).
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METHODS

The experiments were carried out with human subjects, whose distal phalanx of the index finger of the non-dominant hand touched a cold surface. The experiments were repeated for each subject under different experimental conditions (i.e., type of material, surface temperature of the materials ($T_s$) and contact force) in a balanced order. The response variable was contact temperature ($T_c$) measured over time.

Apparatus

Four materials, i.e., aluminium, steel, nylon-6 and wood, were chosen to be representative of a broad range of thermal properties (contact factor). The contact factor is defined as the square root of the product of the thermal conductivity $\lambda$ (W/mK), the density $\rho$ (kg/m$^3$) and the specific heat $C$ (J/kg K). The thermal characteristics of the materials are given in Table 1.

INSERT TABLE 1

Solid blocks of the four materials with dimensions 96×96×96 mm were selected as the contact objects. The surfaces of materials were polished. The blocks were suspended on a counterbalanced system in order to regulate the finger contact force at 1.0, 2.9 and 9.8 N. The surface temperature of the contact material was achieved allowing the blocks to equilibrate with the ambient temperature (in either a cool-box or climatic chamber) before each exposure.

Data was collected at four different laboratories using either a hand-cooling box with only the hand exposed to cold air, or in a climatic chamber with the subject’s whole body exposed to the cold. Hand-cooling boxes were located in climate controlled room ($T_a = 20^\circ$C, RH = 50%) and were employed in two laboratories. Air temperature inside the cool-box was regulated between $-35^\circ$C and $+5^\circ$C using a temperature control module allowing an accuracy of $\pm 0.5^\circ$C. Each cool-box had an access hole to allow the subject to insert their hand and part of the forearm.
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Also, the boxes were furnished with a three-layer Plexiglas window and lighting so that the hand could be observed. In the other two laboratories, experiments were performed in a climatic chamber regulated at an air temperature between –40 and +2 °C and a relative humidity of 50%.

The contact temperature \((T_C, °C)\) was measured continuously with copper-constantan thermocouples T-type diameter 0.2 mm or copper-constantan thermocouples, 0.5 mm. The time constant of the sensor was 0.47 s and the accuracy was ± 0.2 °C (-5 to +36 °C). The thermocouple was positioned in the middle of first phalanx of the left index fingertip and was secured by a small piece of surgical tape (Blenderm, 3M) leaving the tip of the thermocouple exposed.

Participants

After the experimental protocol was approved by the ethical advisory committee of the institutions conducting experimental trials, forty healthy participants (20 women and 20 men) aged 18 to 35 years volunteered for the experimental study. They were not acclimatised to cold and none had any history of vascular or neurological disorders or cold injury. The instruction and information of the details, discomforts and risks associated with the experimental protocol were given to the participants before they signed a written consent. They were instructed not to consume alcohol 24 hours before, drink tea or coffee, or work physically during 1-hour before the experiment. All subjects were right-handed, non-smokers and had experience with moderate cold exposure.

Anthropometric measurements of the index finger on the non-dominant hand of the subjects were carried out. The volume of the finger was measured by water displacement, immersing the index finger to first phalanx/proximal flexion crease of the finger. Finger contact area was
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measured by scanning a fingerprint at the three levels of contact force (1.0, 2.9 and 9.8 N) into a customised computer programme. Each measurement was carried out three times and the average of the three measurements was used. Mean characteristics are shown in Table 2.

**INSERT TABLE 2**

**Procedure**

Experiments were distributed across the four laboratories collecting data (10 participants per laboratory) in 24 experimental conditions in order to cover the broadest range of exposure in terms of surface temperature (\(T_s, ^\circ C\)), and to replicate conditions with participants from different laboratories.

Each participant was tested over five sessions on separate days and at the same time of the day. Each experimental session began with the participant resting for a period of 30-min in a room, and was asked to rate his or her whole-body thermal sensation on a thermal sensation scale (ISO 7730, 1994). The sensation scale used was a reduced 5-point bi-polar scale: +2 Warm, +1 Slightly Warm, 0 Neutral, -1 Slightly Cool, -2 Cool. Subjective votes were recorded at 5-min intervals. For the experiments carried out with a cool-box, the environmental conditions within the room were selected to induce the thermal sensation equivalent to -1 (slightly cool) at a standardised clothing insulation of 0.4 to 0.5 clo. For the experiments carried out in a climatic chamber, clothing insulation was selected to also achieve a sensation vote of -1. These levels of clothing insulation were dependent upon the environmental conditions of the chamber. For chamber conditions between +2 and -10ºC, a clo value of ~1.5 was worn, and for conditions between -15 and -40ºC, a clo value of ~2.0 was worn. The thermal sensation of slightly cool was targeted to achieve a state of vasoconstriction.

After the 30-min rest period, each participant touched, with the first phalanx of the index finger of the non-dominant hand, the appropriate material block at the required surface temperature
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with a given finger contact force. The skin cooling behaviour was monitored throughout the exposure until one of the following withdrawal criteria were met: a contact temperature ($T_C$) of 0°C; a test duration of 120 s; a typical sensation of frostnip about which the participants were instructed (burning/tingling); a sensation of intolerable pain or any other reason for which the participant perceived withdrawal to be necessary.

Database management

The experimental data collected from 1655 tests under 24 experimental conditions were stored and managed in a database. Afterwards a statistical analysis of the pooled database was conducted with the computer software Statgraphics Plus for Windows.

The following four parameters were extracted from the database:

1. **Duration**: total time for the finger touching ($D_{SP}$, in seconds);
2. **Pain threshold**: time for contact temperature to reach 15 °C, ($t(15)$, in seconds);
3. **Numbness threshold**: time for contact temperature to reach 7 °C ($t(7)$, in seconds);
4. **Frostbite threshold**: time for contact temperature to reach 0°C ($t(0)$, in seconds).

The first parameter recorded was touching duration. The duration of touching was limited to 120 seconds. From the curve of evolution of the contact temperature during the experiment, the times needed to reach the three contact temperatures that defined by $t(15)$, $t(7)$ and $t(0)$, were determined by a mathematical interpolation or an extrapolation, the latter for maximally one extra point in the cooling curve. When the cooling curve was such that a certain contact temperature would never be reached, a missing value (-) was encoded, indicating that the data was absent. For instance, when the final $T_C$ reached 10 °C, the $t(15)$ was interpolated, the $t(7)$ was extrapolated and the $t(0)$ was considered as missing value. For $t(15)$ a missing value would imply that the touching time was longer than 2 minutes.
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**Statistical analysis**

Statistical analyses were performed in all five laboratories participating in the project on their own data and subsequently on the merged dataset. The results indicated that most of the distributions of duration in a given condition were non-Gaussian and not symmetrical, especially for $D_{SP}$, limited to 120 seconds when the subject ended the 2 minutes exposure period. Therefore, the means and standard deviations were not computed and medians and quartiles were used for statistical analyses. As the number of data points for some conditions were rather low, the analysis of the limit values was based on the lower quartile in order to protect 75% of the population.

Empirical relations were derived based on the prediction of the lower quartile of the duration $D_{SP}$ and the time to reach the contact temperature of 15, 7 and 0°C, respectively. The duration was empirically correlated with the surface temperature $T_S$ and the contact factor $F_C$ of the material (Table 1). A non-linear regression model was then derived to give the best prediction of the critical times ($t(15)$, $t(7)$ and $t(0)$) as a function of the surface temperature ($T_S$) and the contact factor ($F_C$). In order to make this prediction model as universal as possible, a single model was preferred over having different models for each condition. This choice could affect the predictive quality of the equation.

The best fitting of non-linear models was obtained in the following form:

$$\text{Time} = \left( \frac{a}{F_C^b} \right) \exp \left( c \times F_C^d \times T_S \right) \quad (1)$$

Where: $a$, $b$, $c$ and $d$ are the constants that were estimated by an iterative non-linear regression procedure. For each model, the first general expression was simplified when some of the coefficients were not significant.
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RESULTS

Descriptive statistics of the database

Descriptive statistics (mean, standard deviation, median, lower and upper quartiles) regarding spontaneous touching duration ($D_{SP}$) under 24 experimental conditions are given (Table 3). The number of tests for $D_{SP}$ values less than 120 seconds are also given in Table 3. It can be seen that 752 of these 1655 duration were below the limit value of 120 sec. The limit duration of 120 seconds was reached for most of the experimental conditions with wood and nylon. Also, the duration for touching aluminium and steel at surface temperatures higher than 0 °C was 120 seconds (Table 3).

INSERT TABLE 3

Descriptive statistics for the times to reach the contact temperatures ($T_C$) of 15, 7 and 0°C (i.e., $t(15)$, $t(7)$ and $t(0)$) are given (Table 4). The values could be evaluated in 1448 cases out of the 1521 for $t(15)$, 1490 cases out of 1563 for $t(7)$ and 990 cases out of 1130 for $t(0)$, respectively. This is due to the number of missing values shown in Table 4.

INSERT TABLE 4

Tables 3 and 4 show that the number of points available to determine the lower quartile (25th percentile, $P_{25}$) was limited under some conditions. This was dependent upon the combinations of thermal properties and surface temperature of the materials. Furthermore, the $P_{25}$ values for $D_{SP}$ increase with increasing the material surface temperature (Table 3). However, the $P_{25}$ values for the times to reach the $T_C$ of 15, 7 and 0 °C display an inconsistent pattern for wood - the lowest contact factor (Table 4). This may reflect the distribution of the test conditions over the different laboratories and test environments, which for wood with its slow cooling would have the largest impact, as indeed observed here.

Empirical modelling

Touching experiments are representative of short-term exposure to cold. Finger cooling is most likely to occur only for touching times less than 100 s. Hence, lower quartile values from
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experiments with wood and nylon above 100 s were not taken into account. Therefore, the final model for touching duration $D_{SP}$ was derived only with data from steel and aluminium, which is shown in the following form (Equation (2), $R^2=0.99$):

$$D_{SP} = \left( \frac{180.9}{F_C^{0.425}} \right) \exp \left( 0.057 \times F_C^{0.475} \times T_S \right) \quad (2)$$

The final models for touching time to reach a contact temperature of 0, 7 and 15 °C, respectively, are shown as follows:

- for time to reach $T_C$ of 0°C, ($R^2 = 0.99$, only for steel and aluminium):
  $t(0) = \left( \frac{980.5}{F_C^{1.03}} \right) \exp \left( 0.21 \times T_S \right) \quad (3)$

- for time to reach 7°C, ($R^2 = 0.99$, only for nylon, steel and aluminium):
  $t(7) = \left( \frac{454.6}{F_C^{1.807}} \right) \exp \left( 0.21 \times F_C^{0.467} \times T_S \right) \quad (4)$

- for time to reach 15°C ($R^2 = 0.93$, only for nylon, steel and aluminium):
  $t(15) = \left( \frac{13.7}{F_C^{1.097}} \right) \exp \left( 0.108 \times T_S \right) \quad (5)$

All the models were accurate, as indicated by the proportion of the variability in the model for the dependent variable ($R$-squared or $R^2$) being close to 1. The models provide data to be used to establish temperature limit values for cold touchable surfaces to protect against cold injury, but also to avoid pain and numbness. Figures 1-3 show the observed and predicted values from the models for each parameter used.

INSERT FIGURES 1 – 3

It is evident from the Figures 1-3 that the time for the $T_C$ to reach 15, 7 and 0 °C are notably faster in the cases of touching at the lower surface temperature. The time to reach the critical temperatures when touching the cold metallic surfaces was significantly shorter than that when touching the non-metallic surfaces under all the conditions studied. The predicted values are lower than the observed values, indicating a degree of safety.
Since the P_{25} values of time to reach 0 °C from wood and nylon were longer than 100 sec, the expression for the prediction of t(0) cannot be used for these non-metallic materials. The final prediction model for the time to reach the contact temperature of 0 °C was derived only for steel and aluminium under conditions of T_S < 0°C in Equation (3). Also, the P_{25} values of time to reach 7 °C from wood were longer than 100 seconds, which were not taken into account for the models of t(7) in Equation (4). The data of P_{25} of time to reach 15 °C for material of wood were lower than 100 sec (Table 4), but it was impossible to derive a valid prediction of the inconsistent patterns (Figure 3). The model for t(15) was derived from the data of P_{25} from nylon, steel and aluminium in Equation (5).

After incorporating the effects of material contact factor and surface temperature for the prediction of t(0), t(7) and t(15), it was found that variation in finger contact force did not contribute any further significant predictive power to the empirical model for any level of contact cooling risk.

Secure time thresholds

As mentioned earlier the results have proved that the surface temperature was a function of time for T_C to reach a criterion. The criteria were three levels corresponding to frostbite (T_C = 0 °C), numbness (T_C = 7 °C) and pain (T_C = 15 °C). The thresholds for finger touching various cold surfaces are shown in Figures 4-6.

**INSERT FIGURES 4 – 6**

The experimental data did not show any occurrence of cooling to 0°C for the case of a finger touching nylon and wood. Hence the frostbite threshold for the contact with nylon and wood do not exist in the range T_S from -40 to 0 °C (Figure 4). The thresholds for numbness and pain
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were less than 100 s when the finger touched these four materials at surface temperatures between –40 and +2 °C.
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**DISCUSSION**

The present study investigated the influences of thermal properties of a contact material, surface temperature and finger contact force upon skin cooling behaviour of the fingertip during short-term (<120 s) contact. The two principle factors influencing contact cooling time across the conditions and participants studied were thermal properties of the material (expressed as a contact factor) and surface temperature.

The aim of the model derived was to provide a universal equation that could be applied to a range of conditions to predict the contact duration required to reach skin temperatures associated with three different levels of contact cooling risk – all influencing safety in the workplace. The three levels of risk were the onset of cold pain ($T_C = 15^\circ C$), the onset of numbness ($T_C = 7^\circ C$) and the onset of skin freezing ($T_C = 0^\circ C$). The final model proposed was a non-linear function of material contact factor and surface temperature, incorporating different constants for each predicted level of risk.

Greater contact forces have been previously demonstrated to significantly affect skin cooling behaviour of the contact site during exposure to metallic surfaces (Chen et al. 1994b), though no such effect was found for non-metallic surfaces (Geng et al. 2000b). In the model presented here, finger contact force was not found to add a significant amount of predictive power and was therefore omitted from the equation. The absence of significance for this effect may be attributed to data being collected in different laboratories, as well as to the mixing of whole body exposures and hand-arm-only exposures. These factors will have introduced more variability in the data and created more overlap between the pressure condition data. The predictive model in the present study was required to be universally applicable to the broad range of conditions typically present in the workplace, including both metallic and non-metallic materials and for a mix of pressure situations. Hence, it was deemed preferable to pool all
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obtained data into an as large as possible dataset, rather than to try to discriminate between all possible effects in more controlled but very small datasets separately. The data and equations presented are therefore representative of a wide range of contact cooling exposure types, and require fewer caveats than when only a small dataset would be analysed in more depth.

A further reason for the lack of significance of contact pressure differences may have been the level of vasoconstriction present in the participants who were ‘slightly cool’. In support of this notion, it has been demonstrated that a significant difference in contact cooling response exists between an arterial occlusion and a vasodilated condition (Jay and Havenith, 2005) showing the impact of blood flow on cooling responses. Furthermore, it has also been shown that this blood flow is modulated by the contact pressure, in that laser-Doppler skin blood flow of the fingertip reduces exponentially with increasing finger contact force, and finally, that the extent of this reduction decreases dramatically with a cooler thermal state of the lower arm (Jay and White, 2006). It is reasoned that where vasoconstriction is present due to a ‘slightly cool’ thermal state of the person, like in the present experiment, the closure of the capillaries by greater contact forces will have less impact than in a warmer state with high ‘uncompressed’ finger tissue blood flows.

The present study was conducted to develop limit values applicable to the general population; therefore the experimental study was performed upon both males and females as a group. The proposed models for the varying levels of contact cooling risk cover both male sand females. Further studies have scrutinised the finger contact cooling data with respect to gender. A gender difference in finger cooling time has been reported, with typical females showing faster skin cooling rates than typical males under slow cooling conditions (Geng 2001; Jay and Havenith, 2004a). These differences have been attributed to typical differences in hand size between males and females, in terms of surface area and mass. Also, females have less capacity
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for metabolic heat production of the extremities (Pathak and Charron, 1987). In a subsequent study with a greater subject pool and by design matching gender for hand anthropometry (Jay and Havenith, 2004b), it was demonstrated that after uncoupling hand size and gender, no difference exists in contact cooling between males and females under slow cooling conditions. They also concluded that skin cooling was dependent upon hand/finger size of the individual, with the best predictor being finger volume (Jay and Havenith, 2004b). For a general prediction model as developed here males and females were therefore not separated, but seen as representing the range of hand sizes present in the general population, independent of gender.

The effect of individual variability upon contact cooling response has been investigated (Geng, 2001; Rissanen et al., 2000). Individual tissue properties of finger skin, blood flow through the micro-circulation under the skin and subsequent heat input may also influence contact cooling behaviour (Holmér, 1997). Furthermore, initial skin temperature of the hand and metabolic rate of whole body as well as constitution of the contact were also considered. To cover most of the individual variation and ensure protection for 75% of the population in contact with cold surfaces, the non-linear predictive models are based on the database of lower quartile (P25) values. These experiments were carried out with healthy human subjects between the ages of 18 to 35 years, however it should be considered how these responses apply to the wider population, particularly as a function of age. Collagen fibre density of the human dermis increases with age up to 40 years, following which it begins decreasing at a similar rate. Furthermore, in the reticular dermis the relative volumes of elastic fibres also increase with age attaining the highest values beyond the 40s (Vitellaro-Zuccarello et al. 1994). These data suggest that the relative insulation provided by the skin of the fingertip should be similar at 60 years to that at 20 years. While it is acknowledged that other factors such as differences in peripheral blood flow may also change as a function of age, the models in the present study are
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considered to be applicable to the finger skin of healthy males and females between the ages of 15-60 years.

Contact temperature ($T_c$) was used as a measure of skin cooling response in the present study. Upon contact, equilibrium is achieved at some point intermediate between the two initial temperatures of the contacting skin and surface, this is the ‘contact temperature’ (Vendrik and Vos, 1957). It has been demonstrated that these relative values are reproducible and indicative of the absolute skin temperature values (Stoll, 1977), and are used frequently by clinicians.

From an ergonomic point of view, an estimate of the skin cooling risk is possible by measuring the surface temperature of the cold object and the contact time to reach a defined criterion. As mentioned, earlier studies justify that the criteria would be levels corresponding to 0 °C for frostnip (Danielsson, 1996), 7 °C for numbness (Provins and Morton, 1960) and 15 °C for pain (Havenith, et al., 1992; Geng, et al., 2001). The determination of contact time is more convenient than the measurement of the contact temperature. It is apparent that frostbite injury may occur with finger contact of an aluminium surface at –20 °C for only 1 second, at –15 °C for less than 3 seconds, and at –10 °C for approximately 5 seconds (Figure 4). The time thresholds are useful and informative for the protection of finger/hand skin in cold operations. They give recommended, longest contact times for different cooling criteria for design of workstations and hand tools.

The data obtained from two different sets of cold exposures (whole-body and hand-only) were intentionally mixed into the database. The first one refers to situations such as cold rooms where heavily clad individuals must touch cold and dry objects. The experiments did not concern conditions where the objects are wet or iced, however thin ice layers have been subsequently demonstrated to accelerate contact cooling rate (Rissanen and Rintamäki, 2005).
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The other exposure conditions referred to environments where the hands only are exposed to cold goods. Such conditions are likely to occur in industry where workers may contact refrigerated pipes or pieces of machinery. In some cases, these cold surfaces might be iced or wet, however these situations were not considered in the present research. In addition, fluids below 0 °C may comprise an acute risk of frostbite. Examples of such fluids are ethereal gasoline, ammonia and nitrogen. Similarly, solid carbon dioxide gives rise to a risk of frostbite. Therefore it is necessary to consider that the risk for frostbite can increase during skin contact with cold liquid and other such substances.
CONCLUSIONS

In conclusion, the present data has demonstrated the strong link between the risk of skin damage and the thermal properties of the materials touched, with the Aluminium falling into the highest risk group of the materials tested here. For Aluminium and steel, skin temperatures of 0°C occurred within 15 to 20 s of contact at material temperatures as high as -4°C and within 2 to 6 s at -15°C. For non-metallic surfaces, onset of numbness occurred within 15 to 65 s of contact at -35°C and onset of cold pain occurred within 5 s of contact at -20°C. The predictive model subsequently developed was a non-linear expression incorporating the effects of material thermal properties and surface temperature. This new tool is used to protect workers against the risk of cold injury, numbness and pain by establishing the temperature limits of cold touchable surfaces for a broad range of materials, and is now proposed as guidance values in a new international standard (ISO/DIS 13732-3, 2005).

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**Table 1.** Thermal properties of the 4 contact materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal conductivity $\lambda$ (W / m K)</th>
<th>Specific heat $C$ ($10^3$ J / kg K)</th>
<th>Density $\rho$ ($10^3$ kg / m$^3$)</th>
<th>Contact factor $CF$ ($10^3$ J / s$^{0.5}$ m$^2$ K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium</td>
<td>180.00</td>
<td>0.90</td>
<td>2.77</td>
<td>21.18</td>
</tr>
<tr>
<td>Steel</td>
<td>14.80</td>
<td>0.46</td>
<td>7.75</td>
<td>7.27</td>
</tr>
<tr>
<td>Nylon</td>
<td>0.34</td>
<td>1.48</td>
<td>1.20</td>
<td>0.78</td>
</tr>
<tr>
<td>Wood</td>
<td>0.22</td>
<td>2.20</td>
<td>0.56</td>
<td>0.52</td>
</tr>
</tbody>
</table>
Limits for fingertip cold contact

Table 2. Participant physical characteristics (mean ± standard deviation)

<table>
<thead>
<tr>
<th></th>
<th>Age (year)</th>
<th>Weight (kg)</th>
<th>Height (cm)</th>
<th>Finger length (cm)</th>
<th>Finger volume (cm³)</th>
<th>*1st phalanx length (cm)</th>
<th>*1st phalanx volume (cm³)</th>
<th>Contact surface (cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean ± SD</td>
<td>23.8 ± 4.4</td>
<td>71.11 ± 14.83</td>
<td>173.96 ± 10.61</td>
<td>7.77 ± 1.13</td>
<td>19.19 ± 6.40</td>
<td>1.83 ± 1.11</td>
<td>3.75 ± 1.40</td>
<td>2.37 ± 0.46</td>
</tr>
</tbody>
</table>

*data from three Laboratories
**Limits for fingertip cold contact**

**Table 3.** Descriptive statistics of the database: test duration limited to 120 sec.

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Labels</th>
<th>Surface temperature (°C)</th>
<th>Total values</th>
<th>N values below 120 sec</th>
<th>Lower quartile (sec)</th>
<th>Median (sec)</th>
<th>Upper quartile (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Wood</td>
<td>-40</td>
<td>30</td>
<td>0</td>
<td>120.0</td>
<td>120.0</td>
<td>120.0</td>
</tr>
<tr>
<td>2</td>
<td>Nylon</td>
<td>-35</td>
<td>18</td>
<td>11</td>
<td>81.6</td>
<td>101.4</td>
<td>120.0</td>
</tr>
<tr>
<td>3</td>
<td>Wood</td>
<td>-33</td>
<td>18</td>
<td>1</td>
<td>120.0</td>
<td>120.0</td>
<td>120.0</td>
</tr>
<tr>
<td>4</td>
<td>Nylon</td>
<td>-30</td>
<td>35</td>
<td>5</td>
<td>120.0</td>
<td>120.0</td>
<td>120.0</td>
</tr>
<tr>
<td>5</td>
<td>Wood</td>
<td>-30</td>
<td>36</td>
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<td>120.0</td>
<td>120.0</td>
<td>120.0</td>
</tr>
<tr>
<td>6</td>
<td>Wood</td>
<td>-25</td>
<td>36</td>
<td>1</td>
<td>120.0</td>
<td>120.0</td>
<td>120.0</td>
</tr>
<tr>
<td>7</td>
<td>Nylon</td>
<td>-25</td>
<td>34</td>
<td>5</td>
<td>120.0</td>
<td>120.0</td>
<td>120.0</td>
</tr>
<tr>
<td>8</td>
<td>Wood</td>
<td>-20</td>
<td>60</td>
<td>3</td>
<td>120.0</td>
<td>120.0</td>
<td>120.0</td>
</tr>
<tr>
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<td>Nylon</td>
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<td>5</td>
<td>120.0</td>
<td>120.0</td>
<td>120.0</td>
</tr>
<tr>
<td>10</td>
<td>Wood</td>
<td>-15</td>
<td>30</td>
<td>5</td>
<td>120.0</td>
<td>120.0</td>
<td>120.0</td>
</tr>
<tr>
<td>11</td>
<td>Nylon</td>
<td>-15</td>
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<td>12</td>
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<td>120.0</td>
<td>120.0</td>
</tr>
<tr>
<td>12</td>
<td>Steel</td>
<td>-15</td>
<td>119</td>
<td>119</td>
<td>8.4</td>
<td>14.2</td>
<td>22.1</td>
</tr>
<tr>
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<td>Alum.</td>
<td>-15</td>
<td>118</td>
<td>118</td>
<td>3.2</td>
<td>7.6</td>
<td>14.0</td>
</tr>
<tr>
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<td>Wood</td>
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<td>120.0</td>
<td>120.0</td>
</tr>
<tr>
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<td>Nylon</td>
<td>-10</td>
<td>127</td>
<td>5</td>
<td>120.0</td>
<td>120.0</td>
<td>120.0</td>
</tr>
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<td>16</td>
<td>Steel</td>
<td>-10</td>
<td>117</td>
<td>113</td>
<td>12.4</td>
<td>20.0</td>
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</tr>
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<td>Alum.</td>
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<td>113</td>
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</tr>
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<td>Nylon</td>
<td>-4</td>
<td>30</td>
<td>2</td>
<td>120.0</td>
<td>120.0</td>
<td>120.0</td>
</tr>
<tr>
<td>19</td>
<td>Steel</td>
<td>-4</td>
<td>108</td>
<td>76</td>
<td>47.9</td>
<td>70.3</td>
<td>120.0</td>
</tr>
<tr>
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<td>Alum.</td>
<td>-4</td>
<td>111</td>
<td>84</td>
<td>17.0</td>
<td>47.6</td>
<td>118.9</td>
</tr>
<tr>
<td>21</td>
<td>Wood</td>
<td>0</td>
<td>27</td>
<td>5</td>
<td>120.0</td>
<td>120.0</td>
<td>120.0</td>
</tr>
<tr>
<td>22</td>
<td>Nylon</td>
<td>0</td>
<td>87</td>
<td>1</td>
<td>120.0</td>
<td>120.0</td>
<td>120.0</td>
</tr>
<tr>
<td>23</td>
<td>Steel</td>
<td>+2</td>
<td>115</td>
<td>25</td>
<td>120.0</td>
<td>120.0</td>
<td>120.0</td>
</tr>
<tr>
<td>24</td>
<td>Alum.</td>
<td>+2</td>
<td>117</td>
<td>39</td>
<td>102.6</td>
<td>120.0</td>
<td>120.0</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>1655</td>
<td>752</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 4. Descriptive statistics of the database: time for contact temperature (T_c) to reach criteria of 15, 7 and 0 °C

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Surface temp. (°C)</th>
<th>Time for T_c to reach 15 °C</th>
<th>Time for T_c to reach 7 °C</th>
<th>Time for T_c to reach 0 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Labels</td>
<td>Total values</td>
<td>Available values</td>
<td>Lower quartile (sec)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sec</td>
<td>Sec</td>
<td>Sec</td>
</tr>
<tr>
<td>1 Wood</td>
<td>-40</td>
<td>30</td>
<td>30</td>
<td>2,40</td>
</tr>
<tr>
<td>2 Nylon</td>
<td>-35</td>
<td>18</td>
<td>18</td>
<td>1,00</td>
</tr>
<tr>
<td>3 Wood</td>
<td>-33</td>
<td>18</td>
<td>18</td>
<td>23,0</td>
</tr>
<tr>
<td>4 Nylon</td>
<td>-30</td>
<td>35</td>
<td>35</td>
<td>1,10</td>
</tr>
<tr>
<td>5 Wood</td>
<td>-30</td>
<td>36</td>
<td>36</td>
<td>13,0</td>
</tr>
<tr>
<td>6 Wood</td>
<td>-25</td>
<td>36</td>
<td>36</td>
<td>24,5</td>
</tr>
<tr>
<td>7 Nylon</td>
<td>-25</td>
<td>34</td>
<td>34</td>
<td>4,00</td>
</tr>
<tr>
<td>8 Wood</td>
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<td>54</td>
<td>54</td>
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</tr>
<tr>
<td>9 Nylon</td>
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<td>50</td>
<td>50</td>
<td>2,30</td>
</tr>
<tr>
<td>10 Wood</td>
<td>-15</td>
<td>21</td>
<td>21</td>
<td>0,60</td>
</tr>
<tr>
<td>11 Nylon</td>
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<td>12 Steel</td>
<td>-15</td>
<td>113</td>
<td>113</td>
<td>0,40</td>
</tr>
<tr>
<td>13 Alum.</td>
<td>-15</td>
<td>109</td>
<td>109</td>
<td>0,30</td>
</tr>
<tr>
<td>14 Wood</td>
<td>-10</td>
<td>50</td>
<td>49</td>
<td>5,30</td>
</tr>
<tr>
<td>15 Nylon</td>
<td>-10</td>
<td>120</td>
<td>120</td>
<td>6,10</td>
</tr>
<tr>
<td>16 Steel</td>
<td>-10</td>
<td>109</td>
<td>109</td>
<td>0,70</td>
</tr>
<tr>
<td>17 Alum.</td>
<td>-10</td>
<td>111</td>
<td>111</td>
<td>0,50</td>
</tr>
<tr>
<td>18 Nylon</td>
<td>-4</td>
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<td>26</td>
<td>12,0</td>
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<tr>
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<td>-4</td>
<td>98</td>
<td>98</td>
<td>1,00</td>
</tr>
<tr>
<td>20 Alum.</td>
<td>-4</td>
<td>105</td>
<td>105</td>
<td>0,70</td>
</tr>
<tr>
<td>21 Wood</td>
<td>0</td>
<td>17</td>
<td>17</td>
<td>2,00</td>
</tr>
<tr>
<td>22 Nylon</td>
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<td>72</td>
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<td>+2</td>
<td>108</td>
<td>108</td>
<td>1,80</td>
</tr>
<tr>
<td>24 Alum.</td>
<td>+2</td>
<td>105</td>
<td>105</td>
<td>1,10</td>
</tr>
</tbody>
</table>

Despite a maximum experimental touching duration of 120 s, extrapolated contact times to a given T_c criteria above 120 s but equal to or less than 240 s are given. Extrapolated times above 240 s are denoted by >240. Hyphen (-) denotes T_c criteria would never be reached.
Figure 1. Lower quartiles of the time to reach a contact temperature of 0 °C, t(0): observed and predicted values for steel and aluminium.

Figure 2. Lower quartiles of the time to reach a contact temperature of 7 °C t(7): observed and predicted values for all 4 materials.

Figure 3. Lower quartiles of the time to reach a contact temperature of 15 °C, t(15): observed and predicted values for all 4 materials.

Figure 4. Frostbite threshold: surface temperature of the material as a function of contact time for $T_C$ to reach 0 °C (range of TS from −40 to 0 °C, time limited to < 100 sec).

Figure 5. Numbness threshold: surface temperature of the material as a function of contact time for $T_C$ to reach 0 °C (range of TS from −40 to +5 °C, time limited to < 100 sec).

Figure 6. Pain threshold: surface temperature of the material as a function of contact time for $T_C$ to reach 0 °C (range of TS from −40 to +5 °C, time limited to < 100 sec).

![Figure 1](image-url)
Figure 2

![Graph showing the time for a contact temperature to reach 7°C for different materials: Wood, Nylon, Steel, and Alum.](image)

Figure 3

![Graph showing the time for a contact temperature to reach 15°C for different materials: Wood, Nylon, Steel, and Alum.](image)
Figure 4

![Figure 4](image)

Figure 5

![Figure 5](image)

Figure 6

![Figure 6](image)