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Temperature limit values for cold touchable surfaces

Final report on the project: SMT4–CT97–2149

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Preface

Contact with cold surfaces may occur during activities at low temperatures, but also when handling for example frozen food or cold equipment at normal indoor temperatures. Data are sparse on the response of human skin in contact with different materials under cold conditions. For the provision of guidance to risk assessment a research project was called upon within the framework of the 4th RTD-program of the European Union. An application for this dedicated call was approved and the research project SMT4-CT97-2149 Temperature limit values for cold touchable surfaces was started. The Climate group at the National Institute for Working Life was the co-ordinator of the project. The project consortium comprised partners from five different institutions.

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This report describes the work and is an update of the Final report of the project to the Commission (Holmér et al. 2000). The main change is that the standard proposal (Annex A) has been revised according to discussions at meetings with both CEN/TC122/WG3 and ISO/TC159/SC5/WG1 after the delivery of the original proposal.

Stockholm in December 2002

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Contents

Introduction

Work with bare hands occurs in various cold conditions. Outdoors it is often in conjunction with operations of tools and machinery or handling goods. Indoor cold exposure is common in conjunction with storing and distribution of chilled or frozen food. Normally, hands are protected by gloves, but in certain situations, gloves may not be used as they interfere with dexterity and sensory performance of hands and fingers. Intentionally or unintentionally, a person may then contact a cold surface and suffer more or less severe local cooling of the contact surface. Two types of contact exposure can be identified. Touching a cold surface with a small skin segment, for example a finger tip, for short time, usually seconds. Gripping cold materials with the hand, usually for second to minutes and often intermittent.

Contact between bare hands and a cold surface may reduce skin temperature, eventually leading to pain, numbness, manual performance decrement and cold injury. In order to prevent adverse effects during contacting with a cold surface, information is needed on what temperatures of the cold surface that causes these effects.

In TC122/WG3 an attempt to develop temperature guidelines for touchable cold surfaces led to the conclusion that available knowledge was too limited and a proposal for pre-normative research was prepared. The proposal was accepted as a dedicated call within the SMT programme. In the explanatory document specific requirements were specified. It was indicated that the result should be an ergonomics guideline on safe temperatures for cold touchable surfaces, with a structure similar to the standard EN563 that deals with hot surfaces.

A number of factors affect the cooling of the skin surface in contact with a cold surface. These are surface temperatures of material and skin, material properties, skin tissue properties, contact surface area, and contact pressure. All factors interact in a complex way that determines cooling speed and the final equilibrium temperature of the contact surface. The important material properties are thermal conductivity, specific heat, density, mass, surface structure and coating. This indicates that metals are more likely to cause rapid cooling than plastic and wood. Big objects cause more rapid and significant cooling than do small objects. Individual variation is likely to be caused by differences in skin thickness, wetness of skin, size of contacting finger or hand, vascular arrangements and tissue blood circulation. In addition subjective factors such as emotion, mood, habituation etc. may play a role.

For obvious reasons the surface temperature of the contacting skin cannot be readily measured. A sensor positioned in the contact area will measure the contact temperature, which is a function of the heat fluxes between the skin and the object. The temperature is a value between the skin temperature and the object surface temperature. During the cooling process these temperatures approach each other and eventually reach the contact temperature. When equilibrium temperature is reached the contacting surfaces have the same temperature equal to the contact temperature.

As already mentioned a survey of the literature on the subject revealed limited information of use for the preparation of guidelines for work with cold materials with bare hands. A systematic research project would be necessary to provide the basic information on human responses to contact cooling on which accurate and reliable relations between defined effects and exposure conditions could be derived.

The object of this project was to find and compile information on human responses to contact with cold surfaces. Both touching and gripping cold materials have been studied. Three criteria for effects have been applied associated with pain, numbness and cold injury, respectively. The work has covered literature search and actual experimentation with human subjects and an artificial finger. The results of the project have been issued in a document that can serve as a basis for the development of an ergonomics database by appropriate standardisation bodies (TC122/WG3). Firstly, depending on criteria applied, safe contact temperatures have been determined for the given materials under cold exposure conditions. Secondly, safe contact time has been determined for the given combinations of type of material and their surface temperature.

The work of this project contained the following six work packages:

WP1. Literature review and field survey

WP2. Research on actual experimentation with human being,

WP3. Development of one or more cooling models and prediction of severe conditions

WP4. Development of instrumentation (artificial finger) and complementing validation and measurements

WP5. Evaluation of results and compilation of databases

WP6. Draft proposal for guideline document

This report is the first condensed, complete, publicly available report of the whole project.

Definitions

In this report, the following definitions of terms and symbols apply:

Touchable surfaces

A surface of a material (an object) touched by human skin.

Surface temperature (T_S, °C)

The temperature of a material surface, measured in degree Celsius.

Initial hand/finger skin temperature ($T_{sk,h0}$/$T_{sk,f0}$, °C)

The temperature of hand/finger skin before touching a surface measured in degree Celsius.

Contact temperature (T_C, °C)

The temperature of an interface between the finger skin and touched surface, measured in degree Celsius.

Contact duration (D, sec.)

The time during contacting with a surface, measured in seconds.

Thermal inertia of a material

The density (ρ, $10^3 kg*m^3$), thermal conductivity (κ, $W*m^{-1}*K^{-1}$) and specific thermal capacity (c, $J*kg^{-1}*K^{-1}$) of the touched material.

Contact factor (F_C, $Jm^{-2}s^{-1/2}K^{-1}$)

Thermal penetration coefficient, $F_C = (\rho*\kappa*c)^{1/2}$

Time for T_C to reach criteria

Freezing: time for T_C to reach 0 °C, (t(0), sec.)

Numbness: time for T_C to reach 7 °C, (t(7), sec.)

Slight pain: time for T_C to reach 15 °C, (t(15), sec.)

Work packages

All partners have contributed to work undertaken in all packages.

Work package 1 - Literature review and field survey

The purpose of work package 1 was mainly to serve as an update of the existing knowledge of the contact cooling problems and other useful information for the project.

1 Literature review

The search criteria for the literature survey were discussed during the project meetings 1-5. The first version of bibliography-alphabetic list (CS7[1], see pp54) appeared in November 1997. The bibliography was updated to the new versions (CS13, CS15, CS22 and CS62-64) in an alphabetic order by different forms (Vancouver and Medline formatting).

Regarding the compilation of the literature review, a table of the contents (CS18) was distributed in the meeting 4. The assignment of the corresponding review for each partner (CS25) was issued in the meeting 5. The different sections of the literature review have been written by each partner. Partner 4 has completed a compiled literature review (CS79 and CS87).

2 Field survey

In order to provide an overview of actual problems of touching and handling cold surfaces in work places, a study on field survey of food processing industry in Finland has been carried out. The study involved questionnaire and measuring temperature, etc.

2.1 Questionnaire study

The aim of the questionnaire study was to get information from the representatives of the food processing industry regarding to:

- materials and surface temperatures of goods, machine parts, handles, levers and tools
- information of working facilities: temperature, cooling system, air flow, surface materials
- information of work schedule, work clothing and hand protection.

[1] CS with numbers are consecutively reported administrative and scientific documents within the ColdSurf project.

Two questionnaires for recording the contact on cold surfaces under the occupational conditions (CS19a and CS26) were used in the field survey study. Seven food processing companies in Finland participated in the study. Five of them were in meat processing industry and two were processing milk products. Altogether 1500 questionnaires were sent, and in the companies they were distributed to the divisions where the facilities were cooled.

2.2 Temperature measurements
The measurements were performed in a meat processing company. Healthy female subjects, age 20 - 35 years, were tested. Each measurement lasted for about four hours. Skin temperature was measured on the body (6 sites) and on the hand and fingers of both hands (10 sites) using thermistors (YSI 400 series). Hand and finger skin temperatures were measured on both dorsal and palm side of the hand. Thermal sensation (ISO 10551), cold pain and rate of perceived exertion (RPE, Borg 1998) were asked at 15 minutes intervals.

Work package 2 - research

The package was divided in two parts:
Touching experiments: Subjects contact a defined piece of a material during a short period (up to 300 seconds). Contact area (finger tip) and contact pressure (0.98, 2.94 and 9.81 N) were determined.
Gripping experiments: Subjects grip a rod of a material with a gripping force of 500 g. Gripping was applied constantly with the longest contact period for 30 minutes.

1 Objectives

The objectives were:
to find out temperature limits of human finger skin touching the cold surface of different materials at various pressure levels;
to determine maximum allowable duration of touching given combinations of material and surface temperature;
to determine maximum allowable duration of gripping five materials as a function of the initial surface temperature of materials.

2 Materials and methods

2.1 Selection and test of the materials
Five materials were selected for the experimental studies according to information provided in EN563. The materials were tested for basic heat transfer properties at the Finnish State Test Centre in Tampere (VTT). Table 1 presents the thermal properties of the materials.

For touching experiments 11×11×11 cm solid cubes were used. For gripping experiments solid cylindrical rods with a diameter of 4 cm and a length of 40 cm were used. In addition, in one set of experiments three diameters (8, 4 and 2 cm) of aluminium rods were used in the gripping experiments, in order to study the effect of the size of the rods on contact cooling.

Table 1. Properties of materials used for the cold contact experiments

Material	Thermal conductivity, λ, ($Wm^{-1}K^{-1}$)	Specific heat, c, ($J\ kg^{-1}K^{-1}$)	Density, ρ, (10^3 kg m^{-3})	Penetration coefficient, F_C ($J\ m^{-2}\ s^{-1/2}\ K^{-1}$)
Wood	0.22	2196	0.56	520
Nylon-6	0.34	1484	1.20	778
Stone	2.07	750	2.80	2084
Steel	14.80	461	7.75	7271
Aluminium	180.0	900	2.77	21183

Surface and contact temperatures were measured with specially prepared small thermocouples.

2.2 Experimental protocol

2.2.1 Touching experiments. Four partners carried out experiments on touching either in a hand cooling box (2) or in a cold climatic chamber (2). The cubes were suspended inside box or chamber in a counter balance system, so that the contact pressure could be controlled. The surface temperature of the material (T_S) was measured with a thermistor and varied from –40 to +5 °C. In the middle of the palm side of the fingertip (index finger) a small thermocouple was placed (0.1 mm diameter), so that it was within the contact area of the finger and the block. As shown in Table 2, a number of conditions were studied. More than 1734 experiments were carried out with human subjects at 4 different laboratories.

Table 2. Experimental conditions of finger touching test. Forty subjects (20 males and 20 females) touched the cold surfaces with 3 pressures in each condition

Temp., °C / Run by / Material	-40, -35, -30	-25, -20	-17, -15	-10	-5, -4	0, +2	+5
Aluminium & Steel			LUUK (-17) NIWL (-15) TNO (-15) FIOH (-15)	NIWL LUUK TNO FIOH	NIWL (-4) LUUK (-5) TNO (-5) FIOH (-4)	NIWL (+2) TNO (0) FIOH (+2)	LUUK
Nylon	FIOH (–40 &-30)* LUUK (-35)	FIOH (-20) NIWL (-20) LUUK (-25 & -20)	NIWL (-15) TNO (-15)	NIWL LUUK TNO FIOH	NIWL (-4)	NIWL (+2) TNO (0) FIOH (+2)	
Wood	FIOH (–40 &-30) LUUK (-35)	FIOH (-20) NIWL (-20) LUUK (-25)	TNO (-15)	NIWL TNO		TNO (0)	

*Surface temperature of the material

The experiments were repeated for each subject under different conditions. The parameters studied randomly involved:

- type of material (steel, aluminium, nylon and wood);
- surface temperature of the materials (-40, -30, -25, -20, -15, -10, -5/-4, 0, 2 and 5 °C);
- pressure levels (0.98, 2.94 and 9.81 N);

Effect of gender on the response of T_C with time was also investigated in the experiments. The touching duration depended on several criteria: subject feeling pain or numb or risk of frost-nip. Experiments were stopped when T_C reached < 0 or 1 °C within 1 second). The detailed experimental procedure was as follows:

1. The subject sat in the climate chamber for more than 20 minutes. The subjective response on thermal sensation of the whole body was recorded and the sensors were placed on the finger;
2. The finger skin temperature and the subjective response on thermal sensation were recorded just before the cold exposure;
3. The subject inserted his/her hand into a cold box or entered a cold climatic chamber with the same temperature as the surface temperature of the material. Measurements of T_C and T_{sk}. were started
4. The subject started touching a cold surface for a certain duration (based on both the type of material and their surface temperature) and rated the subjective responses on thermal/pain sensation.
5. The subject moved his/her hand out of the cold box after touching the selected material and regained the T_{sk} up to 20°C (in warm water sometimes) (2 labs see p3). Subjects withdraw his finger from the material and left the cold chamber for re-warming outside.
6. Experiments were repeated with other pressure levels, material, and temperatures.

2.2.2 Gripping experiments. The protocol and the number and frequency of measurements differed slightly between the five laboratories. Typically 5-6 male subjects and 5-6 female subjects were exposed to the selected experimental conditions in each laboratory. Subjects were trained with the facilities during one pre-experiment. Experiments were distributed among partners according to their experimental facilities and the special needs of the study. All five partners carried out experiments on gripping either in a hand cooling box or in a climatic cold chamber. A total of 483 individual experiments were performed as shown in Table 3.

Before the cold exposure subject and rod were equipped with temperature sensors. One partner adopted an infrared temperature device for determination of hand skin temperature at defined time intervals. Four partners used thermocouples for continuous determination of the contact temperature during gripping. Rods of five different materials were used (Piette *et al.* 2000). Rods were mounted in a counter balance system so that the final weight supported by gripping was 500 g. The subject then gripped the rod and adjusted the gripping pressure necessary to balance the hanging rod. Subjective ratings of thermal sensation, pain and numbness were recorded during the cold exposure. Subjects were allowed to quit whenever they felt uncomfortable with the cold situation. In practice, the stop criteria were either extensive pain or a contact temperature lower than 0 or +1 °C.

Table 3. The experimental conditions of hand gripping test

Temp., ∞C / Run by / Material	-30	-20/-16	-10	-5	0/+1	+5
Aluminium & Steel			NIWL (5)	UCL (12) FIOH (11) NIWL (10) LUUK (10)	FIOH (11) TNO (8) LUUK(10) NIWL(10)	UCL (12) TNO (8) LUUK(10)
Nylon	UCL (12)* FIOH (11) LUUK (10)	UCL (12) FIOH (11) NIWL (8/2) LUUK (10)	UCL (12) FIOH (11) NIWL (10) LUUK (10)			
Wood	UCL (12) FIOH (11) LUUK (10)	UCL (12) FIOH (11) LUUK (10)				
Stone		UCL (12) NIWL (8/2) LUUK (10)	UCL (12) FIOH (11) NIWL (10) LUUK (10)			
Air	FIOH (1) LUUK (10)	UCL (12) NIWL (8/2) LUUK (10)	UCL (12) FIOH (1) NIWL (10) LUUK (10)	NIWL (10) LUUK (10)	NIWL (10) LUUK (10) FIOH (1)	LUUK (10)

*Number of the subjects participated

Two standard tests (Semmes-Weinstein filaments and O'Connor model 32021) were utilised for performance evaluation. The pressure tactile sensitivity test was performed using filaments of different sizes. The investigator touched with filaments of increasing size ("pressure") on the distal extremity under index and little finger's metacarpus and pad of the middle finger. The subject responded within 3 seconds without seeing. The filament size of 1.65 represents a pressure force of 8 mg and was used as the lightest force in the test (Tomancik, 1987). For the finger dexterity test, the subject was required to fill the first row of holes in a panel with 3 pins per hole from left to right as quickly as possible. The time needed to complete the task and number of mistakes (incorrect pins were filled or fell down) were recorded. To evaluate and analyse the effect of contact cooling on manual performance, the pressure tactile sensitivity and finger dexterity tests were performed before and after each cold exposure.

2.3 Sticking experiments

Sticking on cold aluminium and steel by wet skin of fingertip and hand was studied in a laboratory of the FIOH.

One voluntary male subject served for both fingertip and hand sticking experiments. The experiments were carried out with both bare index finger and gloved finger (covered with a latex surgeon's glove). Hand gripping experiments were only done with gloved hand.

The metal bar was hanging from a hand gripping dynamometer (Newtest, Oulu, Finland) in a vertical position in a climatic chamber at -20 to -5 °C. The bars were stabilised in each temperature for at least 4 hours before measurements. Peak forces during the release of finger and hand were measured.

The finger (bare or covered) was wetted by immersing in water for about 1 second. Thereafter the bottom (diameter 40 mm) of a metal bar (aluminium or steel) was touched with the finger at a pressure of ca. 50 g for 2 seconds. The finger was then pulled downwards until the release finally happened (took 1-2 seconds). In each session, 3 - 4 trials were performed.

In similar experiments, the hand was covered by surgeon's glove and wetted in the same way as in the fingertip test. The metal bar (aluminium or steel) was gripped with a force comparable to lift 500 g for 2 seconds. After that the gripping was released, and hand was pulled downwards until the release of glove from the bar finally occurred (took 1-3 seconds). In each session, 3 - 4 trials were done.

Touching the metal bars with dry, uncovered finger was performed at -10 to -30 °C as additional sticking tests. The sticking was also investigated by taking metal bars from a cold climatic chamber (-15 and -40 °C) to a room of 21 °C, RH 30 %. Due to a rapid condensation of moisture, a thin layer of ice developed quickly, and the sticking tests were done within about 3 minutes after removal from the climatic chamber.

4 Data management

The experimental data collected from the subjects were managed using Microsoft Excel. Each individual curve of the finger skin-surface interface temperature (contact temperature, T_C) versus contact time in the cold was subsequently plotted from all the records. The contact time of critical contact temperatures (T_C = 15, 7 and 0 °C) for each cooling curve was obtained by inter or extrapolations.

Work package 3 - Modelling

1 Objectives

This work package aims at producing an analytical model of finger skin cooling, in order to allow inter- and extrapolation of skin cooling in relation to material properties and temperature. Models would allow data to be obtained for conditions under which real data on subjects could not be collected for ethical or other reasons.

2 Methods

2.1 Overview the models of extremity cooling

As shown in Figure 1, an overview of the various models separated for exposure types has been carried out within the project (CS48 and CS65).

It was concluded that the most interesting and promising model type is that by Lotens, as the others either did not include touching of materials or lacked other relevant parameters. The second option was to work with purely empirical models. An attempt was made by TNO to create a model similar to Lotens' using the MATLAB®-software for the touching conditions.

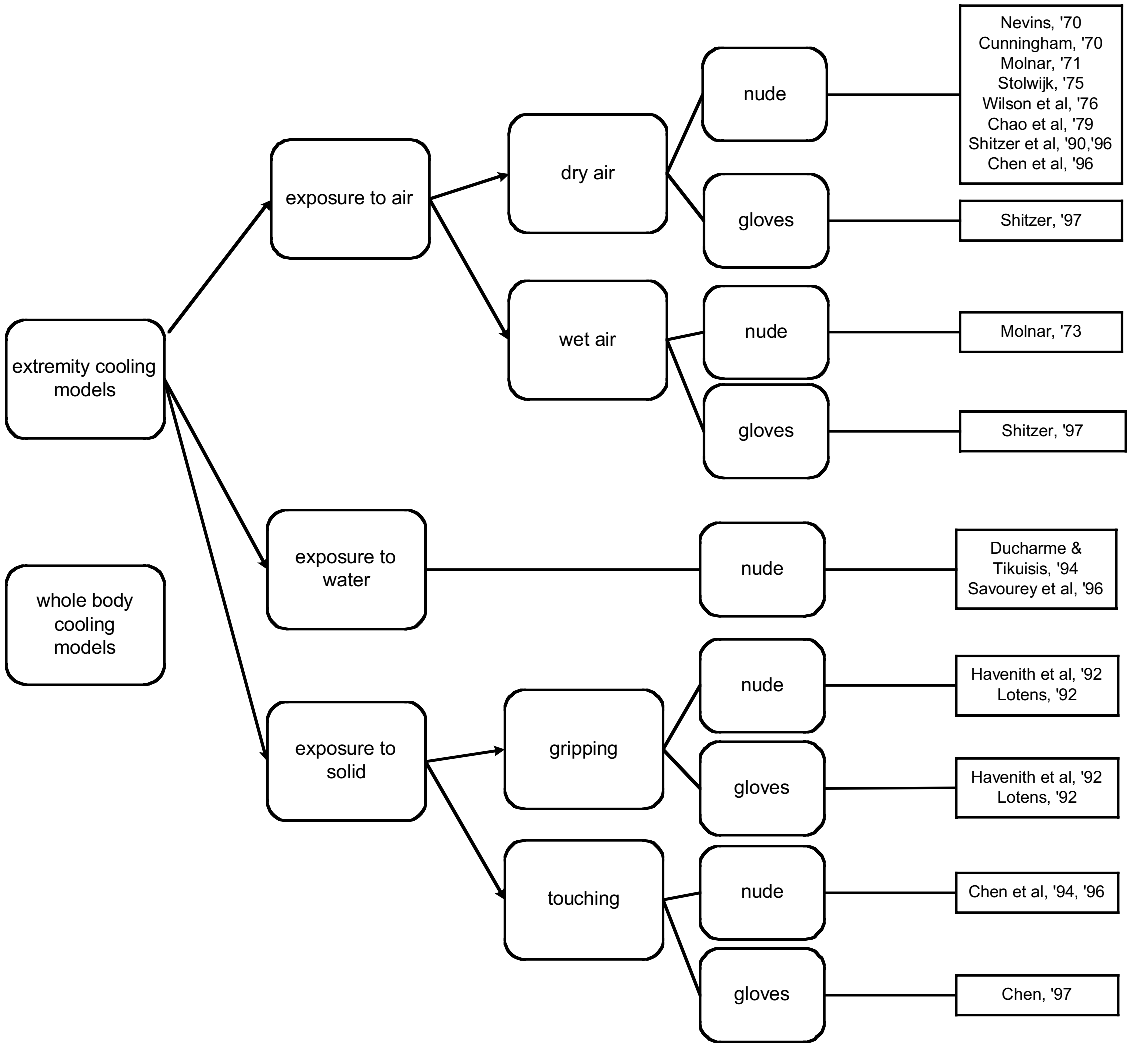


Figure 1. Overview of available models, in terms of exposure types.

2.2 Adapt the existing models of extremity cooling

2.2.1 Development of the model for finger contact cooling. To identify the most relevant parameters of a finger-cooling model, the large number of measurements performed within the ColdSurf project were used. A simple model was developed by partner 3 to describe the cooling curves of the finger touching the cold surface.

The schematic cross section of the seven element contact cooling model is presented in Figure 2. Optimization of the model parameters resulted in a close fit of the model output to the data. The optimization was defined as the minimum of the squared differences between simulation and measurement, using a Nelder-Mead simplex method. This was performed by the MATLAB® program that was also used to build the model. From the fit of the simulation to the data, the sensitivity of the simulation to changes in the parameters could be determined (CS49). This led to identification of five parameters with which it was possible to fit the model simulations to almost all experimental data by the Nelder-Mead Simplex method (CS49).

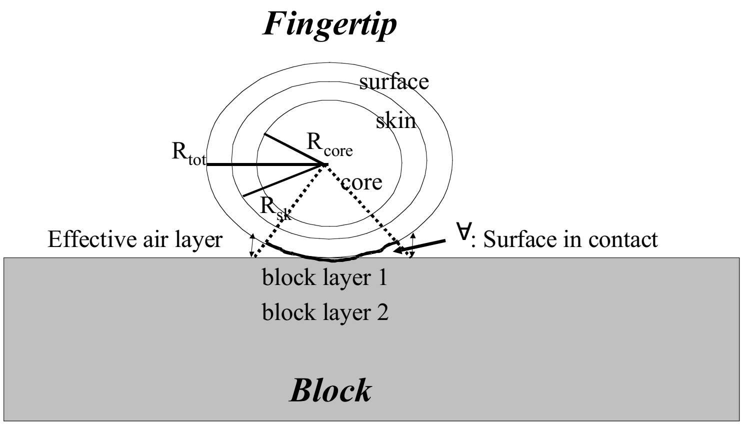


Figure 2. Schematic presentation of the model to simulate contact cooling of the fingertip. All parameters are denoted in the text. The finger is represented as a cylindrically shaped object. The grey square represents part of the block (CS84).

The validation of the model was performed using the experimental data of the touching experiments.

2.2.2 Development of the model for the hand grip cooling. For applications relating to hands in contact with cold surfaces, only the model by Lotens (1992) has the appropriate basic characteristics of the analytical models. It was therefore decided to use the Lotens model as a basis for hand gripping cooling modelling, as shown in Figure 3 (CS65)

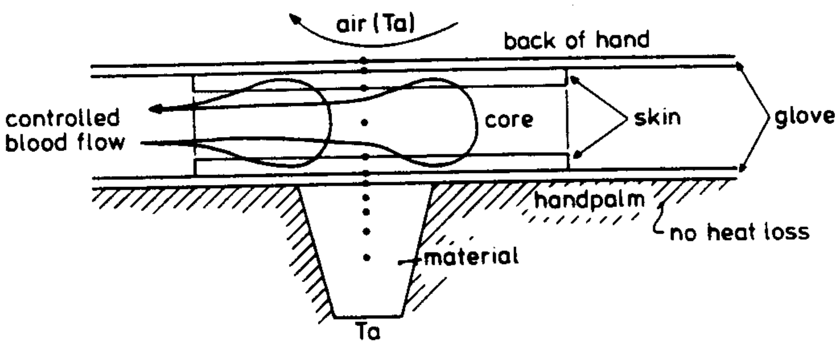


Figure 3. Schematic representation of the cooling model according to Lotens. It contains 11 compartments or nodes (5 nodes for the material, 2 for the gloves, 3 for the hand and 1 for environmental air).

The source code for the model was obtained, and several minor modifications were made, e.g. the minimal glove thickness was reduced, as in the old model this still affected heat loss. The model was used to perform simulations, using data from experiments at LUUK. For the material characteristics data obtained by the FIOH were used.

Furthermore, the effect of changing 2 parameters in the model was tested. The first parameter is hand thickness, the second vasoconstriction. In the original model the hand thickness used is 3 cm. This is thicker than observed in most subjects. Hence, it was tested how the results varied when this was reduced to 2 cm. This generates the middle ‘smooth’ lines in the graphs. Clearly, the performance improves, but not quite sufficient.

Reducing the blood flow to the hand by increasing the vasoconstrictor response (in addition to reducing hand thickness) provides an additional improvement to the model. Simulation results (lowest ‘smooth’ lines) now get close to the median in the data, except for nylon. Interestingly, in the original validation of the model by Lotens, the simulation results for nylon were also the most deviating. Currently no cause or solution to this problem has been identified.

Work package 4 – Development of instrumentation

1 Objectives

The aim was to develop an instrument that could simulate the human finger and measure the contact surface temperature. The instrument would be used to obtain complementary data for extreme conditions when human experiments would not be possible.

2 Experimental work

2.1 Initial work with manufacturer

A sensor simulating a finger tip (artificial finger) was been designed and developed to measure the heat exchange of the contact interface when touching an extremely cold surface. A prototype of the artificial finger was developed by a Swedish manufacturer of instruments (SWEMA). To improve the prototype, more than 30 tests of the artificial finger touching various cold surfaces were carried out at ambient temperatures of -6, -10, -15 and -20 °C in a cold chamber of the NIWL. The results of the tests were analysed and discussed with the manufacturer and the prototype was modified (Figure 4). To validate it, more experiments with the artificial finger under the same conditions as measured with human subjects were carried out.

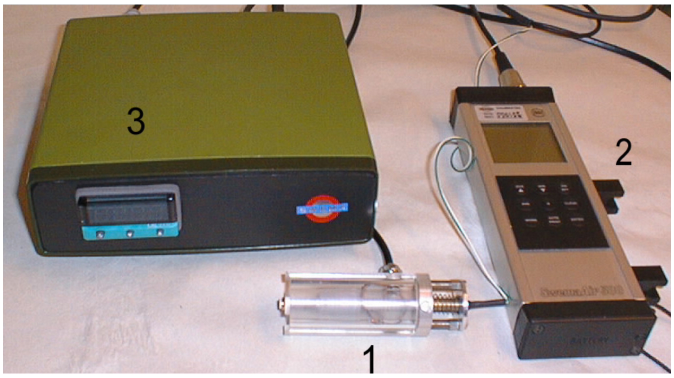


Figure 4. Prototype of the artificial finger.

2.2 Additional experiments with the artificial finger

Additional experiments with the artificial finger were proposed for further validation. Partners 1 and 4 performed the experiments with the third version of the artificial finger touching various cold metallic surfaces (Table 4) in the climatic cold chambers.

Table 4. Experimental design for the artificial finger touching metallic surfaces test

Surface temp. °C	Aluminium (A)		Steel (S)	
-40	A40a	A40b	S40S	S40b
-30	A30a	A30b	S30S	S30b
-20	A20a	A20b	S20S	S20b
-15	A15a	A15b	S15a	S15b
-10	A10a	A10b	S10a	S10b
-4	A4a	A4b	S4a	S4b
0	A0a	A0b	S0a	S0b
+2	A+2a	A+2b	S+2a	S+2b

Work package 5 – Compilation of database

1 Objectives

A database in a standardised format was created into which data from all experiments by all partners were compiled. The database was used to determine relations between material surface temperature, contact temperature and contact time.

2 Methods

2.1 Protocol of the database

All experimental data have been compiled in a database listing material properties, thermal conditions and exposure times for defined criteria. Additional data obtained from tests with an artificial finger model touching cold metallic (steel and aluminium) surfaces at various T_S (–40 to +2°C) were also compiled in the database.

2.2 Management of the database
The experimental data collected from all partners were managed using Microsoft Excel. Two documents in CS 70 (finger touching) and CS71 (hand gripping) list and explain the parameters of two databases, respectively.

The contact time to reach three critical contact temperatures (T_C = 15, 7 and 0 °C) for each cooling curve was obtained by inter or extrapolations. The statistical distributions were computed for each exposure condition and the lower quartiles were considered in order to protect 75% of the population. A non-linear regression analysis was used to empirically predict the duration as a function of the surface temperature (T_S) and the contact factor (F_C) of the material for the three critical contact temperature limits (15, 7 and 0 °C). Statistical analysis was conducted with STATGRAPHICS Plus.

The details of the development of the database are described in CS83.

Work package 6 – Draft proposal for guideline document

1 Objective
To integrate all results obtained from the research of the project and provide basic information about temperature limit values for cold touchable surfaces to CEN TC122/WG3;

Prepare a guideline document for the specification of safe time limits of hand/ finger contacting various cold surfaces.

2 Method

A discussion of the outline and content of the guideline document was held during the final meeting in Brussels. To guide the discussion, copies of EN563: 1994 and prEN 13202:1999 (CS77 and CS78) were distributed to partners before the meeting.

Partner 5 provided the database results (Tables and Figures) for the draft. The results of the database obtained from the experiments with both human subjects (WP2) and an artificial finger (WP4) were integrated. The co-ordinator made a proposal for guideline document with tables and graphs for submitting to WG3. The draft document was discussed by TC122/WG3 at their meeting in Munich on April 10-11.

The proposal describes methods for the assessment of different risks when a cold surface is touched by bare hand/finger skin. The contact time (t) for the critical T_C limits (15, 7 and 0 °C) on cold surfaces were empirically correlated with major factors such as thermal penetration coefficient (contact factor, F_C) and surface temperature (T_S) of the material, respectively. The statistically non-linear models (empirical models) based on the database of lower quartile was utilised to estimate the finger/hand contact cooling.

Results

1 Literature review and field study

1.1 Literature review

The partners in the project have reviewed the effects of contact cooling on human hand. A large number of papers were on skin cooling were obtained from literature search. Most of the, however, dealt with air or skin cooling. Basically, only two studies reported on contact cooling of skin in a way that was relevant for this project. The gathered information was structured in several sections.

1.1.1 Properties of the human hand

Human hand structure and function, structure, function and physical properties of the skin, thermal sensation on the skin as well as thermoregulation of the hand were reviewed. Basic data were obtained from standard text books of anatomy and physiology.

1.1.2 Human responses during contact cooling

The direct contact of the fingers with a cold object will result in more significant thermal effects than exposure to cold air alone. The skin reaction to contact with a cold solid surface will depend on the rate at which heat transfers from the skin to the surface. This depends on the properties of both skin and material. Metal, for example, will “absorb” heat more easily than wood, for similar conditions. During rapid cooling, the initial warning of cold pain is often missing and the development of frostbite is often not noticed by the affected person.

There was no specific information about the effects of contact cooling on manual performance. The relationship between the critical hand skin temperature and manual performance have been studied mostly during convective hand cooling.

Sticking of wet skin on cold metal surfaces is a familiar phenomenon during occupational and leisure time activities. Especially children have gained painful experiences by touching metal with their tongue. Although the problem is well known, the knowledge about the quantitative measures of this phenomenon has been lacking and no published data is available to our knowledge.

1.1.3 Thermal conductance in peripheral tissues

The problem is to determine the evolution of the temperature of the skin when placed in contact with a cold surface.

The basic hypothesis is that, the surface being cold, the environment is also cold and neither sweating nor perspiration occur on the surface of the skin.

The heat balance of the part of the body exposed (the hand) must take into account:

- the metabolic heat production in that segment
- the blood perfusion
- the arterial-venous counter-current heat exchange
- the conductivity of the tissues when not perfused
- the thickness of the skin.

All these factors play a role when an effect such as numbness is considered, as the numbness will develop following a cooling of the whole hand. On the contrary, frostbit will occur locally, resulting from an intense and rapid cooling of the superficial layers of the skin in contact with the cold surface. In that case, it is likely that items 4 and 5, the conductivity of the superficial tissues and the thickness of the skin, are the main factors.

The situation is likely to be between these two extremes:

- for loss of dexterity: which might result of the decrease or loss of sensitivity of the mechanoreceptors in the skin, but also from numbness in the whole hand;
- for pain: which can occur locally near the contact surface or globally in the whole hand.

1.1.4 Contact cooling in the industry

Workers in the cooled facilities of the food processing industry face many health and performance risks due to the cold environment, cold products, repetitive and monotonous manual work, air movements and moisture.

Although the handling of cold products is mentioned as an important source of cold hazards in industry, the specific role of contact cooling is not studied. The evidence comes indirectly from frequent complaints of discomfort, cold pain and numbness.

1.1.5 Models of extremity cooling

Apart from these classifications, the models differ on various aspects. In modelling terms, for analytical models for the simulation of extremity cooling the relevant parameters are:

- Presence of metabolic heat production in the simulated tissue. Often this heat input to the system is lumped with other heat sources (see below) into a single input.
- Presence of circulatory input to the tissue. Often lumped with metabolic heat production. This input can vary greatly, when considering different thermal states of the body. Variations of a factor 20 up to 100 are observed in different models, usually dependent on their range of application.
- Presence of counter current heat exchange. When blood flows into the extremity in a cool thermal state of the body, it passes the afferent veins, which return most of the cool blood from the periphery. This cold blood is warmed by the arterial blood (and the arterial blood cooled by the cold venous blood), thereby reducing the heat input into the extremity and thus conserving body heat. In some models this is taken care of in the form of a reduced ‘effective’

blood inflow, in others the CC heat exchange is modelled in relation to the thermal state of the body.
- Geometric layout of the model. Most models are one dimensional, simulating heat loss from the body core to environment with reduction factors for geometry. Others have both radial and axial flow, simulating whole extremities consisting of several segments.
- The number of layers. This parameter is very important for the functionality of the model. Many layers make it complex; few layers do not allow simulation of fast cooling processes with high diffusivity media.
- The medium for which the model was designed. Most models are designed for cooling in an air environment, using convective and radiative heat transfer as heat exchange avenues. Others were designed for water, where convection/conduction are essential. Finally, models for contact with solids use mainly conduction as governing heat exchange mechanism, with convection and radiation for non-contact areas.
- The option of simulating a clothing material between the extremity and the environment. This may be a garment or a glove.

1.1.6 Assessment of contact cooling

The contact cooling can be affected by three main factors such as properties of the object's surface, human hand skin (as well as individual) and the constitution of contact. Hence, all of the factors should be considered as the contact cooling is analysed.

The freezing finger skin temperature in fast cooling of contact metallic material was reported from -0.6 °C to -2.2 °C, and the freezing hand skin temperature of gripping contact was shown above 5 °C. These critical temperature values were obtained at certain conditions. Thus, further measurements of contact skin temperature with different materials under various cold conditions are needed to ascertain or re-determine the critical values of temperature for hand protection in the cold.

A relationship between physiological thermal state, subjective sensation and contact cooling is still unclear. The subjective sensation can be influenced by many factors, such as motivation etc. Consequently, the subjective assessment on contact cooling should be performed carefully.

1.2 Field study

1.2.1 Questionnaire and interview

Altogether 1117 workers (75 % of the workers who got the questionnaire) gave their response. The age of the subjects (54 % men, 46 % women) is presented in Table 5. 56 % of the workers were smoking. Most workers (87 %) were standing during their work.

Table 5. Age of the subjects responded to the questionnaire

Age (years)	Men (%)	Women (%)	All (%)
Below 20	5	6	5
21 - 30	46	36	41
31 - 40	26	24	25
41 - 50	18	25	21
51 - 60	6	8	7
More than 60	0.3	0.8	0.5

The biggest group of the respondents was working at 0 - 5 °C (Figure 5).

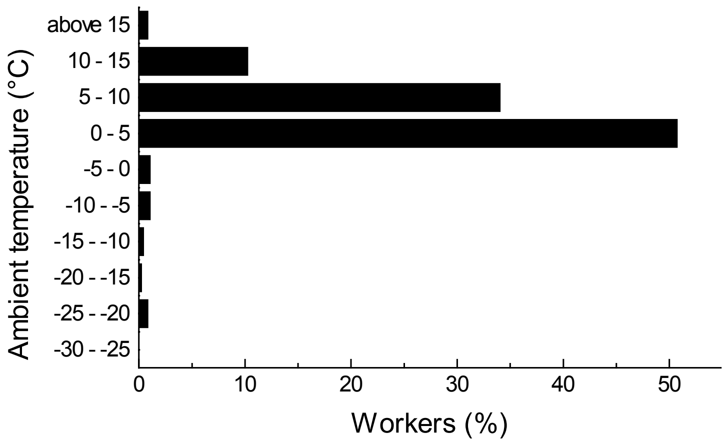


Figure 5. Percentage of workers in different ambient temperatures.

Product temperature was often almost the same as ambient temperature. However, there was a considerably large number of products with temperature between 0 and -5 °C (Figure 6).

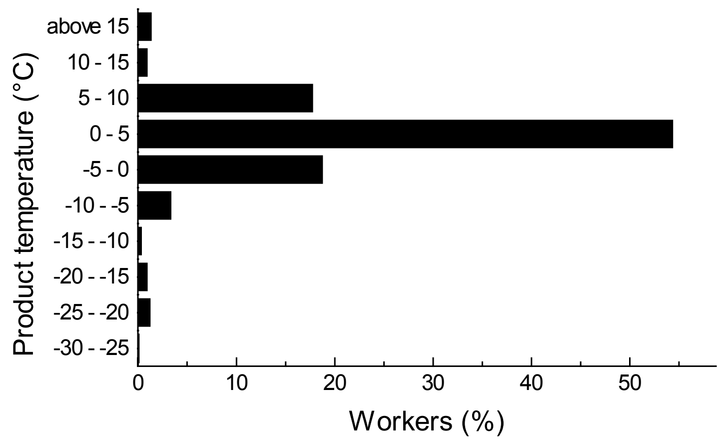


Figure 6. Percentage of workers handling items with different surface temperatures.

Working time in cold was usually (in 92 % of workers) 6-8 h/day. More than halves of the workers were exposed to cold in 31 - 60 min periods (Table 6).

Table 6. Length of working period in cold (min)

Continuous working time in cold (min)	Workers (%)
1 - 10	5
11 - 30	2
31 - 60	56
61 - 90	15
91 - 120	22

The handling of cold items during the workday is presented in Table 7. In addition to touching the cold items by hands, 40 % of the workers lean on cold surfaces often or nearly all the time. For the majority of workers (76 %) the total handling time of cold items was 6 - 8 h/day.

Table 7. Handling of cold items in work

	%
Never	0.6
Seldom	4
Quite seldom	4
Often	27
Almost all the time	65

The length of handling period is presented in Table 8. The surface of the items was usually (67 % of responses) wet. 96 % of the workers used protective gloves while handling cold items.

Table 8. The usual length of handling period of cold items

Handling period (min)	%
1 - 10	12
11 - 30	6
31 - 60	56
61 - 90	11
91 - 120	11
more than 120	4

Environmental hazards: The most important environmental hazards in food processing industry were low temperature, noise and moisture (Table 9). The working environment was sensed most often cold (47 %) or cool (27 %). Moreover, 18 % of workers sensed the environment very cold. For 52 % of the workers the cold products were the primary cause of cold hazards (Table 10).

Table 9. Environmental hazards complained most frequently

	No harm	Slightly harmful	Very harmful
Noise	8	58	35
Cold	4	44	52
Draft	8	40	53
Moisture	26	48	26

Table 10. Factors producing marked amount of discomfort and hazards

	%
Cold environment	57
Draft	55
Cold products	52
Wet hands	38
Wet feet	25
Cold machines/surfaces/items	18
Air movements	11
Something else	2

Hands and fingers were the most susceptible body parts for cold hazards: 60 % of the subjects reported to suffer a lot of hand and finger cooling (Table 11). Cold complaints were especially frequent when frozen products were handled. Complaints of cold pain and numbness of fingers were also frequent.

Table 11. Cold hazards reported in different parts of the body

	Not at all	Slightly	To some extent	A lot
Cheek	33	38	21	9
Nose	21	34	30	15
Ear	45	34	17	4
Chin	45	36	14	5
Neck	18	26	35	22
Shoulder	22	26	34	18
Lower back	34	31	24	11
Upper and lower arm	39	34	21	6
Wrist	17	26	36	22
Hand and finger	2	9	29	60
Thigh	33	34	25	8
Knee	39	34	21	6
Calf	45	34	17	4
Foot	30	25	26	19
Toe	18	23	28	31

Women complained always more cold hazards than men did. This can be caused by anthropometry (smaller body size). However, the results show clearly that women's work was physically less strenuous than men's work, consequently producing less heat. Moreover, women did more repetitive work and handled more frequently cold and even frozen products than men.

1.2.2 Temperature measurements

Temperature measurements show low finger temperatures, especially when handling frozen products (Table 12).

Table 12. Lowest finger temperatures, thermal sensations of fingers and cold pain in fingers during different tasks (individual values). Divisions 1 and 2 produce semi-finished meat products, division 3 is for packing of sausages and division 4 is for handling poultry

Division	Task	Product temperature (°C)	Lowest finger temperature (°C)	Lowest thermal sensation of finger	Cold pain
1	Packing marinated beefburgers	-5 - -7	9.8	cool	slight
	Packing marinated pork slices	-2 - 0	16.6	neutral	no
	Packing beef slices	-2 - 0	17.6	slightly warm	no
	Packing marinated cutlet	-2 - 0	16.6	neutral	no
	Packing fresh cutlet	-2 - 0	13.9	cool	no
2	Removing membranes	2	16.1	cold	no
	Finishing fillets	2	16.4	cold	no
	Cutting fillets by machine	2	12.3	cold	slight
	Flattening fillets by machine	2	13.7	very cold	slight
	Slicing beefs by machine	-5 - -7	12.1	cold	no
3	Packing sausages	5 - 7	13.7	cold	no
	Cutting sausages	5 - 7	11.5	cold	no
4	Cutting chicken legs	<1.5	14.5	cold	no
	Cutting chicken breasts	<1.5	13.8	cool	no
	Filleting poultry by machine	<1.5	15.8	very cold	no

2 Experimental research

Some results of the finger touching research, which have been reported in the separate progress reports (CS30 and CS52), are summarised below.

2.1 Finger touching experiments

2.1.1 Effect of parameter on response of contact temperature with duration
Type of material: To investigate the finger cooling of subjects (male or female) touching various material in the cold, a series of tests were conducted under other conditions such as pressure and surface temperature. Figure 7 shows a difference in the T_C among the four materials at a higher pressure of 9.81 N in the very cold situations. The difference between the metallic materials and the non-metallic materials is significant. The T_C reduced rapidly when the finger touched the cold metallic surfaces at -15 °C. A gradual change of the T_C with time occurred for the finger contacting the non-metallic surfaces at -20 °C. The difference still existed at lower pressures (0.98 and 2.94 N) (CS30 and CS52).

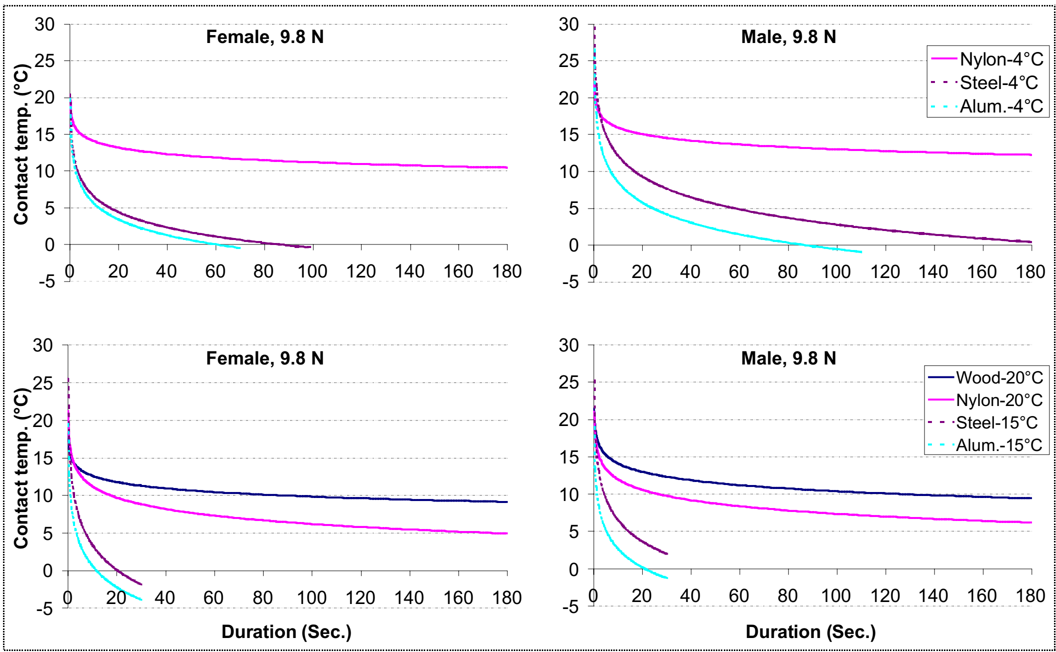


Figure 7. Contact temperature versus cold touching duration of 4 materials with a pressure of 9.81 N at –4 and –20/-15.

Surface temperature: Figures 8 shows the respective results on the effect of surface temperature of aluminium on the finger cooling. It is seen that the surface temperature has a significant impact on the finger cooling at a higher pressure of 9.81 N. The T_C decreases with decreasing the surface temperature. This phenomenon also occurred at lower pressures (0.98 and 2.94 N), and other materials such as steel, nylon and wood (CS30 and CS52).

Gender: A gender difference on the response of finger cooling is seen by all the records of the curves of T_C versus the contact duration under various conditions in figures 7 and 8. In general, the contact duration for the critical T_C of female is significant shorter than that of male. Also, the female appeared to have lower initial finger temperatures compared to the male. The gender difference was suggested to consider for the experimental determination of the critical T_C and the contact time limits for the critical T_C. A comparison between male and female responses to the finger contact with cold materials is discussed (Jay *et al*. 2000).

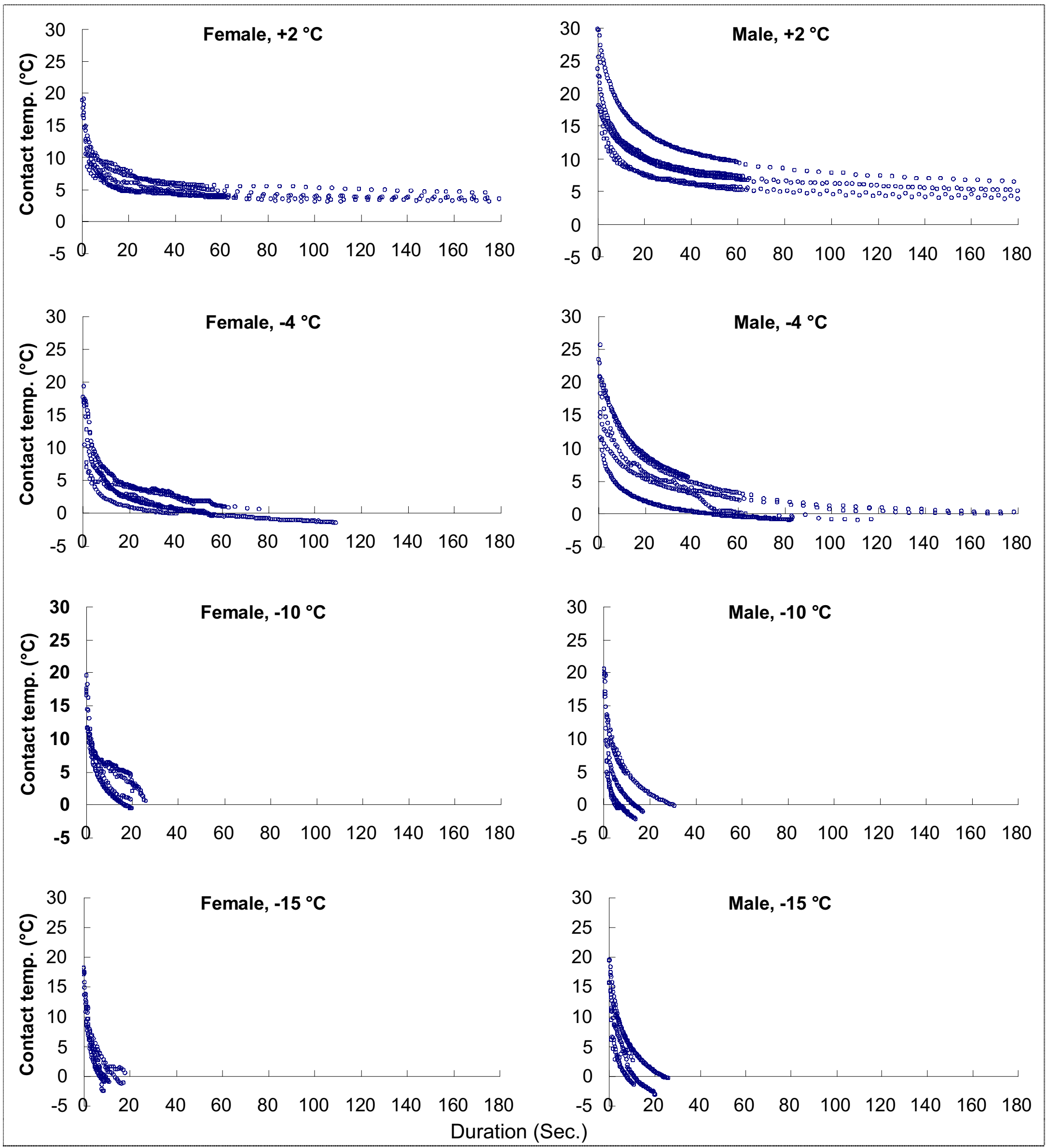


Figure 8. Contact temperature versus cold touching duration of aluminium with a pressure of 9.81 N at 4 different surface temperature

Pressure level: The variation of the T_C versus contact time with respect to pressure levels as finger touching the cold aluminium and nylon at -4 °C is shown in Figure 9 (Geng *et al*. 2000). This effect is significant when the finger touched the surface of aluminium and the nylon at –4, -10 and –15/-20 °C. A higher pressure gives a rapid rate of finger cooling on the cold surfaces of the materials. This trend is more significant for the cold surfaces of metals like aluminium, compared to the non-metals (nylon).

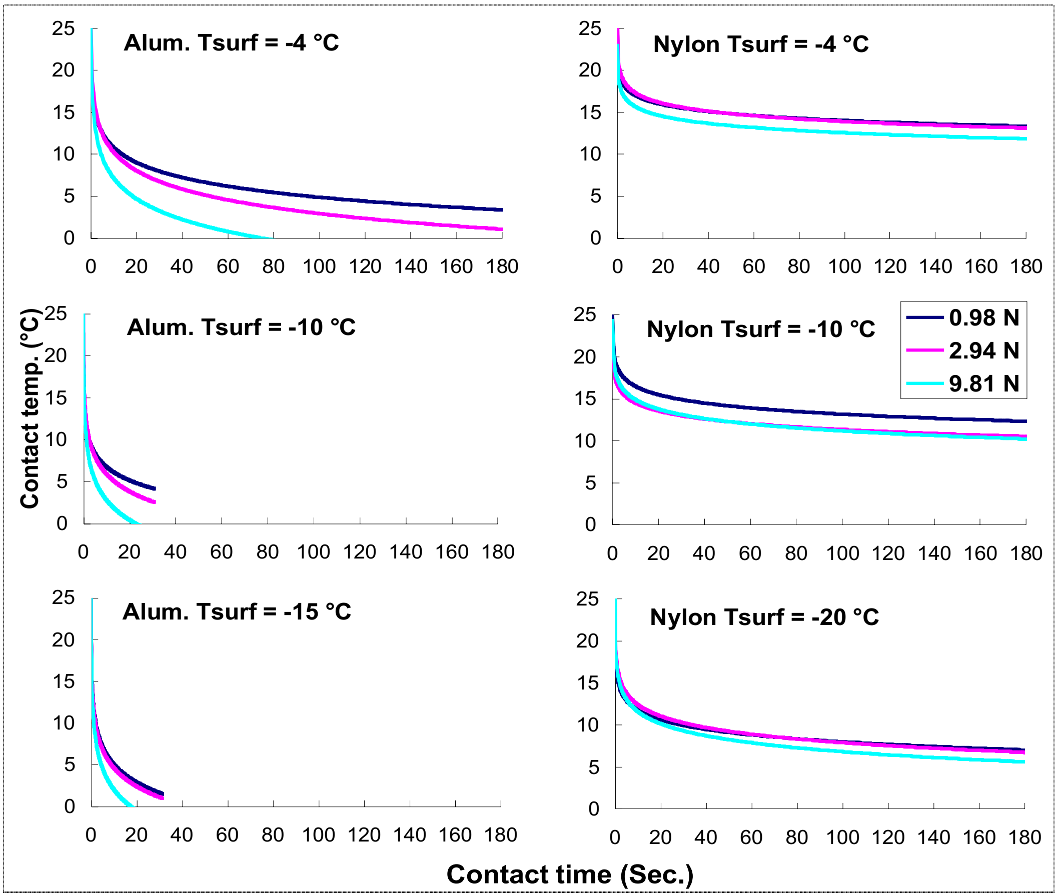


Figure 9. Contact temperature versus cold touching duration of aluminium and nylon with 3 pressure (0.98, 2.94 and 9.81 N) at different surface temperature.

2.1.2 Subjective response on thermal and pain sensations

In addition, the subjective responses on thermal and pain sensation versus the T_C and the contact time were investigated. The corresponding results at different pressures on the aluminium at –15 °C and on the nylon at –20 °C are seen in Figure 10 (Geng *et al*. 2000). From the results, a large variation of the sensations on the T_C and the contact time appears among individuals' responses. Also, female seems more sensitive to the cold surfaces. The pain sensation increased and thermal comfort decreased with decreasing the T_C when the cold surface of aluminium was touched. For finger touching the cold nylon at –20 °C, the variation of both sensations with pressure is not significant and the T_C does not vary with different pressures. It is interesting to see that the cold sensation of -4 (very, very cold) started when the T_C reached about 10 °C at a pressure of 0.98 N, about 7 °C at 2.94 N and 6°C at 9.81N in the case of the cold aluminium. The intolerable pain sensation (4) started when the T_C reached 8 °C at 0.98 N, 7 °C at 2.94 N and 5 °C at 9.81 N (Figure 10). The subjects may have less sensation of the cold and pain when touching on the cold surface of aluminium of –15 °C at higher pressures.

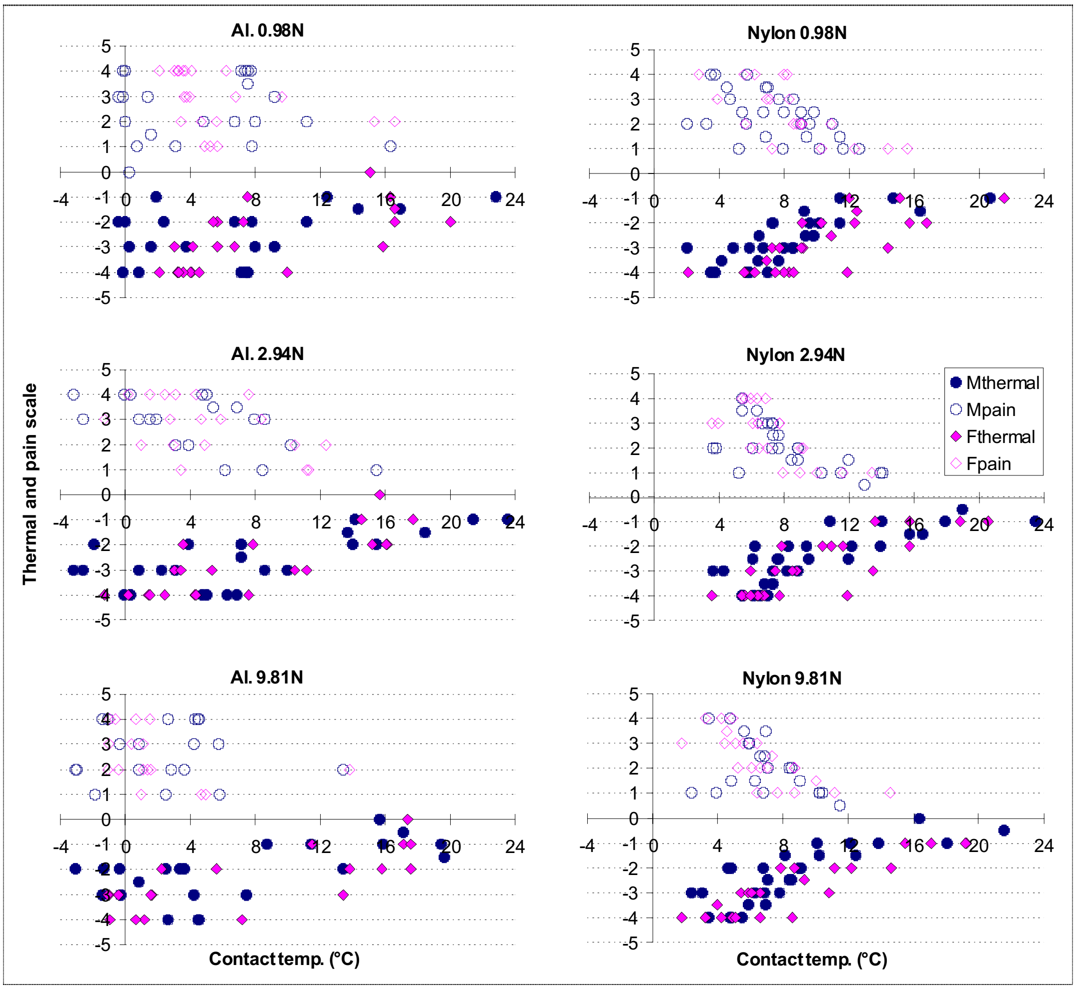


Figure 10. Subjective responses on thermal and pain sensation versus the contact temperature at three different pressures on the aluminium at –15 °C and on the nylon at –20 °C.

2.1.3 Contact time of finger touch on cold surfaces for the critical T_C (15, 7 and 0 °C)

Table 13 shows the secure time to reach each critical contact temperature (15, 7 and 0 °C) for the hand/finger protection against the cold. The time to reach 15 °C (pain threshold) was either interpolated or extrapolated. The time to reach 7 °C (numbness threshold) and 0 °C (freezing threshold) was estimated.

It is seen 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.

Table 13. Time for contact temperature to reach criteria of 15, 7 and 0 °C (touching database)

Conditions			Time for T_C to reach 15 °C				Time for T_C to reach 7 °C				Time for T_C to reach 0 °C			
	Labels	T_S (°C)	Total values	Mean (sec)	Median (sec)	25% (sec)	Total values	Mean (sec)	Median (sec)	25% (sec)	Total values	Mean (sec)	Median (sec)	25% (sec)
1	Wood -40	-40	30	14.61	3.20	2.4	30	127.05	131.50	107.0	13	211.69	200.00	198.0
2	Nylon -35	-35	18	1.89	2.00	1.0	18	44.06	31.00	17.0	17	776.12	210.00	150.0
3	Wood -33	-33	18	65.44	46.00	23.0	18	250.00	245.00	195.0	18	5724.44	9999	395.0
4	Nylon -30	-30	35	9.00	1.80	1.1	35	65.49	42.00	28.0	32	215.47	202.50	153.0
5	Wood -30	-30	36	33.31	24.50	6.1	36	181.19	167.50	139.0	10	277.70	274.50	239.0
6	Wood -25	-25	36	59.86	24.50	3.0	36	783.72	256.00	188.5	21	3591.57	400.00	340.0
7	Nylon -25	-25	34	7.88	4.00	3.0	34	152.85	127.00	101.0	27	338.33	320.00	270.0
8	Wood -20	-20	54	62.93	54.26	18.5	57	233.08	234.49	179.0	13	300.98	317.68	269.3
9	Nylon -20	-20	50	6.76	3.35	2.3	60	116.89	122.00	84.5	38	294.11	263.50	236.0
10	Wood -15	-15	21	40.08	2.10	0.6	24				10	260.35	282.00	254.0
11	Nylon -15	-15	46	21.78	4.45	1.7	47				18	258.09	277.50	227.0
12	Steel -15	-15	113	1.36	0.80	0.4	119	5.07	2.80	1.7	119	15.56	9.90	5.6
13	Alum. -15	-15	109	0.82	0.60	0.3	117	2.95	1.91	0.9	115	9.62	5.10	1.9
14	Wood -10	-10	50	292.15	63.00	5.3	39	250.36	228.00	167.0	3	387.06	389.61	378.0
15	Nylon -10	-10	120	56.44	30.00	6.1	113	362.75	293.00	206.8	13	389.74	365.00	341.0
16	Steel -10	-10	109	3.08	1.00	0.7	117	9.43	4.60	2.9	114	31.31	22.60	15.1
17	Alum. -10	-10	111	2.11	0.80	0.5	113	5.89	3.12	1.2	113	17.55	11.37	6.1
18	Nylon -4	-4	26	76.62	32.66	12.0	27	267.22	247.23	217.3	2	471.77	471.77	450.6
19	Steel -4	-4	98	2.55	1.25	1.0	108	12.77	7.00	4.2	108	111.85	94.18	55.0
20	Alum. -4	-4	105	1.80	1.00	0.7	111	13.86	6.00	2.4	111	86.34	56.80	18.0
21	Wood 0	0	17	62.08	5.90	2.0	22	312.37	309.50	218.0				
22	Nylon 0	0	72				56	340.49	348.86	280.5				
23	Steel +2	2	108	5.27	2.95	1.8	111	84.32	68.00	31.0				
24	Alum. +2	2	105	4.52	2.00	1.1	115	35.52	20.00	10.0				
	Total		1521				1563				915			

2.2 Gripping experiments

2.2.1 Statistical analysis hand cooling in gripping

Hand cooling on the cold rods depends mainly on gripping duration, the temperature of the cold surface, the type of material, individual as well as some other physiological factors. To determine which factors have a statistically significant effect on the final contact temperature, gripping time and subjective sensation, a multiply-factor analysis of variance (ANOVA) was utilised. The main independent variables, which affect hand cooling during gripping, involved the subject and experimental condition (type of material and the surface temperature). In addition, the hand skin temperature ($T_{hsk}0$) and thermal sensation (Thermal 0) before gripping were selected as co-variate factors for the ANOVA. The results of the ANOVA for each response are summarised in Table 14.

Table 14. Results of the ANOVA analysis (Samples number: 90, from partner 1)

10 or 5 subjects × 10 conditions

Responses	Main effects		Covariates
	Individual	Conditions	T_{hsk} 0
Gripping duration (sec.)	$p<0.001$	$p<0.001$	NS*
T_c at end of gripping (°C)	NS*	$p<0.001$	$p=0.001$
Thermal at end of gripping	$p<0.001$	$p<0.05$	NS*
Pain at end of gripping	$p<0.001$	$p<0.001$	NS*
Numbness at end of gripping	$p<0.001$	NS*	NS*

* - No statistically significant effect on the variable at 95% confidence level

The results of the ANOVA showed that the subject factor has a significant impact on the gripping duration and subjective sensations (thermal, pain and numbness) at 95% confidence level except for the T_C after gripping**.** As expected, the exposure conditions affected significantly the gripping duration, the contact temperature and the subjective sensation score (thermal and pain) at the end of gripping. The hand skin temperature before gripping ($T_{hsk}0$) as a co-variate factor was statistically associated with the T_C after gripping. However, the gripping duration was not significantly associated with the $T_{hsk}0$.

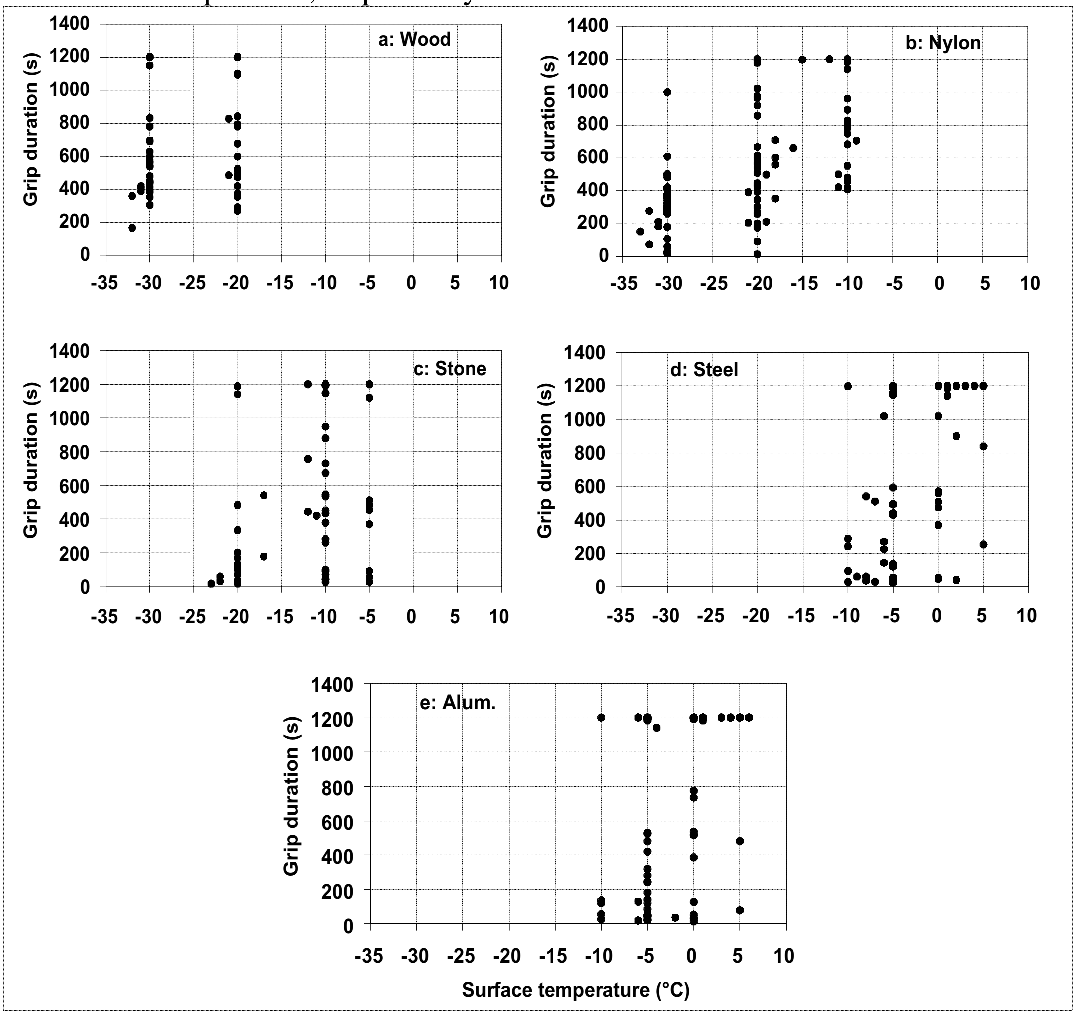
2.2.2 Individual variation during gripping cold surfaces

Individual variation existed in the contact temperature during gripping a cold rod. When gripping a non-metallic bar (e.g. nylon), the size of the hand was related to finger and palm temperatures: the bigger the hand the slower was the cooling rate. This may be due to two reasons: bigger hands have greater mass of superficial tissue (heat storage) and the surface to mass ratio is smaller than in small hands. The contact temperature is determined by physical processes (heat transfer from the hand to the cold surface and environment) and physiological processes (e.g. the changes in blood flow in the skin). Due to the relatively low thermal conductivity of nylon, heat transfer from the skin to the nylon bar was slower and heat loss could have been compensated for by heat from circulation.

During gripping the metallic bar (e. g. aluminium), the dimensions of the hand seemed not to have any role on the finger and palm cooling. The cooling rate of the skin surface was obviously so fast and the cooling so local that the anthropometry of the hand had no effect. Individual variation in cooling rates during contact cooling can not be explained only by hand anthropometric measures but also by differences in circulation in the hand (Rissanen *et al.* 2000)

2.2.3 Duration of gripping cold surfaces

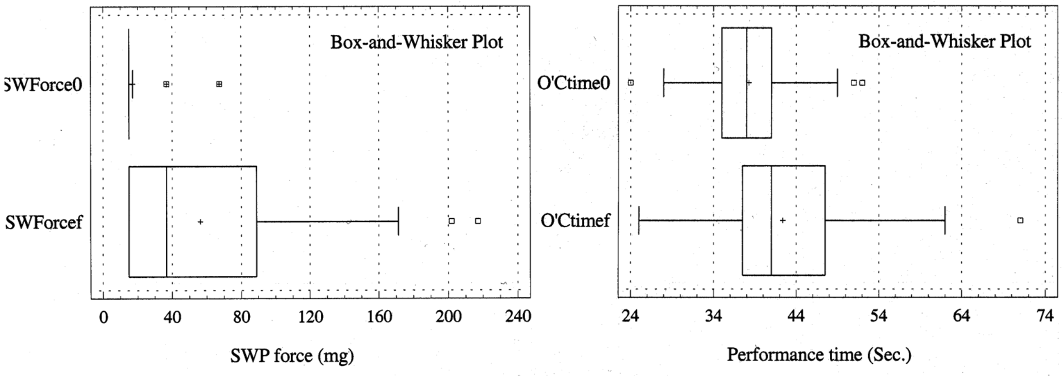
Figures 11a to 11e showed the gripping duration for each material as a function of the surface temperature, respectively.



Figures 11. Gripping duration for each material versus the surface temperature.

2.2.4 Effect of hand gripping cooling on manual performance

The Box-and-Whisker plots, as shown in Figures 12 and 13, presented the results. There is a statistically significant difference between the means of SWP force for tactile sensitivity before and after gripping at 99 % confidence. The result of the finger dexterity test also showed that the performance time after griping was significantly longer than that before gripping.



Figures 12-13. Comparison of hand SWP sensitivity and finger dexterity before and after gripping.

Furthermore, a relationship between finger dexterity performance reduction and cold air temperatures was studied. The results of the relationship where the hand was 'gripping' air, are presented in box – plots in Figure 14 (Powell *et al.* 2000). This plot showed that performance reduction increased with decreasing air temperature.

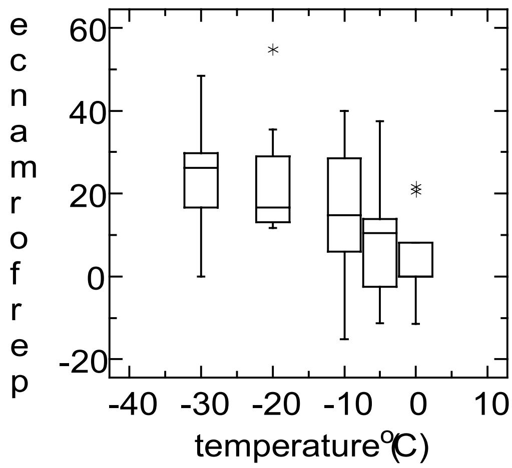


Figure 14. Relationship between performance reduction and air temperature.

2.3 Results of sticking experiments

2.3.1 Sticking force by fingertip

The results of sticking force vs. the surface temperature of the material with bare finger and with covered finger are shown in Figures 15-16. During the fingertip touching, the sticking developed at the surface temperature of aluminium below -5 °C or that of steel below -7 °C. The sticking force increased steeply when the temperature of metals decreased to –10 °C. The change in the sticking force between -10 and -20 °C was small (Figure 15). The results of maximal sticking force with bare finger (Figure 15) and covered finger (Figure 16) did not differ markedly. The maximal sticking force at –20 °C was approximately 1.5 kg when the cold steel was touched.

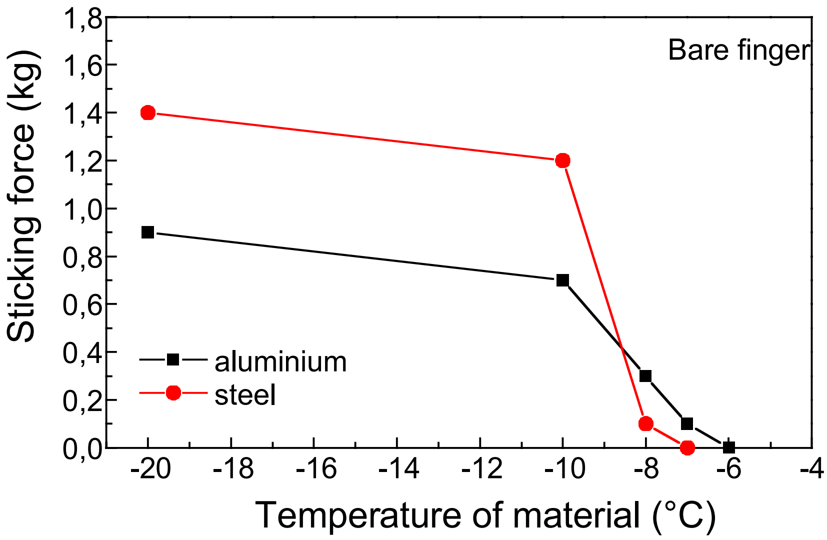


Figure 15. Sticking force with bare finger (values are means of 3 - 4 measurements).

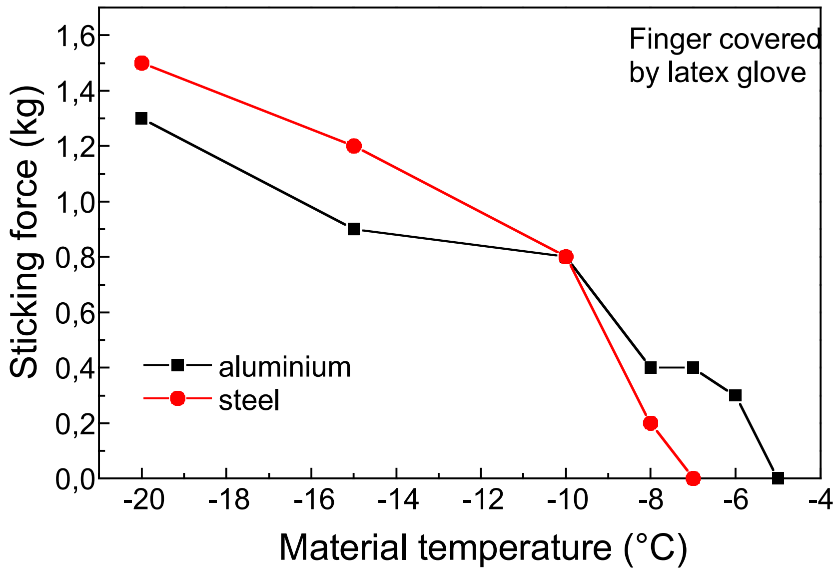


Figure 16. Mean ticking force with finger covered by latex glove.

The tests with dry fingers did not show any sticking response when dry or ice-covered cold metal was touched.

The results showed that dry fingers do not stick on cold metal (aluminium or steel), even when a thin ice layer covered it. Wet skin started to stick on the cold surface of the metal when its temperature decreased below –5 °C. The sticking force increased steeply when metal temperature decreased to -10 °C. The sticking force between -10 and -20 °C did not vary markedly. The differences between the sticking forces with aluminium and steel were not marked except during the contact with bare finger, when the force was higher with steel.

The sticking of a bare finger was quite reliably simulated with a finger covered by a latex surgeon's glove.

2.3.2 Sticking force by gripping with covered hand

The results of hand gripping experiments in Figure 17 gave very similar results as the fingertip sticking experiments. Sticking started when the temperature of aluminium below -5 °C and steel temperature below -7 °C. The sticking force increased steeply when metal temperature decreased to –10 °C and thereafter the increase in the sticking force was less steep. The maximal sticking force was much higher compared to the finger sticking force (ca. 8 kg at –20 °C, Figure 17).

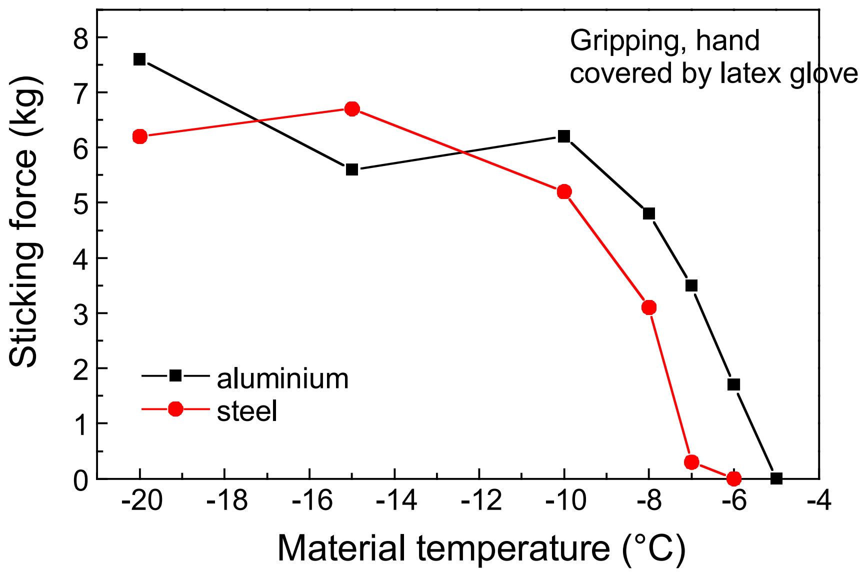


Figure 17. Sticking force with hand covered by latex glove. Values are mean of 3-4 measurements.

3 Modelling

3.1 Modelling of fingertip contact cooling

From the large number of measurements that have been performed within the project, the most relevant parameters of the model have been identified. In Figure 18, the result of the simulated cooling of the finger surface to actual data from one of the laboratories is presented. Optimisation of the model parameters resulted in a close fit of the model output to the data. The parameter set of the model could be optimised to all experimental data sets from the touching experiments, similar to figure 18 (Hartog *et al*. 2000).

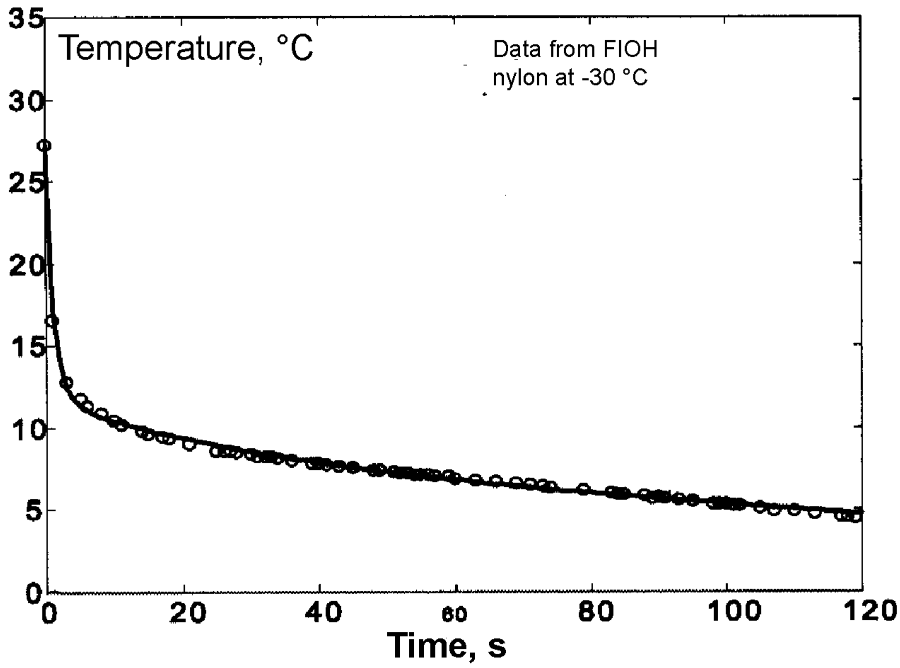


Figure 18. Model simulation fitted to experimental data from touching Nylon at –30 °C. The circles represent the experimental data, the line through the points is the model simulation. The data are from an experiment performed by FIOH.

In order to develop safety limits for contact cooling, a general model would be preferable for all possible conditions, that can predict the behaviour of the lower 25th percentile of the population. After studying the effects of the different parameters it seemed that only the first parameter (R_{skin}/R_{tot}) needed to be changed for different materials. The size of this parameter was dependent on the contact coefficient (F_C). The following equation for this parameter seemed to provide the best results over all conditions.

$$R_{skin}/R_{tot} = -0.025*\ln(F_C) + 1.15 \qquad (1)*$$

*(See CS84)

In CS84 (Figures 5 to 12), the comparisons of the model to the measured data were presented for all four materials at different temperatures. The thick lines of the model results predict the behaviour of the lower 25th percentile of the population well (Figure 19).

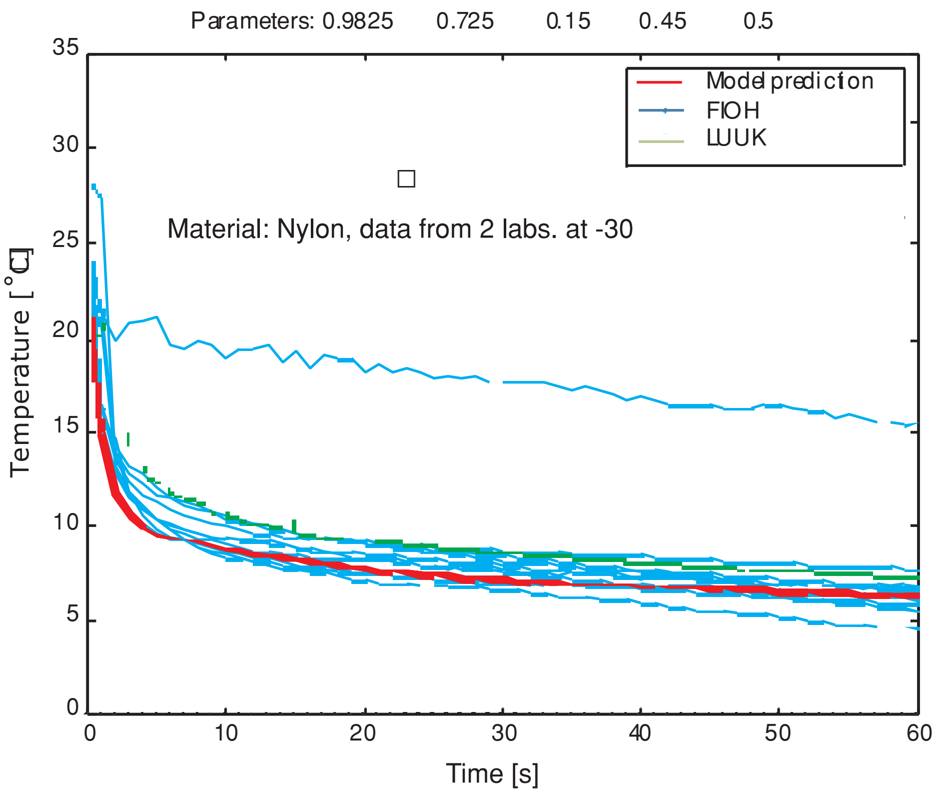


Figure 19. Comparison of measured and predicted values according to model.

3.2 Modelling of hand cooling during gripping

Figure 20 shows an example of the results when simulations are compared with data for mean contact temperature (data from FIOH). The lowest curve (thin vasoconstricted hand), follows the fastest cooling curves quite well (CS65).

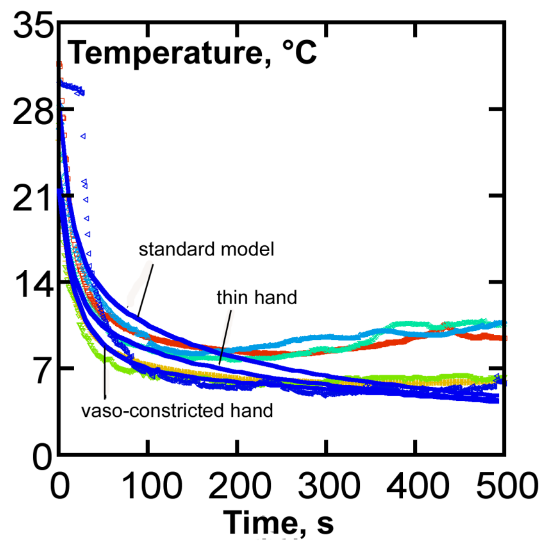


Figure 20. Gripping stainless steel at -5 °C (FIOH data, Mean of the contact side). Continuous smooth lines: model results (top: standard model; middle: thin hand; bottom: thin, vasoconstricted hand). All other lines are individual records.

4 Instrument for contact cooling measurement

4.1 Change in T_C of artificial finger in contact with metal surfaces at temperatures ≤-20 °C

It is not acceptable for ethical reasons, to expose human subjects to cold metallic surfaces at surface temperatures below –20 °C. Figure 21 illustrates the cooling curves of the artificial finger touching various metallic surfaces at extremely cold temperature below –20 °C.

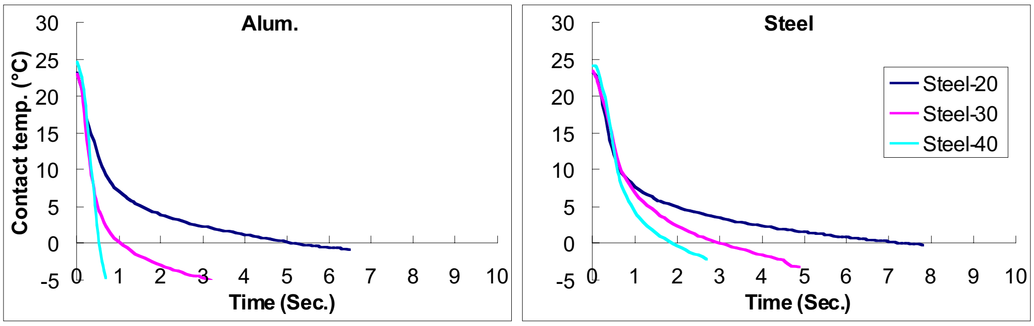


Figure 21. Change in T_C of artificial finger in contact with metallic surfaces (alum. and steel) at temperature –20, -30 and –40 °C.

4.2 Comparison of cooling curves for artificial and human fingers

Figure 22 shows that the cooling behaviour of the artificial finger follows a similar pattern as that measured with human fingers. The cooling curve obtained from the artificial finger covers the lowest cooling curve from human fingers. This reflects that the measuring results with the artificial finger can be considered as the lowest temperature limit for the protection of human finger in the cold.

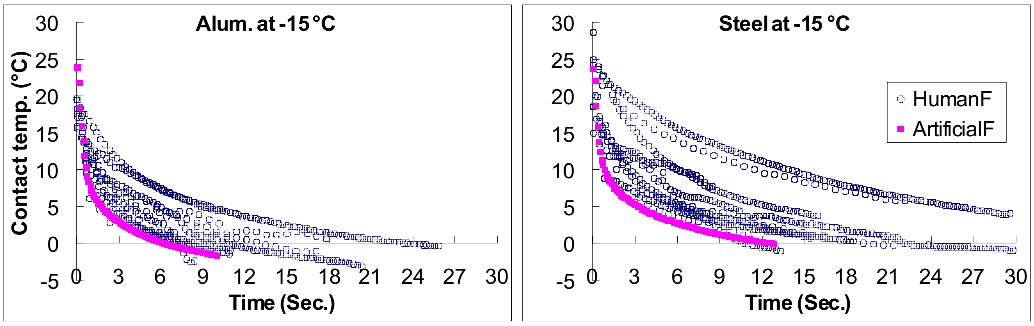


Figure 22. Comparisons of cooling curves between the artificial finger and human finger where touching cold metallic surfaces at –15 °C.

Figure 23 shows the contact time for T_C to reach the freezing criterion (0 °C) at various surface temperatures using the artificial finger under extremely cold conditions. For instance, freezing injury might take place when finger touches the cold aluminium surface at –40 °C for only 0.7 seconds, at –30 °C for about 1.2 seconds and at –20 °C for about 5.2 seconds.

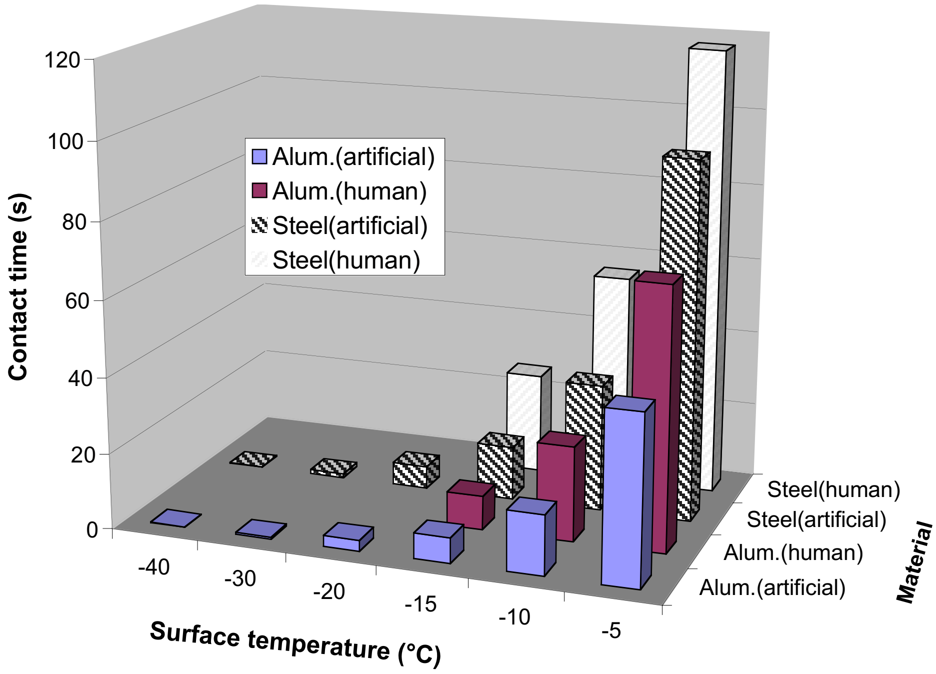


Figure 23. Contact time for T_C to reach freezing criterion (0 °C) at various surface temperatures using the artificial finger under extremely cold conditions: $T_S \leq 20$ °C and both human finger and artificial fingers at $T_S \geq -15$ °C.

5 Database

5.1 Finger touching experiments

The number of touching experiments were 1657 tests under 24 exposure conditions (Holmér *et al.* 2000). In order to protect 75 % of the population, Figure 24 describes the lower quartile contact duration as a function of the surface temperature of various materials (aluminium, steel, nylon and wood). In practice, the modelling of the contact duration should be concerned only for the cases of cold steel and aluminium.

Table 14 gives the experimental conditions, the number of tests and the descriptive statistics regarding the duration of the test (mean, standard deviation, median, lower and upper quartiles). The duration of the test was limited to 120 seconds.

Table 14. Descriptive statistics of the touching database: test duration limited to 120 sec.

Conditions	Labels	Surface temperature (°C)	Total values	N values below 120 sec	Mean (sec)	Standard deviation (sec)	Lower quartile (sec)	Median (sec)	Upper quartile (sec)
1	Wood -40	-40	30	0	120.00	0.00	120.0	120.00	120.0
2	Nylon -35	-35	18	11	98.99	21.46	81.6	101.40	120.0
3	Wood -33	-33	18	1	119.64	1.51	120.0	120.00	120.0
4	Nylon -30	-30	35	5	119.00	2.61	120.0	120.00	120.0
5	Wood -30	-30	36	0	120.00	0.00	120.0	120.00	120.0
6	Wood -25	-25	36	1	119.84	0.93	120.0	120.00	120.0
7	Nylon -25	-25	34	5	116.07	11.45	120.0	120.00	120.0
8	Wood -20	-20	60	3	119.73	1.71	120.0	120.00	120.0
9	Nylon -20	-20	60	5	117.81	8.05	120.0	120.00	120.0
10	Wood -15	-15	30	5	115.78	21.16	120.0	120.00	120.0
11	Nylon -15	-15	51	12	111.12	26.08	120.0	120.00	120.0
12	Steel -15	-15	119	119	17.02	11.72	8.4	14.24	22.1
13	Alum. -15	-15	118	118	10.50	9.22	3.2	7.60	14.0
14	Wood -10	-10	58	4	119.44	3.32	120.0	120.00	120.0
15	Nylon -10	-10	127	5	118.96	6.26	120.0	120.00	120.0
16	Steel -10	-10	117	113	28.49	26.55	12.4	19.96	31.3
17	Alum. -10	-10	113	113	18.20	16.60	7.8	13.40	25.4
18	Nylon -4	-4	30	2	118.96	4.12	120.0	120.00	120.0
19	Steel -4	-4	108	76	77.03	37.09	47.9	70.25	120.0
20	Alum. -4	-4	111	84	57.98	43.86	17.0	47.55	118.9
21	Wood 0	0	27	5	115.62	15.10	120.0	120.00	120.0
22	Nylon 0	0	87	1	119.95	0.42	120.0	120.00	120.0
23	Steel 3	3	115	25	114.10	17.51	120.0	120.00	120.0
24	Alum. 3	3	117	39	108.11	21.11	102.6	120.00	120.0
	Total		1655	752					

Also, the contact time to reach the critical contact temperature (15, 7 and 0 °C) were estimated (CS83).

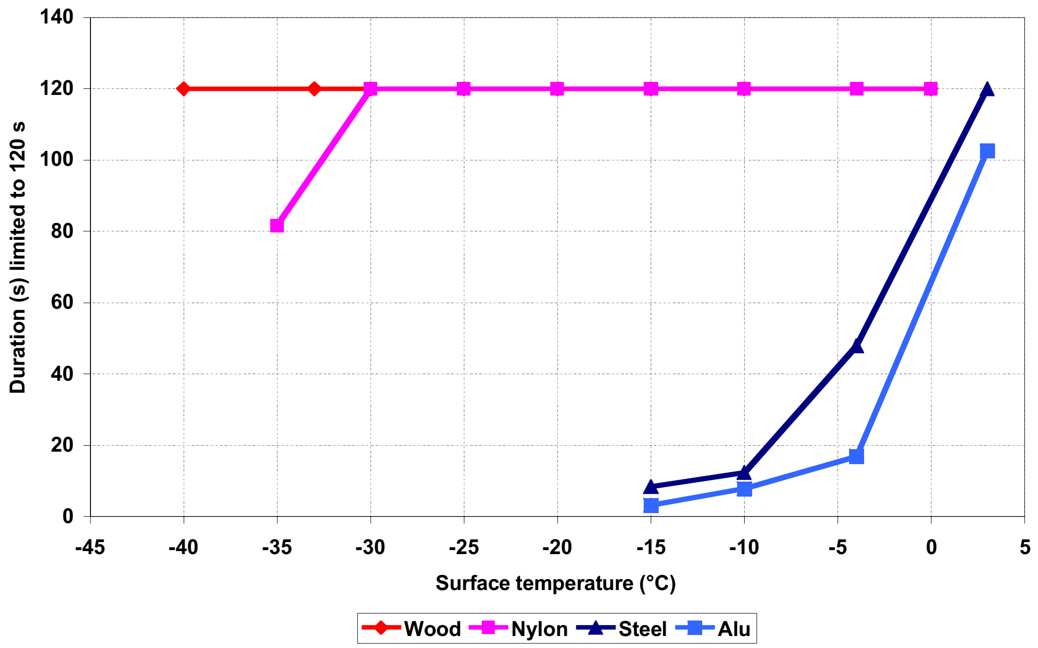


Figure 24. Lower quartile of touching duration versus the material's surface temperature.

5.2 Hand gripping experiments

The gripping database includes 584 tests under 21 exposure conditions. A fifth material, stone, was also studied in addition to wood, nylon, steel and aluminium. Some experiments of gripping in air were conducted to get reference values. Table 15 provides the descriptive statistics for the gripping experiments with duration limited to 1200 seconds under each condition. The gripping duration affected the median and the upper quartiles, but not the lower quartile (373 of 553 data points were below a duration limit of 1200 seconds).

The mean duration of gripping the cold stone below –20 °C or the cold aluminium and steel at –10 °C was significantly shorter, compared to that from other conditions. The shortest mean gripping time was 248.4 seconds when gripping the stone at –20 °C (Table 15).

Figures 25 shows the lower quartile of the gripping duration.

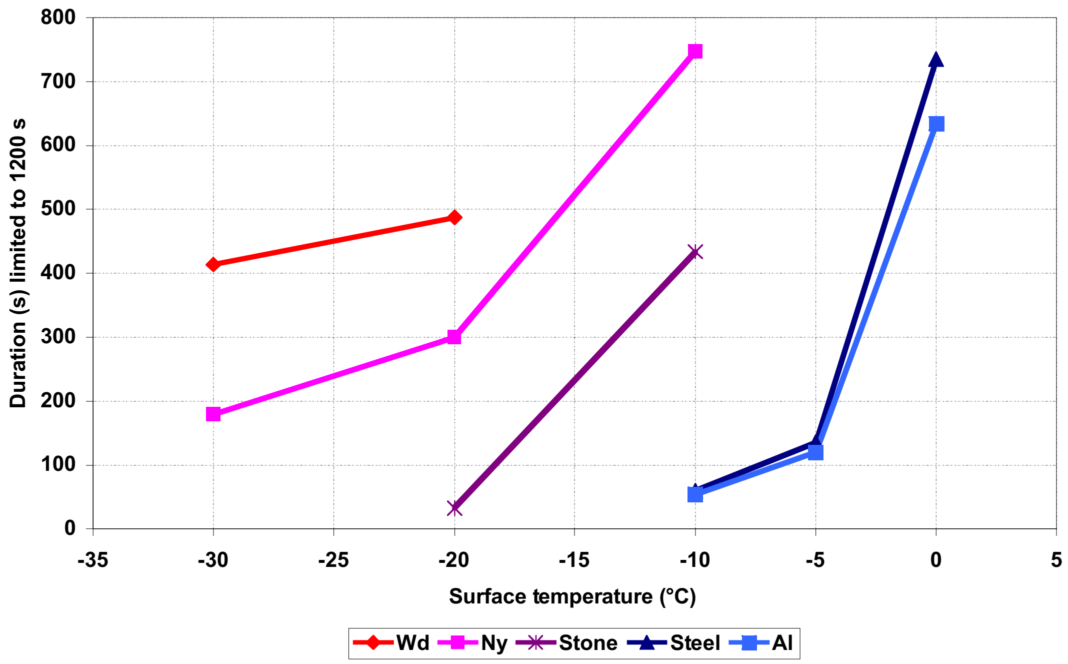


Figure 25. Lower quartiles of the gripping duration versus material's surface temperature

Table 15. Descriptive statistics of the grip database: test duration (limited to 1200 sec.).

Conditions	Labels	Surface temperature (°C)	Total values	N values below 1200 sec	Mean (sec)	Standard deviation (sec)	Lower quartile (sec)	Median (sec)	Upper quartile (sec)
1	Wood -30·	-30	33	27	642.0	319.3	414.0	540.0	780.0
2	Nylon -30·	-30	33	33	296.2	192.8	180.0	300.0	366.0
3	Air -30·	-30	10	10	524.7	207.6	364.0	574.0	698.0
4	Wood -20	-20	32	20	821.3	353.0	487.0	811.5	1200.0
5	Nylon -20	-20	42	38	580.8	346.6	300.0	524.5	857.0
6	Stone -20	-20	20	20	248.4	346.5	33.0	115.2	266.5
7	Air -20	-20	28	20	775.8	353.0	482.3	662.3	1200.0
8	Nylon -10	-10	42	26	970.9	299.8	747.0	1193.0	1200.0
9	Steel -10	-10	9	9	282.8	381.8	60.0	94.0	287.1
10	Alum. -10	-10	5	4	307.0	501.2	54.2	120.6	134.9
11	Stone -10	-10	41	29	792.7	444.4	434.0	950.0	1200.0
12	Air -10	-10	22	11	1048.1	341.9	1193.0	1199.5	1200.0
13	Steel -5	-5	39	27	716.5	507.1	135.9	1020.0	1200.0
14	Alum. -5	-5	42	31	663.9	526.5	120.0	526.0	1200.0
15	Stone -5	-5	10	8					
16	Air -5	-5	21	11	1149.1	191.4	1195.0	1199.1	1200.0
17	Steel 0	0	36	19	956.1	407.4	735.0	1194.5	1200.0
18	Alum. 0	0	40	19	932.3	439.8	634.5	1200.0	1200.0
19	Air 0	0	22	7	1197.3	4.6	1195.0	1200.0	1200.0
20	Steel 5	5	7	2					
21	Alum. 5	5	19	2					
	Total		553	373					

Figures 26 shows the lower quartile of the gripping time to reach 15°C.

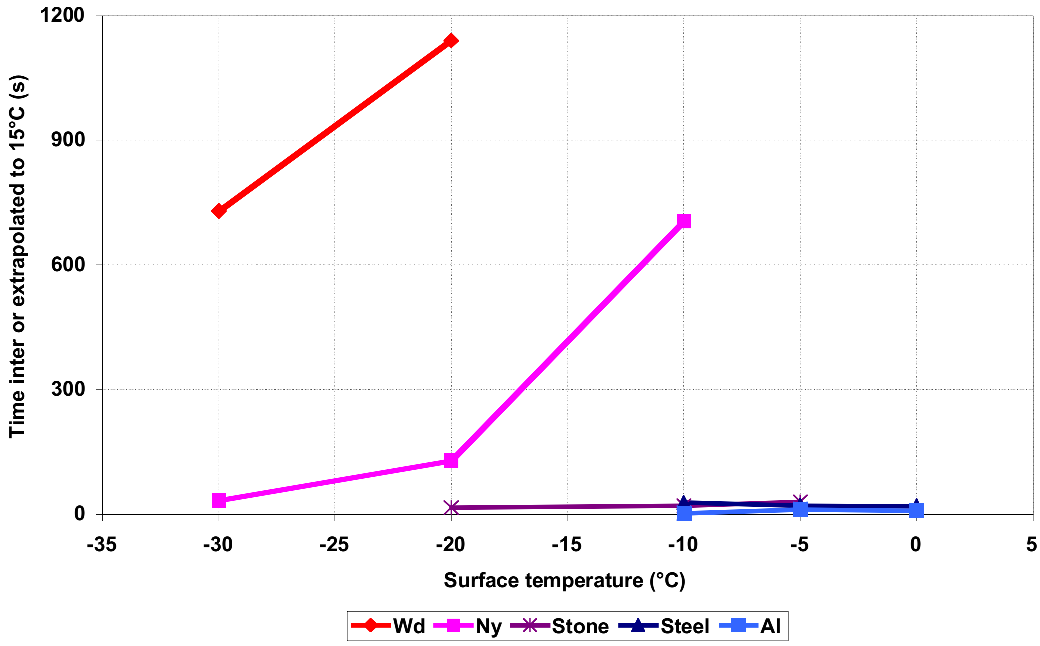


Figure 26. Lower quartile of the gripping time to reach a contact temperature of 15°C.

Table 16. Descriptive statistics of the gripping database: time for contact temperature to reach 15°C.

Conditions	Labels	Surface temperature (°C)	Total values	N values below 9999	Mean (sec)	Standard deviation (sec)	Lower quartile (sec)	Median (sec)	Upper quartile (sec)
1	Wood -30·	-30	33	17	5297.6	4642.7	730.0	1626.0	9999.0
2	Nylon -30·	-30	32	30	748.0	2430.3	33.8	81.6	268.6
3	Air -30·	-30	8	6	2687.8	4517.2	90.0	301.0	5327.0
4	Wood -20	-20	31	17	5298.8	4367.8	1140.0	2400.0	9999.0
5	Nylon -20	-20	41	36	1513.5	3228.7	129.0	195.2	600.0
6	Stone -20	-20	20	20	50.7	47.0	16.2	43.4	68.7
7	Air -20	-20	26	21	2441.2	3774.2	405.0	740.0	1118.0
8	Nylon -10	-10	42	20	5678.7	4632.4	705.0	9999.0	9999.0
9	Steel -10	-10	9	9	64.3	73.6	28.2	49.1	62.9
10	Alum. -10	-10	5	5	7.3	5.7	2.9	5.4	9.3
11	Stone -10	-10	41	41	182.4	411.6	20.4	40.0	138.5
12	Air -10	-10	22	12	5330.1	4403.0	1220.0	2930.0	9999.0
13	Steel -5	-5	39	36	857.8	2676.4	21.6	37.9	172.1
14	Alum. -5	-5	42	40	550.9	2140.3	12.0	31.7	151.0
15	Stone -5	-5	10	7	3043.9	4800.0	30.0	56.0	9999.0
16	Air -5	-5	20	7	6870.0	4390.4	1535.0	9999.0	9999.0
17	Steel 0	0	36	31	1499.6	3468.5	20.1	59.6	297.9
18	Alum. 0	0	40	36	1037.4	3025.8	9.5	27.9	61.2
19	Air 0	0	21	1					
20	Steel 5	5	7	5					
21	Alum. 5	5	19	16					
	Total		573	439					

The descriptive statistics for inter and extrapolation of gripping time for the contact temperature to reach 15°C is shown in Table 16. For most of the tests, the contact temperatures at the end of the tests were higher than 15 °C (15.9 $\pm$ 5.2 °C), which could be evaluated in 439 of 573 tests.

5.3 Empirical relationship of contact time with contact coefficient and surface temperature of the material

Empirical relations were derived based on the prediction of the lower quartile (75% protected) of the duration (D) and the time to reach the contact temperature of 15, 7 and 0°C, respectively – defined by t(15), t(7) and t(0). The duration was empirically correlated with the surface temperature T_S and the contact factor F_C of the material (Table 1).

The data used to derive these empirical expressions varied from one model to another. The prediction model will only be used in the restricted ranges of contact duration:

- Touching experiments are representatives of short-term exposure to cold, lasting less than 100 seconds. Therefore, lower quartile values above 100 s were not taken into account.
- Gripping experiments are related to longer exposure duration, generally between 100 and 1000 sec. All the data points were used to derive the model for gripping duration.

A non-linear regression model can be obtained to predict the time as a function of the surface temperature (T_S) and the contact factor (F_C). The non-linear model obtained had the following form:

$$\text{Time} = (A / F_C{}^{B}) \exp (C\, F_C{}^{D}\, T_S) \qquad (2)$$

Where: A, B, C and D were constants which can be estimated by the non-regression iterative procedure. For each model, the first general expression was simplified when some of the coefficients were not significant.

The final models for the touching experiments were:

- for touching duration, **D** (limited to 120 seconds, only for steel and aluminium):
  $$D = (180.9 / F_C{}^{0.425}) \exp (0.0570\, F_C{}^{0.475}\, T_S) \qquad R^2=0.99$$
- for time to reach 15°C, **t(15)** (only for nylon, steel and aluminium):
  $$t(15) = (13.70 / F_C{}^{1.092}) \exp (0.108\, T_S) \qquad R^2 = 0.93$$
- for time to reach 7°C, **t(7)** (only for nylon, steel and aluminium):
  $$t(7) = (454.6 / F_C{}^{1.800}) \exp (0.1202\, F_C{}^{0.467}\, T_S) \qquad R^2 = 0.99$$
- for time to reach 0°C, **t(0)** (only for steel and aluminium):
  $$t(0) = (980.5 / F_C{}^{1.029}) \exp (0.2104\, T_S) \qquad R^2 = 0.99$$

The final models for the gripping experiments were:

- for gripping duration, **D** (limited to 1200 seconds, for wood, nylon, stone, steel and aluminium):

  $$D = (1251 / F_C^{\,0.241}) \exp(0.0742\, F_C^{\,0.617}\, T_S) \qquad R^2 = 0.94$$

- for time to reach 15°C**, t(15)** (only for wood and nylon):

  $$t(15) = 2991 \exp(0.295\, F_C^{\,2.790}\, T_S) \qquad R^2 = 0.99$$

The analysis of paired values for time to reach 15 °C versus spontaneous grip duration in the experiment indicated that the ratio was in average equal to 0.60$\pm$ 0.78. Accordingly, a general model for prediction of t(15) all five materials were derived and used to calculate safe temperatures.

- for time to reach 15°C**, t(15)** (only for aluminium, steel, stone, wood and nylon):

  $$t(15) = (750 / F_C^{\,0.241}) \exp(0.0742\, F_C^{\,0.617}\, T_S)$$

All the primary models were accurate, as indicated by the correlation coefficients close to 1.

Figures 27 to 32 show the predicted values from the models for each parameter. The models were used for all materials, regardless of the fact that they were derived based on the data for certain materials only.

These extrapolations for all the materials give plausible results. The predicted values are lower than the observed values, suggesting a certain degree of safety. However, for wood and nylon, the extrapolated values for t(0) are much lower than the values for t(7). The expression for the prediction of t(0) cannot be used for these non-metallic materials.

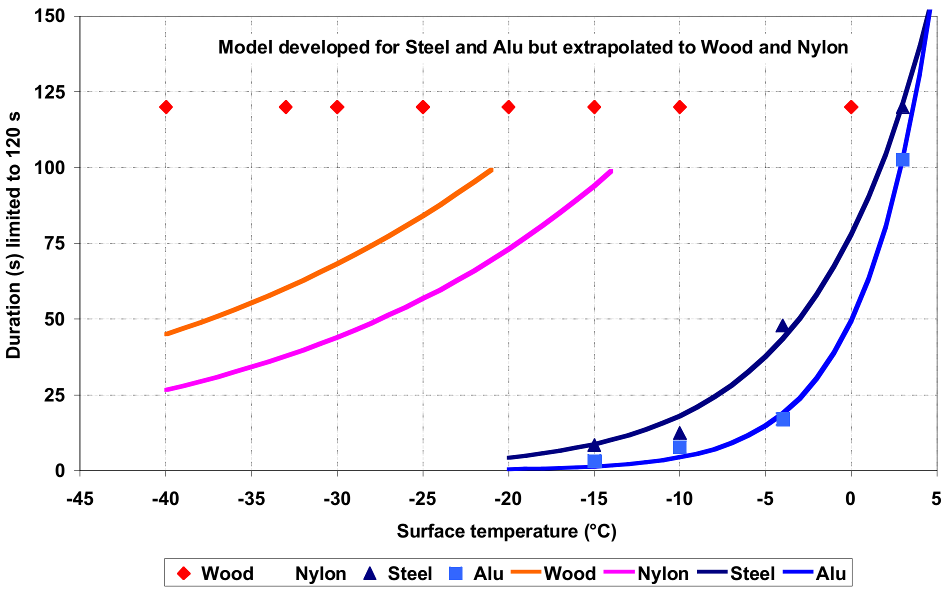


Figure 27. Lower quartile of the touching duration: observed and predicted values.

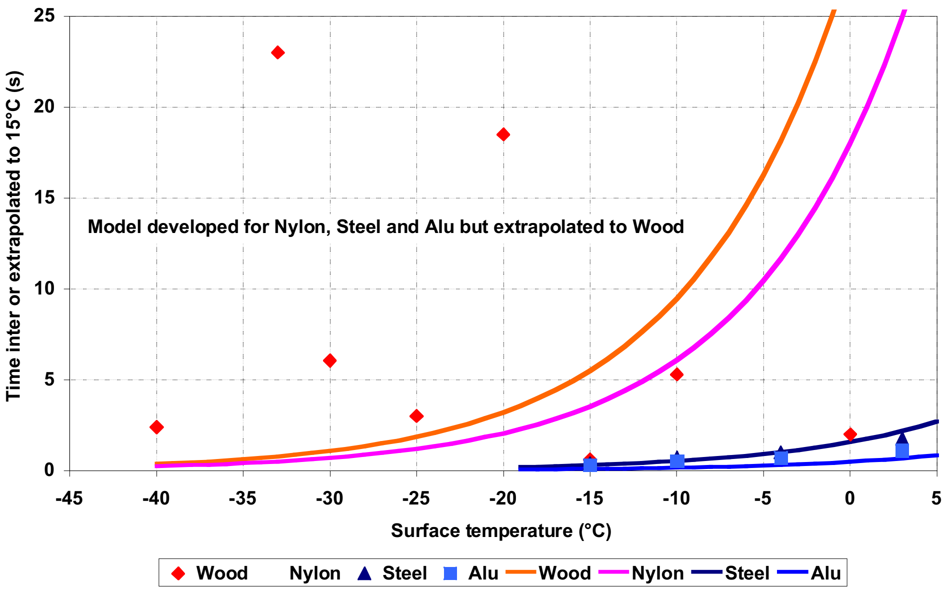


Figure 28. Lower quartile of the touching time to reach a contact temperature of 15°C: observed and predicted values.

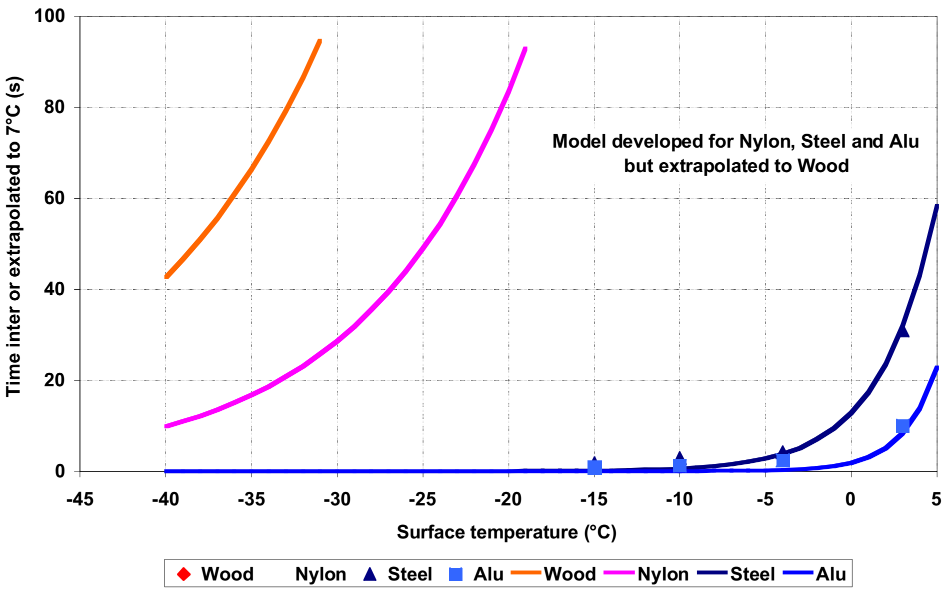


Figure 29. Lower quartile of the touching time to reach a contact temperature of 7°C: observed and predicted values.

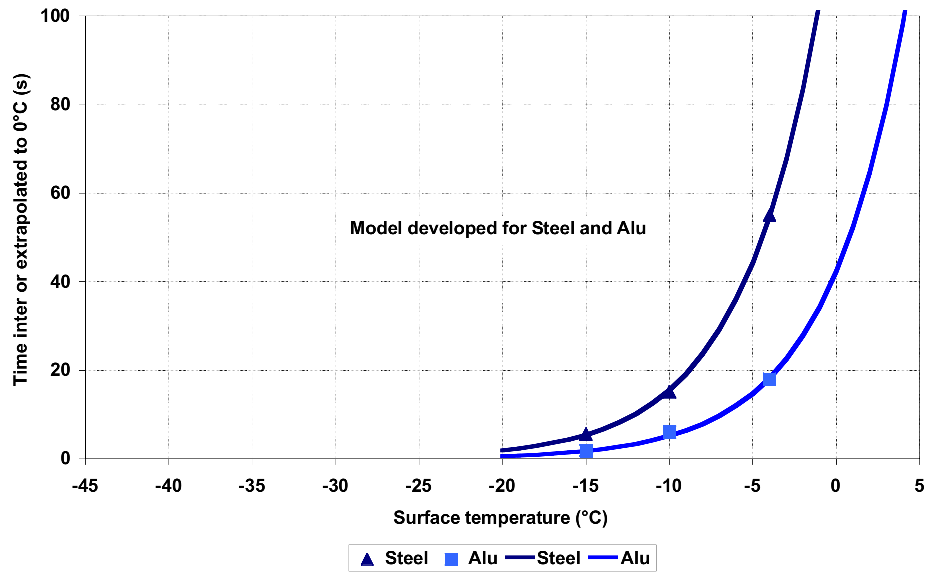


Figure 30. Lower quartile of the touching time to reach a contact temperature of 0°C: observed and predicted values.

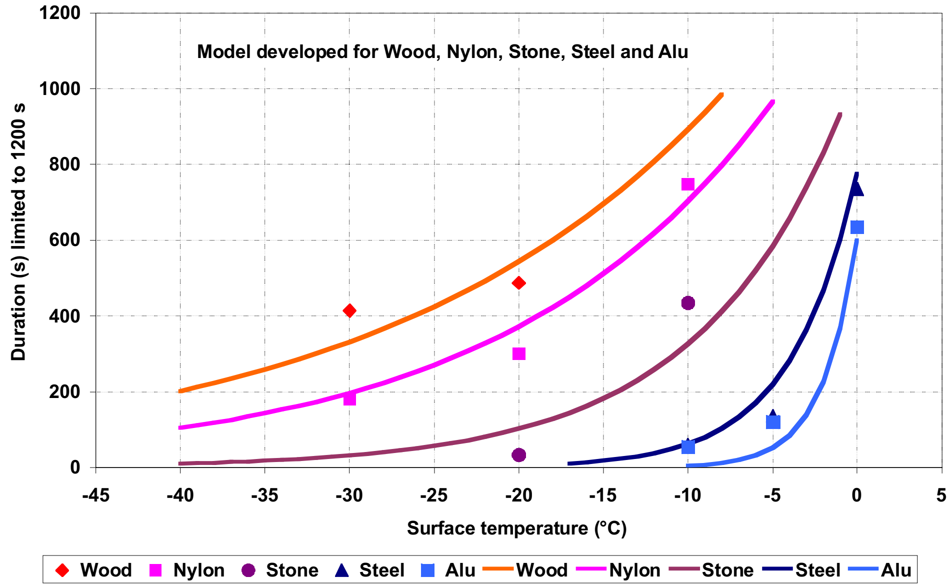


Figure 31. Lower quartile of the gripping duration: observed and predicted values.

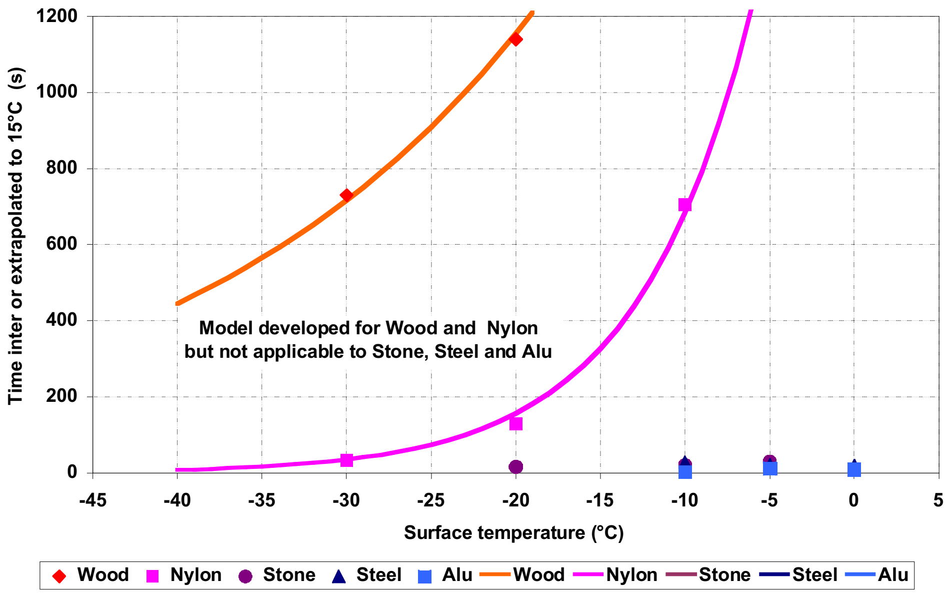


Figure 32. Lower quartile of the gripping time to reach a contact temperature of 15°C: observed and predicted values.

6 Draft proposal for guideline document

As a result of the research, the occurrence of contact cold injury depends on the surface temperature and the time for the T_C to reach a critical temperature. The T_C and the contact time both have been studied experimentally. In the work site, the determination of contact time could be more convenient, compared to the measurement of the T_C when contacting cold surfaces. From the ergonomic point of view, an estimate of the cold risk is possible by measuring the surface temperature of the cold object and the contact time to reach a defined criterion. The duration limit of contacting various cold surfaces can be regarded as a secure time threshold. The determination of contact time is more convenient than the measurement of the skin-surface interface contact temperature. As mentioned the results have proved that the criteria would be levels corresponding to 0 °C (freezing), 7 °C (numbness) and 15 °C (pain). The time limits can be directly obtained from human finger cooling curves on cold surfaces under selected conditions. In addition, the contact time to reach the critical temperature shows large variation among individuals. The individual variation should be considered when the contact time for the critical temperature is determined. To cover most of the individual variation and secure protection for 75% of the population in contact with cold surfaces, the contact time for the critical T_C is determined by using the lower quartile (25%).

In the next section four graphs are presented showing the relation between surface temperature of the material and time to reach the defined contact temperature (15, 7 and 0 °C). This information forms the key element in the draft standard for touching cold surfaces (ISO/CD-13732). At the time of writing the actual standard is still in a draft form, although it has been accepted at both CEN and ISO level. The reader is recommended to consult the final version for correct information and interpretation.

ISO/CD-13732, 2002, Ergonomics of the thermal environment - Assessment of human responses to contact with surfaces. Part 3 - Cold surfaces, International Standards Organisation (nov 2002).

6.1 Threshold data

6.1.1 Freezing thresholds for finger contacting cold surfaces

The freezing threshold values of finger touching three cold surfaces (Aluminium, steel and stone) are shown in Figure 33.

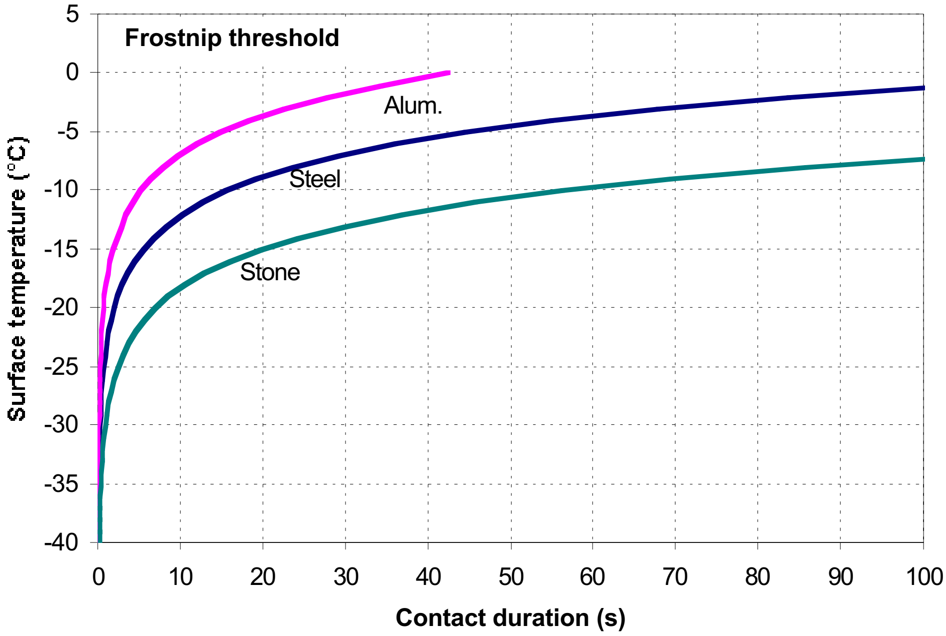


Figure 33. Acceptable surface temperature as a function of time for T_C to reach 0 °C (finger touching the cold surfaces between 0.5 and 100 sec.).

6.1.2 Numbness thresholds for finger contact with cold surfaces

The numbness thresholds for finger touching the five materials are indicated in Figure 34.

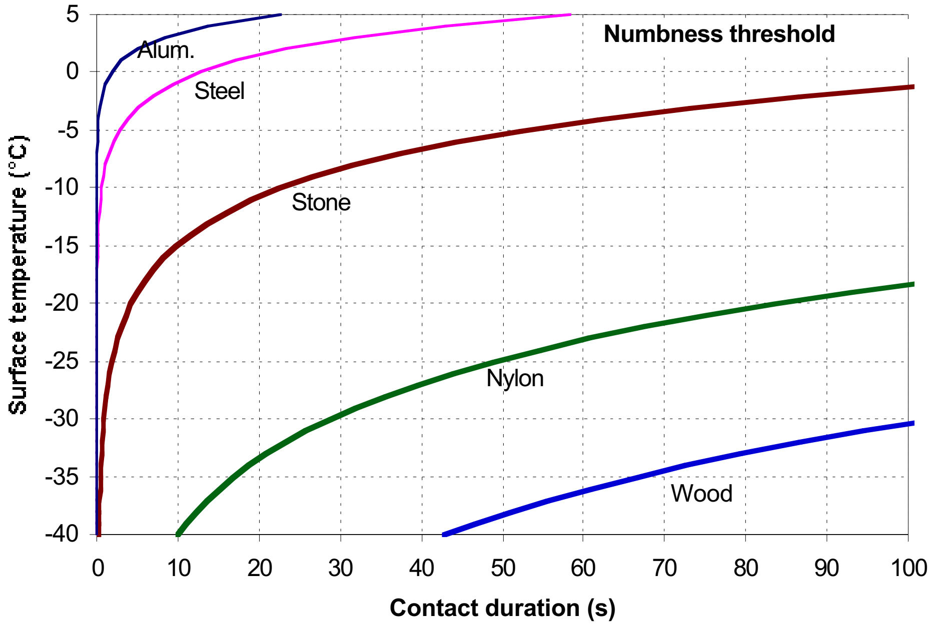


Figure 34. Acceptable surface temperature as a function of time for T_C to reach 7 °C (finger touching the cold surfaces between 0.5 and 100 sec.).

6.1.3 Pain thresholds

The pain thresholds for touching and gripping different materials are indicated in Figures 35 and 36. The curves were plotted only for the case of gripping the wood and nylon in cold since the model was not applicable to stone, steel and aluminium (see CS83).

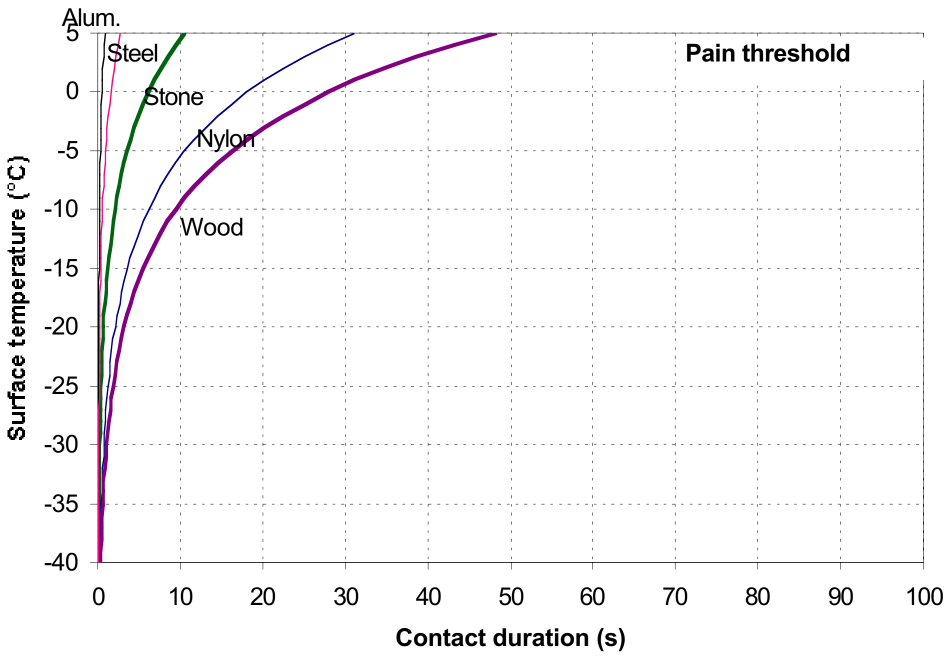


Figure 35. Acceptable surface temperature as a function of time for T_C to reach 15 °C: a) finger touching the cold surfaces between 0.5 and 100 sec.

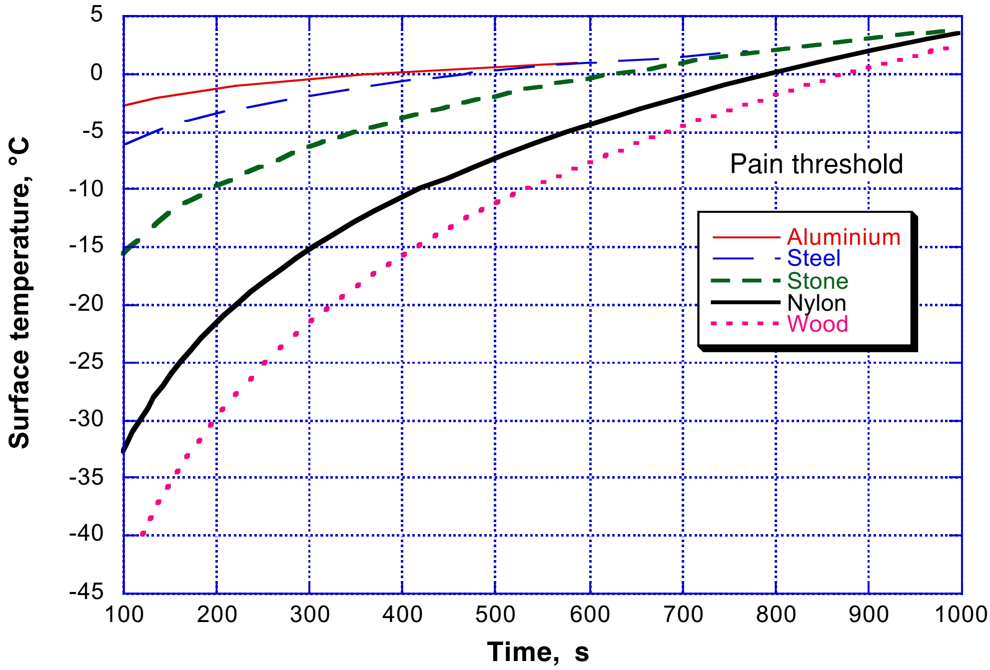


Figure 36. Acceptable surface temperature (pain threshold) as a function of time for T_C to reach 15 °C for gripping different materials between 100 and 1000 sec.

Conclusions

1 Field study

The results of the field study in the food industry show that cold hazards are common in food processing industry, where the most common product temperature is between - 5 and 5 °C. Reports of cold hazards in hands and especially fingers are most common. A majority of workers (52 %) considered that cold products were the reason for marked cold stress. Moreover, 18 % of workers considered that cold machines and surfaces were hazardous. In 67 % of responses the surface of the product was reported to be wet. The most difficult situation seems to be the handling of frozen products at the ambient temperature of 0 - 5 °C.

2 Experimental research

a) *Finger touching*: A more rapid reduction of contact temperature occurred when finger contacted cold metallic surfaces, compared to cold non-metallic surfaces. The contact temperature reduced with the surface temperature (T_s) of the material. Finger cooling showed a significant individual variation. Finger cooling on a metallic surface was affected by pressure. However, this effect became less significant with decreasing the T_S. A very low T_S (e.g. -15 °C) seemed to dominate over the effect of pressure for finger cooling on metallic surfaces. The pressure had little impact on the variation of T_C with time for the nylon surface.

The subjects have less sensitivity for the cold and pain at a high pressure (> 9.81 N) at very low temperatures. It is suggested that the temperature limit for finger protection in the cold be determined with data obtained at low pressures (< 3.0 N).

The safety criteria for contact temperature are suggested to be 0 °C for freezing cold injury, 7 °C for numbness or extremely cold pain sensation and 15 °C for pain sensation.

Recommended contact time for the three criteria of finger contact cooling may be applicable for safety design of work stations, manual material jobs and hand tools in the cold.

b) *Gripping*: The contact temperature reduced rapidly when a cold metallic rod was gripped. However, a gradual decrease of the T_C with gripping time occurred for the case of the cold non-metallic material like nylon and wood. A rapid heat transfer from the hand to the cold surface occurred at a lower T_S in gripping various cold materials. The contact hand cooling caused a rapid decrease of the contact temperature during gripping the cold rods rather than hand convective cooling in air. A temporary increase in the T_C occurred during gripping the cold rods due to a possible effect of the CIVD.

Gripping experiments were conducted to determine the maximum allowable tolerable exposure duration at different temperatures and for different materials. It was found that this duration varies inversely as a function of the contact factor and linearly as a function of the temperature of the material. The duration of gripping the cold metals is significant shorter at –10 °C, compared to the non-metals.

During slow cooling hand dimensions explain part of the great individual variation in palm and finger contact skin temperatures, while anthropometric measures do not seem to play an important role during rapid cooling.

Considerable performance loss (tactile sensitivity and finger dexterity) after gripping the cold rods was found. A decrease of hand skin temperature causes performance loss.

For materials with high contact coefficients, tissue damage would usually result before manual dexterity is severely affected. However for materials with lower contact coefficients it is possible that severe decreases in dexterity would be experienced before tissue damage.

c) *Sticking*: The results of sticking measurement show that: i) dry finger do not stick on cold metals, even when it is covered by a thin ice layer; ii) wet/moist skin starts to stick on cold metal surface when its temperature reduces to below –5 °C; iii) sticking force increases steeply when the temperature of cold metal decreases to -10 °C; iv) between -10 and -20 °C the sticking force did not change markedly.

3 Modelling

Using an analytical model, cooling curves can be simulated of a large range of individuals at different temperatures and at different materials. The advantage of an analytical model is that it can lead to the identification of important parameters in the process and a better understanding of the process (i.e. contact cooling). In this way the reliability of extrapolations can be largely improved.

For an optimal fit of the simulation to the cooling curves, the parameters had to be adapted to each condition (material and temperature). This method served as an aid to describe the most important features of contact cooling at different temperatures and at different materials, without actually measuring all of them.

The analytical model may be used to generate safety margins for a variety of materials at a large range of temperatures. This was achieved by using an ‘average’ model that fitted the fastest cooling rates that were measured. These parameter values may be used to predict cooling curves and set safety limits at different temperatures and materials, as the times to reach 15°C, 7°C or 0°C can be computed for any material at any temperature.

The results of the overall picture concluded that the model in its current state can well be used to predict the worst mean cooling responses observed. The model tends to follow the mean response rather than the ‘worst’ responses.

4 Instrumentation

The cooling behaviour of an electrically artificial finger is similar to that from human fingers when touching on the cold metallic surfaces. However, it is inappropriate for the case of the non-metal. The cooling behaviour of human finger on extremely cold surfaces (lower than –20ºC) can be simulated by an electrically heated, artificial finger model. Further studies on touching cold non-metallic surfaces under very cold conditions (lower than –20°C) are needed.

5 Database

The database for touchable cold surfaces based on the experimental data is useful and informative for the protection of finger/hand in cold operations. Recommended safety contact time for the contact temperature to reach different criteria of finger contact cooling has been statistically derived from the database. A more rapid reduction of contact temperature occurred when finger/hand contacted cold metallic surfaces, compared to the non-metallic surfaces. The contact temperature reduced with the surface temperature of the material. The human finger is able to touch the cold metallic surfaces only for less than 2-6 seconds at –15 °C and for less than 5-15 seconds at
–10 °C.

The duration of permissible cold contact has been found to correlate well with the surface temperature and the thermal penetration coefficient of the material. The non-linear empirical models based on the database of lower quartile (75 % of the population protected) was able to estimate the finger contact cooling of a large range of individuals on the cold surfaces.

6 Draft proposal for standard

Determination of the contact time for critical temperature limits is useful and informative for the protection of finger/hand in cold operations. Recommended contact time for different cooling criteria for design of work station and hand tools is proposed. The document is prepared as a draft standard proposal for cold touchable surfaces

The document provides 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. The standard will be applicable to the healthy hand/finger skin of adults (females and males).

Summary

Holmér I, Geng Q, Havenith G, Hartog E, Rintamäki H, Malchaire J & Piette A. (2003) *Temperature limit values for cold touchable surfaces*. Arbete och Hälsa 2003:7

The aim of the project was to find and compile information on human responses to contact the cold surfaces. The work has covered 1) literature search and field study; 2) experimental studies with human subjects; 3) simulation by mathematical modelling; 4) development of an instrumentation for predicting contact temperature limit, 5) creation of database and 6) preparation of draft proposal for a standard to establish temperature limit values for cold touchable surfaces (CEN TC122/WG3).

The field study in food processing industries has showed that the cold hazards in hands, especially fingers, often occur. The reason for this is hand/finger contact frequently with cold surfaces and cold material. The experimental results with human subjects indicate that a more rapid reduction of contact temperature occurred when finger/hand contacted metallic surfaces, compared to non-metallic surfaces. The reduction in contact temperature is a function of skin- and material surface temperature, thermal properties of the skin and materials and the nature of the contact as well. Manual performance (tactile sensitivity/finger dexterity) reduced after gripping the cold rods for 10-20 minutes. A decrease of the hand skin temperature causes the performance loss. The safety criteria for contact temperatures are suggested to be 0 °C (imply risk for freezing cold injury), 7 °C (risk for numbness) and 15 °C (risk for pain sensation). An analytical model was developed based on the experiments with human subjects. In addition, an electrical heated finger model was developed and used to simulate the cooling reaction of human fingers when touching extremely cold metallic surfaces (<–20°C). All data were used to establish relations between contact temperature, contact time and material used. The cooling curves correspond to the reaction of a person at 75th percentile. The relations are shown for the three criteria mentioned above. The results of the project have been issued in a database. A proposal to European standardisation has been prepared and presented for CEN/TC122/WG3. The information in the standard is applicable to all fields where temperature limit values for products are required, to situations when cold surfaces cause a risk of contact cold injury and as guidance for safety design of workstations and hand tools that are used in the cold.

Sammanfattning (Summary in Swedish)

Holmér I, Geng Q, Havenith G, Hartog E, Rintamäki H, Malchaire J & Piette A. (2003) *Temperaturgränsvärden för beröring av kalla ytor.* Arbete och Hälsa 2003:7

Syftet med projektet var att söka och sammanställa information om människors reaktioner vid kontakt mellan en kall yta och bar hud. Arbetet har innefattat 1) literaturgenomgång och fältstudie , 2) experimentella studier med mätningar på människor, 3) simulering med matematiska modeller 4) utveckling av ett mät-instrument för bestämning av kontakttemperatur, 5) tillskapandet av en databas, 6) framtagandet av förslag på en standard för bestämning av temperaturgränsvärden för beröring av kalla ytor (CEN TC122/WG3).

En fältstudie inom flera livsmedels industrier har visat att händerna, särskilt i fingrarna ofta blir kalla. En vanlig orsak är frekvent kontakt med kalla ytor och material. De experimentella resultaten med försökspersoner indikerar en snabbare reduktion i kontakttemperatur när finger/hand kommer i kontakt med kalla metall-ytor jämfört med andra ytor (som till exempel sten, nylon och trä). Fallet i tempe-ratur var en funktion av hud- och materialytornas temperatur, materialens och hudens termiska egenskaper samt och kontaktbetingelserna. Händernas känsel och fingermotorik minskade efter 10-20 minuters grepp om en kall cylinder. En nedgång av hudtemperaturen är en orsak till denna effekt . Som kriterier för kontakttemperatur har föreslagits 0 °C (innebärande risk för kylskada), 7 °C (risk för känselbortfall) samt 15 °C (risk för smärtupplevelse). En analytisk modell utvecklades baserad på de faktiska experimenten med personer. Dessutom tillverkades en uppvärmd fingermodell för att användas för att simulera ned-kylningsreaktionen vid kontakt med extrem kalla metallytor (<-20 °C). Med hjälp av modellen och dessa data har generella samband mellan kontakttemperatur, kontakttid och material tagits fram. Kurvorna motsvarar reaktionen hos en person i den 75:e percentilen. Kurvorna anges för de tre ovan redovisade effekt-kriterierna. Samtliga data finns registrerade och utvärderade i en databas. Ett förslag till europeisk standard har framtagits och presenterats för CEN/TK122/ WG3. Informationen i standarden kan användas i produktstandarder för att sätta temperaturgränser, för att bedöma risker i samband arbete i kallt klimat och kontakt med kalla ytor samt som hjälpmedel vid design av utrustning och verktyg som används under sådan förhållanden.

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