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Hand Cooling, Protection and Performance in Cold Environment

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To my parents and my family

献给

我的父母，
丈夫，
儿子。

耿秋清

Qiuqing Geng

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Abbreviations

a	Time constant
Al. or Alum	Aluminium
ANOVA	Analysis of variance
AVA’s	Arteriovenous anastomoses
c	Specific heat capacity ($J*kg^{-1}*K^{-1}$)
CCHE	Counter current heat exchange
CEN	Comité Européen de Normalisatuon
CIVD	Cold induced vasodilatation
clo	Unit for thermal insulation of glove, 1 clo = 1/0.155 ($°C*m^2/W$)
D	Contact duration (second or minute)
F_C	Contact factor, penetration coefficient ($(\rho*\kappa*c)^{1/2}$, $J*m^{-2}s^{-172}K^{-1}$)
Fe	Steel
Finger (A+B)	Finger with double gloving A and B
Finger (H+B)	Finger with double gloving H and B
FingL	Little finger
H	Electrically Heated glove
Hand (A+B)	Hand with double gloving A and B
Hand (H+B)	Hand with double gloving H (heated) and B
HandB	Hand Back
HandP	Hand Palm
HSD	Honestly Significant Differences
ISO	International Standards Organisation
κ	Thermal conductivity ($W*m^{-1}*K^{-1}$)
LSD	Least Significant Difference
Ny	Nylon
ρ	Density ($10^3 kg*m^3$)
q	Extremity circulatory heat input (W/m^2)
St	Stone
SWP	Semmes-Weinstein Pressure
t	Time (second and minute)
T_a	Air or ambient temperature (°C)
T_C	Contact temperature (°C)
T_{eq}	Equilibrium temperature (°C)
T_S	Surface temperature (°C)
T_{fsk}	Finger skin temperature (°C)
T_{fsk0}	Initial finger skin temperature (°C)
T_{hsk}	Hand skin temperature (°C)
T_{hsk0}	Initial hand skin temperature (°C)
TS_h0	Thermal sensation of hand before gripping cold

List of Publications

This dissertation is based on the following eight papers, which are referred to in the Roman number. The contents of the papers are presented in Appendices.

I. Geng Q, Holmér I. and Cold Surfaces Research Group (2001) Change in the Skin-Surface Contact Temperature of Finger Touching on Cold Surfaces. *International Journal of Industrial Ergonomics*, 27(6).

II. Geng Q, Holmér I. and Cold Surfaces Research Group (2000) Finger Contact Cooling on Cold Surfaces: effect of pressure. *Proceedings of 9th ICEE Ruhr 2000*, Ruhr-Univerisity Bochum, Germany, pp. 181-184.

III. Holmér I., Geng Q. and Cold Surfaces Research Group, (2001), *Temperature limit values for cold touchable surfaces. Final report on the project: SMT4-CT97-2149.* Arbete och Hälsa, submitted, Stockholm: National Institute for Working Life.

IV. Geng Q, Karlsson E. and Holmér I. (2000) Manual performance after gripping cold surfaces with and without gloves. *Proceedings of NOKOBETEF 6 AND 1st European Conference on Protective Clothing,* Stockholm, Sweden, pp. 208-211.

V. Geng Q, Holmér I. G. Welinder and T. Olsson (2001) Instrument for Measuring Finger Skin Cooling in Contact with Cold Metallic Surfaces. *Applied Ergonomics*. Submitted.

VI. Geng, Q., Chen, F. and Holmér, I. (1997) The Effect of Protective Glove on Manual Dexterity in the Cold Environments. *International Journal of Occupational Safety and Ergonomics,* Vol. 3, No. 1-2, pp 15-29.

VII. Geng, Q., Kuklane, K. and Holmér, I. (1998) Tactile Sensitivity of Gloved Hands in the Cold Operation. *Applied Human Science - Journal of Physiological Anthropology,* Vol. 16, No. 6, pp. 229-236.

VIII. Geng, Q. and Holmér, I. (1998) Hand Dexterity with Different Gloving in the Cold. *Proceedings of International Symposium on Problems with Cold Work,* Stockholm, Sweden, 16-20, November 1997.

Contents

Abbreviations

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Contents

1. Introduction and literature review

Many people throughout the globe live and work in either naturally or artificially cold environment. Manual work in various cold conditions is inevitably required. 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. Intentionally or unintentionally, a person may then suffer cold injuries from a serious local cooling. Three types of hand cooling can be identified: 1) convective cooling (hand is exposed in cold air, usually from minutes up to hours continually); 2) conductive cold exposure (a contact with a cold surface by hand/finger touching or gripping in a short period and often intermittent); and 3) radiation through heat emission to the cold objects. Although the existing international standards are at hand for the assessment of the cold hazards involved, no standard concerns the special problems of contacting cold surfaces so far. Assessment of contact cooling is thus considered necessary.

In order to protect hand in cold operations, a hand wear is ultimately used. The requirements for such a hand wear, apart from providing the hand protection, should maintain local thermal comfort and permit the retention of enough manual precision for safe and efficient work. Since the problems of the gloved hands remain crucial, numerous factors affecting manual performance indicate a need for an integrated approach to use the gloves in the cold. Thus, the manual performance of gloved hands in the cold is still an interesting research subject.

1.1 Hand structure

The hand is a complex “system”. In general engineering terms, it contains hinges, levers, pulleys, pipes, tunnels, thermostats and its own electrical systems as well as pressure, pain, and temperature sensors. It is used to grasp, hold, manipulate, and control objects to operate and position of forces.

The hand basically consists of bones, joints, muscles, tendons and skin. The percentage of skeletal muscle in a hand is relatively low. This means that little heat can be generated in the hand itself. Raman and Vanhuyse (1975) estimated its metabolic heat production under resting conditions to be about 0.25 Watts. The hand is divided into two basic areas - the fingers and the palm. According to Konz (1983), in the power grip the hand makes a fist with four fingers on one side of the held object and the thumb reaching around the other side to “lock” in the index finger (e. g., grasping hammer). The hand’s complexity is also related to its dynamic anthropmetry. The length of the back of the hand increases nearly 2.5 cm during bending and flexing while the palmed side of the hand shortens about 1.6 cm (Kennedy *et al.*, 1962).

1.1.1 Skin of hand

The hands have a total skin surface area of about 400 cm^2 (Molnar, 1957); this is about 5 % of the body surface area. The surface to mass ratio in the hand is 10 times larger than in the trunk (Hirata *et al.*, 1993). The skin of the hand has a strong capability to vasoconstriction and vasodilatation and is therefore important for thermal regulation. Hirata *et al.* (1993) illustrated this phenomenon in their recent experiment in which subjects exercised with and without occluded hands. In the occluded state, the core temperature was 0.2 °C higher due to the hampered heat transfer.

Cutaneous innervating of hand was illustrated and described by Rohen and Yokochi (1988). The skin of the little finger tip is mainly innervated by the ulnar nerve, the tip of the ring finger by the ulnar and median nerves, and the remaining finger tips by the median nerve. The ulnar nerve innervates the ulnar part of the palmar and dorsal side of the hand. The radial part of the dorsal side is innervated by the radial nerve; the radial part of the palmar side by the median nerve (Guyton and Hall, 1996).

The palmar and dorsal skins of the hand play a unique role in hand function. The dorsal skin is fine, supple and mobile allowing full flexion of the digits. The dorsal skin contains hair follicles that play a tactile role and reinforce the protection of the underlying tissues. The palmar skin, unlike the dorsal skin, is hairless, inelastic, contains sweat glands and is thicker than the dorsal skin. The skin is richly supplied with sensory nerve receptors. To facilitate uninhibited flexion, the skin contains numerous lines and creases. The skin is firmly attached to the underlying palmar fascia to permit firm gripping of objects, while the dorsal skin is freer (Cailliet, 1994).

Thermal sensations on the hand skin are related to the thermal (cold, warmth and pain) receptors and their excitation. Parsons (1993) had described the structure of human skin, which includes the hand skin. The pain receptors are stimulated only by extreme degrees of heat or cold and therefore are responsible, along with the cold and warmth receptors, for “freezing cold” and “burning hot” sensations (Schmidt and Thews, 1989).

1.1.2 Blood vessels and vascular innervation

Blood is supplied to the hand by two main arteries, namely, the radial and ulnar arteries. These arteries anatomise in the deep palmar arch and to a less extent in the superficial palmar arch (Gray, 1989). The finger arteries arise mainly from these arches. Dorsal and palmar digital arteries run parallel to the phalanges on both sides. The palmar digital arteries are the main supply vessels, the dorsal digital arteries being very small.

The veins of the hand are also divided into superficial and deep. The palmar digital veins mainly open into superficial arches and the palmar metacarpal veins into deep arches. The superficial arches continue in the cephalic, basilica and median antebrachial veins the deep arch drains into the radial and ulnar veins, which unite in the brachial vein (Rohen and Yokochi, 1988).

The blood flow is regulated by opening and closing of the arteriovenous anastomoses in the hand. When the hand is warm, blood flows into the hand where the arteriovenous anastomoses will be open. Blood flows in relatively large quantities from the arteries through the arteriovenous anastomoses to the superficial veins (Havenith *et al.*, 1995).

In the reticular substance of the pons, located in the central nervous system (CNS), a special area is designated for neural control of the circulation. This area is called the vasomotor centre. It receives inputs from the hypothalamus, which signals deviations in central blood temperature and integrates information from thermo-sensors throughout the body. Other higher nervous centres also give an input to the vasomotor centre, such as those involved in stress-reactions. The vasomotor centre sends nerve impulses to the spinal cord, where they exit via the sympathetic part of the autonomic nervous system. The vasomotor centre has a basal firing rate, which leads to a basal vasomotor tone. The vast majority of the nerves to arterial and venous vessels are autonomic, but some nerves may be sensory, for example, to subserve arterial pain (Nelms, 1963).

The postganglionic fibres arising from the three cervical ganglia mainly innervate the blood vessels of the hand. The sympathetic nerves pass through the grey rami communicants and join the mixed peripheral nerve. About 8 % of the fibres in the mixed nerve consist of sympathetic nerve fibres (Guyton and Hall, 1996).

The arterioles in the human skin are innervated by sympathetic constrictor as well as vasodilator nerves (Guyton and Hall, 1996). Capillaries are not innervated. However, sensory endings are so close that the somatic system may play an indirect role in the regulation of blood flow through the capillaries (Nelms, 1963).

The blood vessels of the hand skin are normally subjected to a high degree of vasoconstrictor tone, even though the subject is comfortably warm. Johnson *et al.* (1995) indicated that active vasodilatation occurs in the back of the fingers and hands. The mechanism of active vasodilatation is still subject to debate. Kellogg *et al.* (1995) showed that cutaneous active vasodilatation is mediated by cholinergic nerves co-transmission. Although cholinergic sympathetic pathways are involved, the responsible neurotransmitter is still unknown.

1.2 Hand performance

Hands are important instruments carrying out all kinds of work in daily life of human since hands have a unique combination of tactile sensibility, discrimination, mobility, and exquisite dexterity. In conjunction with speech, hand function dominates mankind’s cerebral cortical function. Convenient function of the hands is determined by several physiological parameters such as reaction time, sensibility, force and mobility. The physiological parameters in turn are influenced by environmental factors, which mainly include air temperature, radiant temperature, humidity and air velocity. In general, hand performance includes mainly the manual dexterity, tactile sensitivity and force capability.

1.2.1 Manual dexterity

Manual dexterity is defined as a motor skill that is determined by a range of motion of arm, hand and fingers and possibility to manipulate with hand and fingers (Heus, Daanen and Havenith, 1995). Fleishman and Hempel (1954) identified the following five basic factors that go to make up overall manual dexterity: 1). *Finger dexterity* involves ability to co-ordinate finger movements in performing fine manipulation. 2)**.** *Manual dexterity* represents an ability to make skilful arm and hand movements without fingertip involvement. 3). *Wrist finger speed* is identified as requiring rapid wrist flexing and finger movements. 4). *Aiming* is defined as an ability to perform quickly and precisely a series of movements requiring eye-hand co-ordination. 5). *Positioning* is the final factor described but is the least well understood. It appears to come into play when precise movements are undertaken as a single localised discrete response. This difference from the aiming involves a movement of the hand from one position to the other.

1.2.2 Tactile sensitivity

Tactile sensitivity is a collective term convening a number of specific sensitivities, which is localised in the skin (Heus *et al.*, 1995). Sensitivity or feeling is not limited to the skin surface, but is also present in deeper structures. That is why there is a differentiation between surface sensitivity and deep sensitivity. Functionally, a distinction is made between somesthesia (body feeling), statesthesia and kinaesthesia (position and motion feeling). The receptors of position and motion feeling are mainly localised in joints and ligaments. These receptors give information about the position and movements of hands and fingers in their environment, while the surface receptors give information about the texture of the material of the object (Bernards and Bouman, 1977). Tactile sensation and discrimination are important to ensure precise, dextrous motor activity of the hand. The skin plays a major role in this function (Cailliet, 1994).

1.2.3 Force capability

Force capability of the hand is mainly determined by a force, which can be developed by the muscles of the upper and lower arm. The maximal force that can be delivered is related to the number of fast-twitch muscles fibres and short time-to-peak tension of maximal isometric contraction of the fast-twitch muscles fibres (Heus *et al.*, 1995).

1.3 Effects of cold

Cold means a constant risk of losing thermal balance. Cold stress is defined as a thermal load on the body under which greater than normal heat losses are anticipated and compensatory thermoregulatory actions required maintaining the body thermally neutral. Cold stress - general expression of an uncompensated tissue cooling caused by the aggregate action of physical, climatic factors (Holmér, 1993). Objectively, the cold load is determined by an interaction of several climatic factors that create a motive force for the emission of heat from the body. The resultant thermal emission is determined by the actions taken, consciously or unconsciously, by the individual, such as the choice end adaptation of clothing, protection and exposure time (Parsons, 1993).

The extremities such as hands, specially fingers, have a surface area that is very large in relation to their volume (Williamson *et al.*, 1984), they are in frequent contact with cold surfaces, compared to other parts of the body. When a person is exposed to the cold and his metabolic rate is insufficient to maintain a positive or neutral heat balance, the body will be cooling down, which leads to a reduction in blood supply to extremities and causes “physiological amputation” with extremity cooling (Havenith *et al.*, 1995). A decrease in skin blood flow causes a loss in sensitivity and a reduction in manual dexterity and grip strength (Parsons, 1993; Vincent *et al.,* 1988). Manual performance loss will result in inefficient work, an increased number of accidents and different types of complaints (Enander *et al.*, 1979). Furthermore, wind chill or contact with cold objects can give rise to cold injuries (Holmér, 1997). Therefore, the hands/fingers are among the most probable locations for cold stress related to thermal discomfort and injuries rather than other parts of the body.

1.3.1 Cold induced vasoconstriction

A strong vasoconstriction in the skin of the hand that is in contact with cold materials is observed in the first minutes of cold exposure. Ducharme and Tikuisis (1991) observed that an effective insulation of the forearm muscles increased manifold during cold exposure due to vasoconstriction in this tissue. This strong vasoconstrictor response in skin and muscle is caused by several factors. The most important mechanism is a reflex excitation of vasoconstrictor fibres (Folkow *et al.,* 1963). The thermoceptors in the cooled skin transmit afferent signals to the thermoregulatory centre in the brain. The centre increases the vasomotor tone and transmits signals to the periphery by the sympathetic nerves. Increased sensitivity of the vascular smooth muscle cells to norepinephrine may contribute to the neutrally mediated vasoconstriction (Shepherd and VanHoutte, 1981). The α_2-receptors, located in the vessel muscle wall are most important. Ekenvall *et al.* (1988) showed that the cold induced vasoconstriction was completely abolished after administration of the α_2-adrenoceptor antagonist rauwolscine.

The cold can also act directly on the smooth muscle surrounding the blood vessels (Keatinge, 1970). The local blood flow is not only affected by the vascular lumen but also by the intrinsic properties of the circulating blood.

1.3.2 Peripheral circulation

Circulation through capillaries and arteriovenous anastomoses (AVA’s)
Normally, a connection between the arterial and the venous circulation is brought about by capillaries. In some parts of the human body such as fingers, lips, cheeks, nose and elbows, direct connections between the arterial and venous network were found by Hale and Burch (1960). These connections are called arteriovenous anastomoses (AVA's). Grant and Bland (1931) found a relation between the number of the AVA's in a body part and the occurrence of cold induced vasodilation. Since this discovery, some researchers (Livingstone *et al.*, 1989a) have stressed the importance of the AVA’s for local temperature regulation. Solid evidence, however, is hard to find because blood flow through the AVA's can not be measured in a simple way. The circulation pattern thus can be changed by a different distribution of blood flow through the AVA's and capillaries. Since the AVA's have a relatively large diameter, the total blood flow in that skin part will increase, and so will the heat transfer to the surrounding tissue and eventually the environment.

Counter current heat exchange (CCHE)
The CCHE means that two adjacent vessels with opposite direction of blood flow interchange heat. The CCHE in humans was first described by Bazett *et al.* (1948) who determined the temperature of the blood inside the radial artery. The contribution of the CCHE to the reduction in heat loss has been mainly investigated with analytical models. Those analytical models show some conflicting results due to differences in the assumptions.

In the skin, the arterial and venous vessels are rather close. However, a difference in temperature between these vessels is so small that almost no CCHE occurs, even though the heat transfer surface is large. Song *et al.* (1987) considered micro-vessels as insignificant in this respect when their dimensions are less than 50 µm. According to Jiji *et al.* (1984), the thermally significant countercurrent arteries and veins are located in the deep tissue (more than 4 mm under the skin surface) and are 50 to 300 µm in diameter. In this area, a combination of vessel length and distance between arterial and venous vessels is optimal for the CCHE. Jiji *et al.* (1984) stressed the influence of the CCHE by pointing at a small arteriovenous temperature difference of only 0.1 to 0.2 °C, while a difference between the temperature in the major supply vessels and the skin temperature amounts to 5-10 °C. Hence, effective rewarming of the blood must have occurred on its way back to the heart.

Raman and Roberts (1989) estimated that the effectiveness of the CCHE in reducing heat loss had a maximum of 30 % at a hand temperature of 25 °C.

1.3.3 Reflex vasodilatation

When one hand is in contact with cold surfaces, the blood flow in the hand is influenced by what happens in other parts of the body. If heat is applied to another part of the body, such as a leg, the vessels in the hand open up and the hand gets warm. This phenomenon is called reflex vasodilatation (Gibbon and Landis, 1932). Sensors in the skin react to the external stimulus and transfer information to the vasomotor centre. This centre integrates the information and sends an adequate response to the effect organs. Pickering (1932) showed that blood temperature also plays an important role in this mechanism. He found no reflex vasodilatation when the venous return of a heated hand was blocked.

Reflex vasodilatation and vasoconstriction are also noted during a hunting reaction. Immersion of the feet in cold water during the hunting reaction in fingers reduced the magnitude of the hunting reaction (Keatinge, 1957). Werner (1983) shows that reflex vasodilatation or constriction not only depends on the skin and core temperatures but also on the rate of change of these temperatures.

1.3.4 Cold induced vasodilatation

When extremity is exposed to a cold environment, the blood vessels in the skin initially constrict in order to prevent heat loss to the surroundings. In a severely cold environment, such as exposure to freezing air, the vessels open up again after about 5 to 10 minutes. This is called cold induced vasodilatation (CIVD). A common teleological explanation of this phenomenon is that it prevents the occurrence of local cold injuries and maintains sufficient dexterity. In the literature, the term CIVD is also often used in a similar meaning as the hunting reaction (Lewis-reaction), i.e., it includes the vasoconstriction phases (Lewis, 1930; Purkayastha *et al.*, 1992). In the review of Daanen (1997), the hunting reaction refers to the vasodilatation and vasoconstriction phases during cold exposure and the CIVD is limited to the vasodilatation phase during cold exposure. Daanen (1997) has extensively reviewed these factors which include body temperature, cooling medium (air vs. water), acclimatisation or acclimation to cold, cold resistance training, hypoxia, sex, age, diet, alcohol, mental stress and pathology.

Rintamäki *et al.* (2000) summarised the hand temperature response during cold exposure, which can be distinguished in several phases such as a) initial cold vasoconstriction, b) the CIVD, c) vasoconstriction, d) hunting reaction and e) final vasodilatation.

1.3.5 Cold impairment on manual performance

The subject on the decrements in manual performance in the cold environments has extensively been studied for years (Mackworth, 1953; Dusek, 1957; Clark and Cohen, 1960; Morton and Provins, 1960; Provins and Clarke, 1960; Provins and Morton 1960; Clark, 1961; Schiefer *et al.*, 1984; Hues *et al.*, 1995). The results obtained from the early studies in this field have proved that hand cooling is one of major contributors to the reduction of manual performance. A significant relationship between hand/finger skin temperature (T_{hsk}/T_{fsk}) and the performance were found. However, the actual at which different grades of impairment occur varies with some factors such as type of task, duration and condition of cold exposure as well as individual factors (Rubin, 1957; Enander and Hygge, 1990; Enander, 1998). The critical T_{hsk} for affecting the performance has been suggested to be some levels, which are corresponding to 22 -20 °C for an initial drop in manual dexterity (Schiefer *et al.*, 1984), below 16 -13 °C for a significant decrease in finger dexterity (Clark, 1961), and 8 – 6 °C for a rapid declination in tactile sensitivity (Provins and Morton, 1960).

Manual dexterity degradation

Performance tests can be distinguished from gross hand tasks to fine finger tasks. Performance decrements are larger the more the task is dependent on finger dexterity. The causes of performance degradation reduced skin sensibility, muscle function, mobility and motivation in the cold. Nerves, muscles, joints and ligaments play a role in manual dexterity (Heus *et al.*, 1995).

In human the normal range of conduction velocity of myelinated fibres is 12-120 m s^{-1} (Åstrand and Rodahl, 1986), with the highest values for the fibres in the arm. Cold can decrease a nerve conduction velocity (De Jong *et al.*, 1966; Vanggaard, 1975). At nerve temperatures below 10 °C (Basbaum, 1973; Vanggaard, 1975), there is no nerve conduction at all. As nerves are located in deeper structures except nerve endings, nerve temperature will follow skin temperature with a large delay and is unlikely to be the main cause for reduction in dexterity (Heus *et al.*, 1995).

The effect of muscle performance on dexterity can act through changes in muscle power, contraction speed or muscle endurance. The influence of exposure at low temperatures on muscle power is a change in maximal power due to a change in maximum contraction velocity and maximum force, but also a change in time to exhaustion. The contraction force of the muscle decreased strongly when the muscle temperature reduced to 28 °C (Clarke *et al.*, 1958). The mobility of the fingers is mainly determined by the mobility of the joints. Cold has an important influence on the joints. It causes the synovial fluid to be more viscous, so that movements are slower. This is called joint stiffness and when it increases, more muscle power is needed to make movements (Heus *et al.*, 1995).

Impairment on tactile sensitivity

The loss of tactile sensitivity of fingers and/or hands somewhat occurs at cold environments. According to some earlier works (Mills, 1957; Stevens *et al.*, 1977), this may be attributed to changes in the properties of the skin or to the effects on biochemical processes at nerve or receptor level. The loss of the sensitivity affects the manual performance in cold operations.

A commonly experienced effect of cold is a sensation of numbness and loss of sensitivity in the fingers. Several methods have been applied to establish how tactile sensitivity is related to cooling. Local circulatory changes in the hand affect tactile sensitivity. Thus, an improvement in discrimination threshold has been shown during the cyclic rises in hand skin temperature (T_{hsk}) accompanying the CIVD. The relationship between measurements of the T_{hsk} and tactile sensitivity is not altogether straightforward. Mackworth (1953) found that a reliable change in sensitivity occurred only when the T_{hsk} of the site tested was as low as 10-15 °C, but close inspection of his curve does indicate a considerable loss in sensitivity at the T_{hsk} between 20 and 15 °C. Provins and Morton (1960) believed that a finger skin temperature (T_{fsk}) of 6 to 8 °C is critical and results in a sudden loss of neural activity in the affected part and thus accounts for the L-shaped function of numbness in relation to the T_{fsk} Also, tactile discrimination at a certain T_{fsk} tends to be better if the hand is in the process of being cooled than if it is being re-warmed. These observations suggested that tactile sensitivity is more closely related to the slowly changing temperature of deeper tissues. Fox (1967) indicated that while there appears to be a strong relationship between ambient temperature and finger numbness, it is ultimately the temperature of the extremity itself, which affects tactile discrimination.

1.3.6 Cold injury

Hands are anatomically and physiologically highly susceptible to heat loss in the cold (Van Dilla *et al.*, 1949). The extremities and, in particular, finger and toes are impressionable to cooling. This is because: 1) the unfavourable surface to mass ratio of human extremities these parts suffer exceptionally high rates of heat loss (Holmér, 1991; Williamson *et al.*, 1984); 2) extremities have little local metabolic heat production due to their small muscle mass and this falls with tissue temperature; 3) the heat balance of extremities are greatly dependent on the supply of heat carried by the bloodstream, but this heat supply is diminished in the cold; and 4) hands/finger touching cold objects soon become cold due to contact cooling by cold surfaces. In addition, skin contact with very cold metallic surfaces even for a very short duration can result in tissue damage.

A cold injury on hands may develop when heat losses from the tissues override the thermoregulatory capacity and temperatures fall to levels, where damages to systems and cell occur (Hamlet, 1988; Wilkerson *et al.*, 1986). Local cold injuries can include two main types:,

a) non-freezing cold injuriy; these occur when tissue temperature is below 10-15°C for longer periods; damage may occur to structures of cells and tissues;

b) freezing cold injuries; these occur when tissue temperature is below 0 °C; they are classified in superficial, when only the outermost layer of the epidermis is hurtand deep injuries, when tissue layers below the skin get solid frozen (Holmér, 1997).

Rintamäki and Rissanen (2000) investigated the effect of cold metallic surfaces on finger sticking. They found that dry fingers do not stick on metal, even when it is covered by a thin ice layer, while wet skin starts to stick on metallic surfaces when its temperature decreases below –5 °C.

Poor physical fitness, insufficient intake of fluids and food, fatigue, alcohol and smoking are factors that may contribute to the development of cold injuries. Poor knowledge, experience, bad equipment and insufficient wear are also important factors predisposing for the cold injury problems during a cold exposure (Holmér, 1994).

It is important to consider that cold injury to the hands can occur during work outdoors in cold climates or work indoors in cold storage areas. The extremities are more affected in the cold exposure, compared to other parts of the body. The cold injury can result in frostbite fingers or potential vibration injury syndromes, and it can aggravate pre-existing arthritic conditions. Cold injuries to the hands often result in a lessening of manipulative skills of fingers. Cold injuries to the extremities, not body core cooling, is a greater risk for women working in the cold. The geometry of women's thinner extremity results in a greater heat outflow for the same circulatory heat input per unit tissue mass. Their enhanced peripheral vasoconstriction further inhibits their ability to maintain safe skin temperature (Burse, 1979).

1.4 Assessment of cold stress

Assessments of cold stress have been studied both by physiological measurements such as heart rate, skin and core temperature and subjective perception (e.g. thermal and pain sensations). Cold stress and risk assessment strategies have been presented and discussed by some researchers (Afanasieva, 1998; Conway *et al.,* 1998; Holmér, 1998; Keatinge, 1998; Parsons, 1998; Rintamäki *et al.,* 1998; Tikuisis, 1998). Methods for assessment of cold stress are given in ISO Technical Report 11079 (ISO/TR-11079, 1993) and other standards (ISO-8996, 1990; ISO/DIS-9886, 1992; ISO-9920, 1993). In addition, Parsons (1993) has guided an example of the application of international standards for the assessment of cold stress.

This section only presents some methods for measuring local cold stress; e.g. skin temperature and subjective scales, and the results in terms of hand cooling and its relation to thermal and pain sensations in various cold environments.

1.4.1 Skin temperature measurement

During cold exposure, the measurement of temperature at various skin sites provides information about cooling rate on various body surfaces. Mean skin temperature is a common physiology parameter of interest for the evaluation of thermal balance and cold stress in the cold environment (Nielsen *et al.,* 1984). In practice, only skin temperature is measured to assess the degree of cooling (Enander, 1984). The skin temperature is commonly measured with sensors (thermistors and thermocouples) taped to the surface. The sensors should be small and in good contact with the surface to eliminate influences of the ambient conditions, particularly under extremely cold conditions. The calibration and location of the sensor, selection of thermocouple and record time interval, etc. are technical effects on the measurement of the skin temperature. The choice of data acquisition with time interval of one minute can be used for the measurement of skin temperature in convective cooling. In the case of conductive cooling, the data acquisition should be as quick as possible for the record of the rapid drop in skin contact temperature of the bare hand contacting cold surfaces, especially with metals.

1.4.2 Assessment of subjective responses to cold and pain

Thermal sensations obey the same psychological law as many other sensory modalities such as loudness, brightness, etc. (Stevens, 1960). Knowledge of changes in cold sensation and pain during longer exposures of large areas of the body is mainly based on work using category-rating scales with semantic definitions (Teichner, 1967). Scaling thermal sensation and pain is more difficult than scaling perceived exertion. A number of subjective judgement scales with various points are used for the rating of thermal sensation. Most of the results obtained from the subjective responses have showed decimal points in the scales (e.g. 0.5, is a feeling between no pain and slight pain). Borg (1998) described “extremely strong-Max P”, which is useful to imagine the strongest pain feeling. However, it seems that the subjects may not easily follow the instruction to rating pain under short period of cold exposure. Up to now, none of the standards deal with the rating scale of pain.

Several studies reviewed by Enander (1984) have indicated a psychological adaptation among cold-accustomed individuals, resulting in reduced pain and cold sensations. However, the data of subjective response is ambiguous due to individual tolerance levels and other influences. People also differ in their previous experiences of cold and pain. Therefore, the instruction must be illustrated in some detail before measurement of subjective responses. The examiner must devote adequate time to explain what the subject is going to rate and how it is going to be done, and so forth. The subjects must understand that it is his/her perception or subjective feeling that he/she shall attend to and not the physical task or the psychological cues (Borg, 1998).

1.4.3 Relationship between finger skin temperature and subjective response

Some earlier studies indicated that people showed more sensitivity to decreases in temperature than to increases. The most cases of exposure in the cold reported the pain in the extremities such as hands and feet, particularly in fingers and toes. Under more extreme cold exposure, pain is induced. A comparison between studies of sensation is difficult due to different methods of cooling. Most of studies on this aspect reported a relationship between the cold exposure duration and either the skin temperature or subjective responses to the cold, respectively. In addition, there appears also a relationship between the skin temperature measured and the subjective responses to thermal or cold induced pain (Stevens and Marks, 1979). It was indicated that cold and pain sensations depend both on the size of the local area cooled and on the amount of cooling. The relationship between skin temperature and thermal cold sensation and pain on hands/fingers has been a subject of a limited number of studies. It is thus necessary to collect more data for the exploration of such a relationship.

1.5 Models of extremity cooling

In the literature different approaches for modelling extremity cooling have been developed. They are often related to the nature of the research problem in the specific studies. They can be classified into:

1) empirical models;
2) analytical models.

Overviews of the various models of extremity cooling for the both cases have been presented (Rintamäki *et al.*, 2000). For models of extremity cooling, the relevant parameters are:

1. Metabolic heat production in the simulated tissue.
2. Circulatory input to the tissue.
3. Counter current heat exchange.
4. Geometric layout.
5. 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.
6. Application medium (air, water, contact).
7. Clothing.

Within the Cold Surfaces research projects two models for contact cooling were derived (Paper III). For finger and hand cooling the model of Shitzer *et al.* (1996) represents a high level of complexity where all important factors were considered. Goldman has proposed a simple heat balance model, that handles the most critical factors: initial finger skin temperature, heat input, glove insulation, time constants of tissues and ambient climatic conditions (Goldman, 1994).

1.6 Gloves used in cold operations

A pair of hand wear suitable for cold operations that both maintains local thermal comfort and permits the retention of enough manual precision, may improve the hand effort and capability in work and increase the efficiency. Also, some important factors to consider in selecting a hand wear are shape, fit and fabric (Litchfield, 1987).

1.6.1 Hand wear against cold

Cooling of the hand has been implicated as a cause for reduced endurance time and loss of manual performance during cold operations. Thus, the thermal insulation of gloves used in the cold should be firstly considered. Elnäs and Holmér (1983) investigated the thermal insulation of hand wear with an electrically heated hand model. They measured the heat transfer coefficient for nine winter mittens compared with measurements on the naked hand. It was considered that the gradient to ambient air in resting air must not exceed 5 ^{o}C for the bare hand and 17 ^{o}C for the best mitten to obtain thermal balance in the hand. Otherwise, the hand skin temperature will be decreased to a lower equilibrium temperature.

To protect hands against the cold gloves and mittens are most often used. Gloves cover each finger individually whereas mittens cover the fingers as a group. Therefore, gloves have more surface area to lose heat and one finger cannot warm another finger. If finger dexterity is not needed, mittens with liners are better than gloves. If finger dexterity is needed, airtight, close-fitting gloves are satisfactory for moderate cold. For more severe weather, a multi-layer approach is desirable, with knit gloves inside and a warm mitten outside. The mitten should extend past the wrist. Important design features require that they are "easy-off" and that they can be attached to the coat with a cord. Wearing gloves and mittens can strongly reduce the risks of skin freezing during cold air exposure and contact with cold objects. However, there are no gloves or mittens capable of maintaining hands warm in severe cold when metabolic rate is low or when heat supply by bloodstream abates (Enander, 1991; Holmér, 1997). A questionnaire survey on the use of protective gloves in the cold conducted with workers in 7 different industries in the northern Sweden revealed that thermal discomfort, performance decrements, limitations on hand and finger movement and bad fit of the gloves were significant problems (Abeysekera, 1992). The same problems of wearing winter glove were reported (Gavhed *et al.* 1999) from a questionnaire survey and a set of field measurements concerning cold problems for occupational work outdoors in winter (e.g., harbour workers, telecommunication technicians, mast workers and customs personnel). It is also important to be aware of the possible side effects of using protective gloves in cold climate. From the viewpoint of ergonomics, the safety gloves for work in the cold should be designed to optimise the manual performance without compromising a good thermal insulation and wearability factors. If heat loss becomes excessive, the circulation to the extremities is rapidly cut off and the cold is first felt in the hands. Once this happens, one cannot get warm by putting on warmer gloves (Renström, 1997).

Furthermore, the physiology, anatomy and anthropometry of the hand, comfort and even appearance in glove design should be considered since an interaction between the hand and the glove affects worker performance and safety, particularly in the cold.

1.6.2 Effect of gloves on manual performance

Use of protective gloves against cold is an effective and commonly simple method. However, one major disadvantage of using gloves is the impairment of the manual performance, especially for some precision works.

A number of studies on the cold effect on tactile have been carried out, but only a few of them have dealt with glove effect. For instance, a previous work (Vaernes *et al.*, 1988) found that the tactile sensitivity of dry gloved hands was somehow decreased after 1 or 2-hour exposure at –2 °C, but a recovery was observed after 3-hour exposure. The tactual performance with wet gloved hands had a stable impairment throughout the exposure. However, there was little information on the effect of glove on the loss of the sensitivity.

Gianola and Reins (1972) compared four glove designs at ambient temperatures of 21 °C and –29 °C using dexterity and tactile discrimination measures. The results indicated that one glove design (a four-compartment configuration with individual compartments for each of three thumb, index and middle digits and a fourth compartment containing the fourth and fifth digits) appeared most promising in terms of amount of protection and dexterity. They (Gianola and Reins, 1976) also modified the four types of gloves evaluated in the previous study and compared them to the US Navy standard on mittens at low temperatures using dexterity tasks. The modifications to the gloves included added urethane foam palm and back insulation.

Rogers and Noddin (1984) studied that 24 U. S. marines performed a battery of several tasks by hands with or without gloves across a range of cold temperatures. To determine whether the decrement due to wearing gloves might be less than the decrement due to cold hands as air temperatures decreased, performance on the battery of tasks was measured with and without gloves. Only three of the tasks were affected by cold temperatures, and the amount of decrement increased as the air temperature decreased. Three tasks deteriorated due to wearing of gloves, two of those affected by cold. From the results obtained, tasks requiring finger dexterity, manual dexterity and wrist-finger speed, performance in the cold with bare hands were better than gloved, at least up to –10 °C. In other words, they concluded that finger dexterity and manual dexterity were deleteriously affected by wearing gloves in the cold.

Furthermore, Parsons and Egerton (1985) investigated the effects of nine glove designs on manual dexterity under cold conditions. The performance of each glove was measured over time. Hand and digit temperatures were also measured throughout. The results indicated that there was an interaction between the restrictive and thermal properties of the designs. All manual performances decreased in the cold. They concluded that selecting a glove in cold operations must consider both thermal effects and glove effects on manual performance. According to Abeysekera (1992), in the use of safety gloves in the cold, special problems mentioned by the respondents were that working with gloves affects their dexterity and generally the gloves lacked adequate insulation to protect their hands from the cold. Performance decrement was significant and so was limitation in hand and finger movement.

In fact, the effect of glove on the force capability is generally mixed. Reduction in grasp force when using gloves has been reported by several researchers (Hertzberg, 1955; Lyman and Groth, 1958; Swain *et al.*, 1970; Sperling *et al.*, 1980). In addition, the work on the influence of gloves on force capability have been also widely investigated in recent years (Riley *et al.*, 1985; Cochran *et al.*, 1986; Sudhakar *et al.*, 1988; Wang *et al.*, 1988; Wang, 1991; Mital *et al.*, 1991; Bellinger and Slocum, 1993). However, there has been found little research on this topic in cold environments from the literature.

2. Objectives

A reduction of hands/fingers temperature during either exposures in cold air or contact with cold objects in cold operations results in manual performance decrements, which impacts the work efficiency and increases the risk of accidents. An efficient and simple approach to solve the problems of hand cooling in cold operations is to use a hand wear. However, the use of protective gloves to minimise heat loss impairs manual functions. No ergonomic requirements for hand protectors have been ever addressed in recent standards. These issues need to be experimentally investigated and analysed based on the data of cold stress and function tests. The objectives of this dissertation thus are:

1) to find and compile information on human hand/finger cooling responses to contact with cold surfaces by touching and gripping;
2) to establish critical temperature and duration of finger/hand in contact with cold surfaces of different materials for safe and efficient manual performance;
3) to develop an ergonomics database for temperature limits on touchable cold surfaces based on experimental data obtained with human subjects and a recently developed artificial finger;
4) to investigate objectively and subjectively the effect of existing protective gloves on manual performance (dexterity and tactile sensitivity) under various cold conditions;
5) to search for an appropriate approach to use double gloving and develop/use of an electrical heating glove in cold operations; and
6) to analyse relations between physical properties of protective gloves and manual performance in cold operations.

3. Summary and discussion of experimental studies

3.1 Cooling response of bare hand to cold

3.1.1 Finger touching cold solid surfaces (Papers I and II)

Contact between bare fingers and a cold surface reduces finger skin temperature, eventually leading to pain, numbness, and manual performance decrement and even cold injury. Some effects of finger contact cooling have been studied (Havenith *et al.*, 1992; Chen *et al.*, 1994). These mainly involved properties of the cold solid surfaces, tissues of human finger skin and the conditions under which contact occurred as well. Many factors affect finger contact cooling and they interact in a complex way. These factors involve type of material, surface temperature of material, pressure, individual, gender, etc. The objective and subjective assessments of finger contact cooling are considered of importance.

In order to study finger touching various cold solid surfaces (Paper I), ten healthy subjects (five males and five females) with an average age of 26±7 years volunteered in the experiments. Experiments were carried out in a hand cooling box that was located in a climate chamber. Controlled evaporation of CO_2 was used for cooling the box. Air temperature of the box was maintained at approximately -20, -15, -10, -4, 0 and 2 °C, respectively, according to the required experimental condition. Four polished cubes made of aluminium, steel, nylon and wood with dimensions 96×96×96 mm were chosen as the contact materials. The thermal properties of the materials are listed in Table 1. The surface temperatures of the material (T_S) were from –20 to +2 °C. Thermocouples of 0.5 mm iron-constantan were connected to a computer for recording of the finger skin-surface interface contact temperature (T_C).

Table 1. Thermal properties of the materials used for the cold contact

Material	Thermal conductivity λ ($W\ m^{-1}\ K^{-1}$)	Specific heat C ($J\ kg^{-1}\ K^{-1}$)	Density ρ ($10^3\ kg\ m^{-3}$)	Contact factor (penetration coefficient) F_C ($J\ m^{-2}\ s^{-1/2}\ K^{-1}$)
Wood	0.22	2196.00	0.56	520.14
Nylon-6	0.34	1484.00	1.20	778.12
Stainless steel	14.80	461.00	7.75	7271.64
Aluminium	180.00	900.00	2.77	21183.48

The subject's left index fingertip touched a defined cube during a short period (180 seconds). Contact pressures (0.98, 2.94 and 9.81 N) were applied. During the finger touching, the T_C and subjective responses of thermal and pain sensations of the finger were recorded continuously. Contact was always interrupted when $T_C \leq 0$ °C or if the subject felt intolerable pain.

Factors influencing finger contact cooling

Change in the finger T_C versus touching duration with respect to the type of material at a pressure of 9.81 N is shown in Figure 1. The finger cooling curves have shown that the T_C dropped rapidly and then reduced gradually when touching the very cold metallic surfaces (aluminium or steel). However, a gradual variation for the finger cooling occurred as the cold surface of non-metallic material like nylon and wood was contacted. As known, the higher thermal penetration coefficient of the material, the higher the rate of heat exchange. The metallic materials have higher thermal penetration coefficient (Table 1). This essentially occurred at the interface of the finger skin-material surface-sensor. Clearly, the non-metallic materials have lower thermal penetration coefficient (or contact factor) and higher heat resistance. The emission of heat from the finger skin to the surface of a non-metallic material is much slower than to the surface of metallic materials. Havenith *et al.* (1992) analysed the observed finger cooling curves by means of the Newtonian cooling law and found that the cooling process appeared to be significantly related to the materials' contact factors. A difference still existed at lower pressures (0.98 and 2.94 N) (Figure 1 of Paper II). Also, the critical cold contact time for touching on the nylon was subjectively longer than that on the aluminium. It is apparent that the material characteristics should be one of the most important specifications for hand/finger protection in the cold. The rate of heat exchange depends on the characters of the interface, i.e. the human skin and cold surfaces. The cooling curves with different trends also indicated that the amount of heat transfer is related to the contact duration, initial temperature of the finger skin, the cold surface as well as contact pressure.

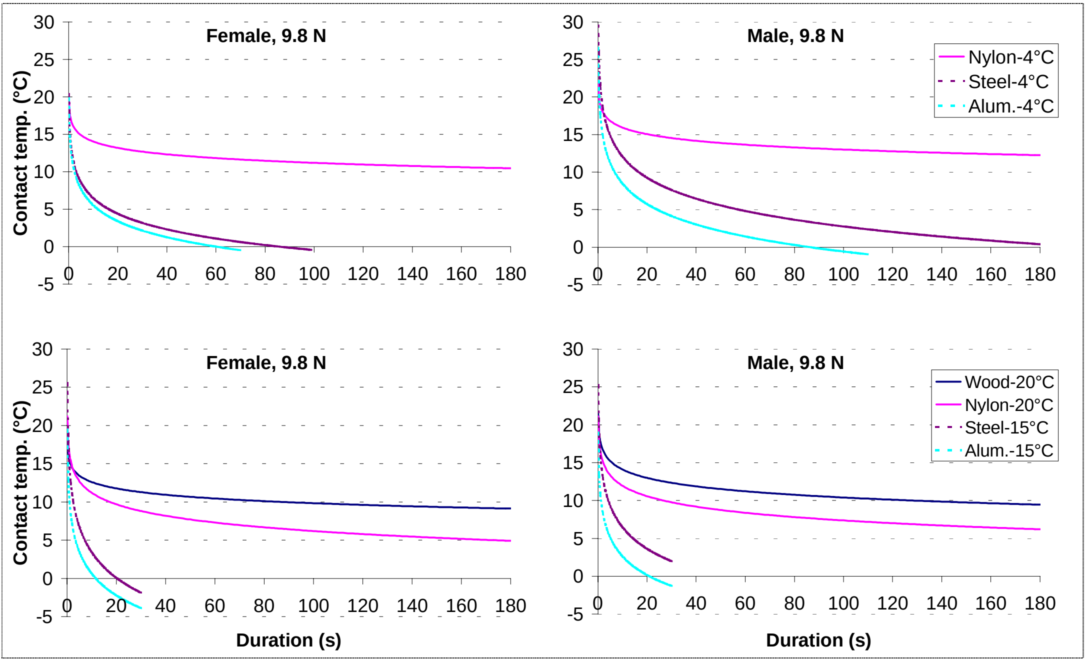

Figure 1. Contact temperature versus touching duration on cold surfaces of different materials at –4 and –15/-20 °C.

Figure 2 shows the results of the effect of T_S of aluminium on the finger cooling. It is seen that the T_S has a significant impact on the finger cooling at a higher pressure of 9.81 N. The T_C decreases with decreasing the T_S. This phenomenon also occurred at lower pressures (0.98 and 2.94 N), and for other materials such as steel, nylon and wood. The T_S of material is an important factor affecting the finger cooling on the cold surface. A rapid heat transfer from the finger to the cold surface occurred at a lower T_S. This effect is significant under various materials and pressures.

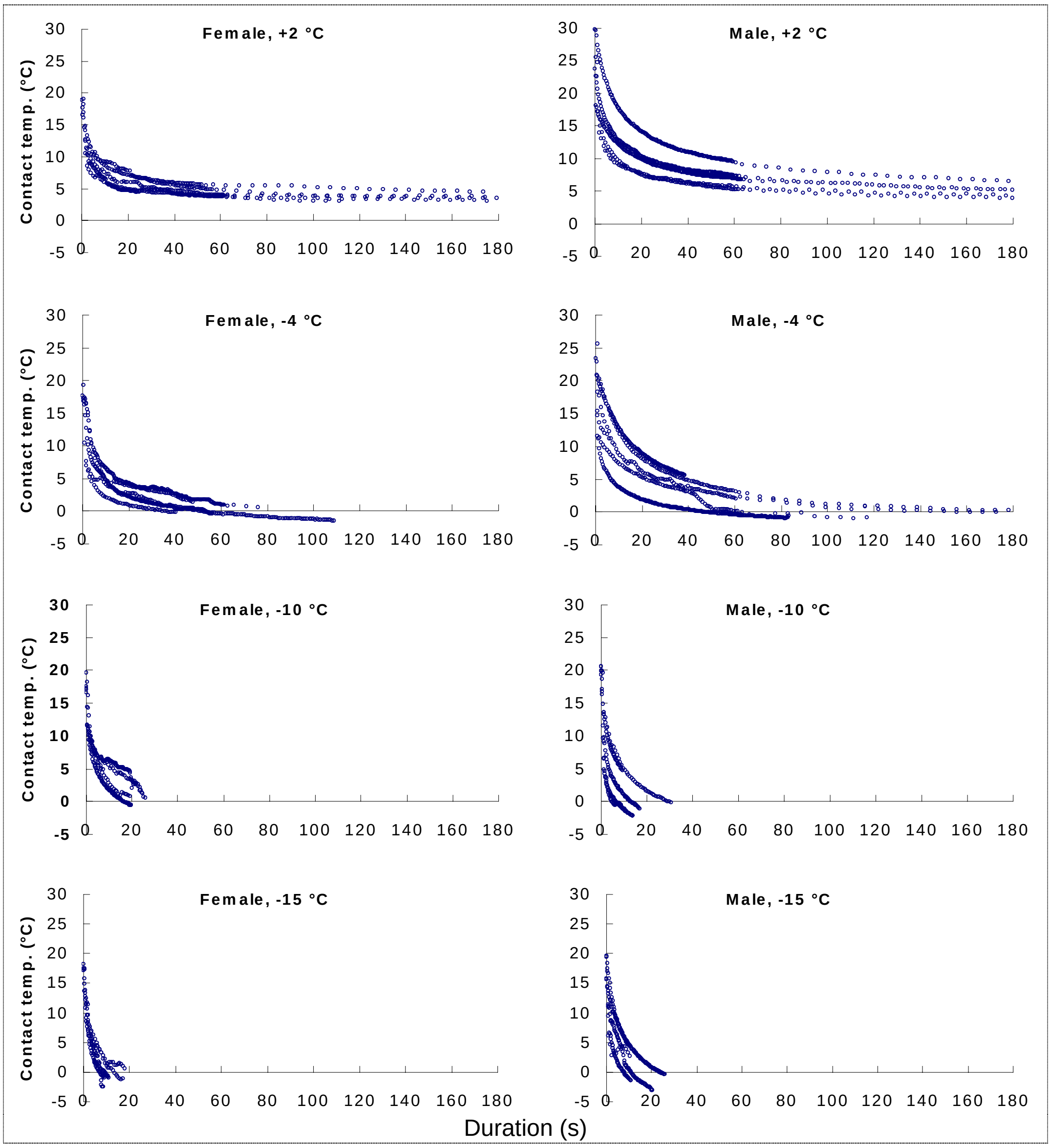

Figure 2. Contact temperature versus cold touching duration on cold surface of aluminium with a pressure of 9.81 N at different surface temperatures.

Figure 3 shows the variation of T_C versus contact time with respect to pressure level for both cold aluminium and nylon at different T_S. 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 surface of metal (aluminium), compared to non-metal (nylon). The pressure has an insignificant impact on the response of the finger cooling on the cold nylon at various T_S. As known, metallic material has a higher thermal thermal penetration coefficient. The emission of heat from the skin of finger to the cold metallic surface apparently increases with pressure. The blood flow from the hand to the finger tip might be blocked because of high contact pressures. Also, a higher pressure increases the contact area of the finger on the cold surfaces (Table 1 of Paper II), which leads to a more rapid rate of finger cooling. The rate of cooling between finger skin and the nylon surface was much slower due to its higher heat resistance. The effect becomes less significant with decreasing T_S, when touching the cold aluminium, especially at -15 °C. The overlap of the boxes indicates that there is no significant difference among the medians of the T_C at various pressures after touching aluminium at –15 °C. This may be because the very cold T_S at -15 °C, dominates over the effect of pressure on finger cooling.

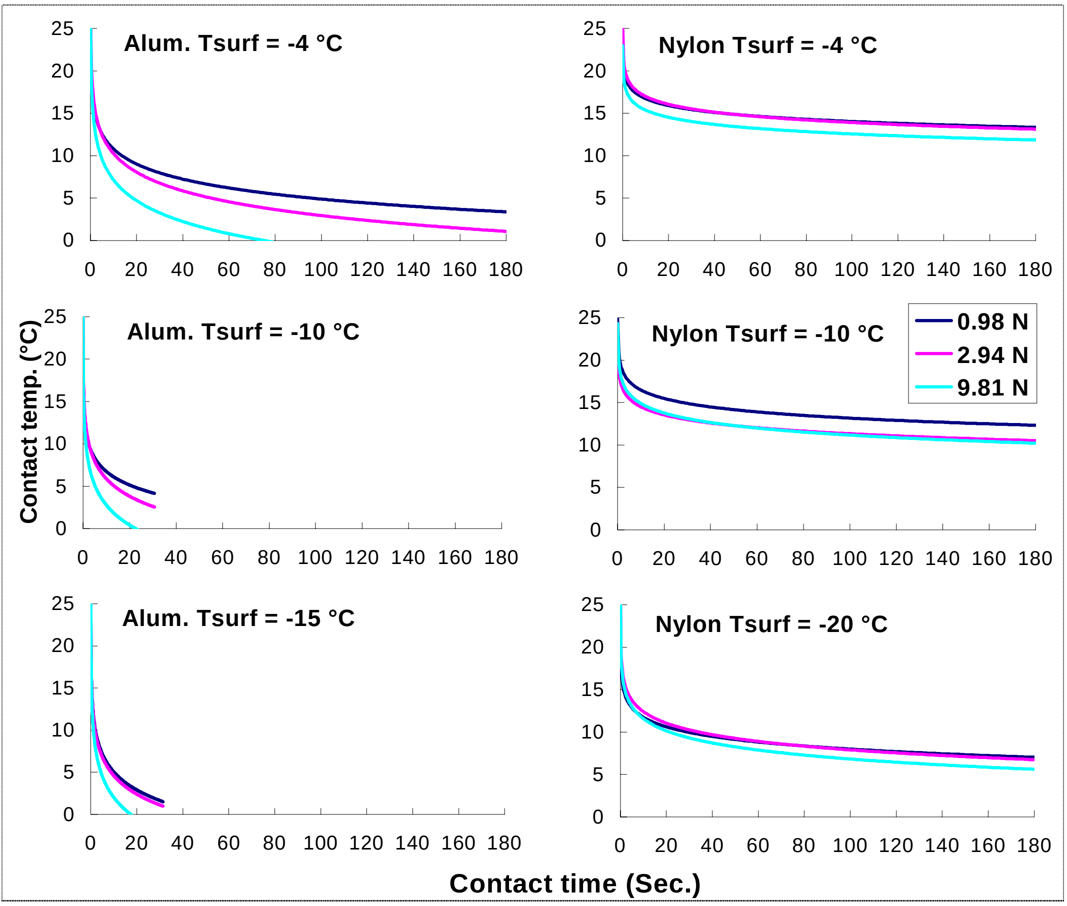

Figure 3. Contact temperature versus cold touching duration on cold surfaces of aluminium and nylon at various pressures and surface temperatures.

A significant effect of individuals on the reaction on the cold surfaces was found. The individual variability and unsteady phases could be explained as individual tissue properties of skin (such as the thickness), blood flow through the microcirculation under the skin and heat input. In addition, the initial skin temperature of the hand and metabolic rate of whole body as well as constitution (physical nature) of the contact could also affect the reaction of skin to contact cooling to some degree. During the experimental observation, a white spot on the finger with numbness feeling initially appeared at T_C close to 0 °C after a quick contact on the cold surface. The spot then became red and disappeared after a short relaxation. This phenomenon occurred for most of the subjects investigated. However, two females kept red spots that faded away after a few days. This exception may be due to the special structure of the finger with its blood vessel distributions or a lower capability of the microcirculation under the skin and heat input. Some previous studies (Havenith *et al.*, 1992; Chen *et al.*, 1994) also indicated the effect of the individual on finger contact cooling. Tissue properties, temperature at the onset of contact and heat input are important physiological factors for the contact cooling (Holmér, 1998).

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 (Figures 1 and 2). For instance, females were found to have lower finger skin temperature and be more sensitive for touching the cold surfaces than male. Pathak and Charron (1987) reported that response to cold stress in women could differ from that of men in several respects. The rate of cooling of the body core is slower in women. However, the rate of cooling of the extremities (feet and hands) is faster among women. Women are generally at a greater risk of cold injury since women have less capacity for metabolic heat production by either exercise or shivering. In addition, the resultant difference between gender is due to the different tissue properties of skin such as thickness, roughness and volume of finger. A psychological difference between cold-accustomed female and male, which causes different sensations of pain and uncomfortably cooling, may be another reason.

Model for finger contact cooling

To identify the most relevant parameters of a model for finger contact cooling, a large number of measurements have been performed. A simple model was developed to describe the cooling curves of the finger touching the cold surfaces. The schematic cross section of the seven-element contact cooling model is presented (Hartog *et al.*, 2000). Optimisation of the model parameters resulted in a close fit of the model output to the data. The optimisation was defined as the minimum of the squared differences between simulation and measurement, using a Nelder-Mead simplex method, which was performed by the MATLAB® that was 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. In this model the fingertip consists of three layers, the outer layers (“skin” and “surface”) are split into two sections, the upper section is completely exposed to air and the lower section is partly exposed to the solid. The part of the fingertip surface that is actually in contact was named effective contact area (A). Using this model the heat exchange between all components can be described and computed. If the heat supply due to blood flow is neglected, the equation has been given by (Hartog *et al.*, 2000). The validation of the model was performed using the experimental data of the touching experiments. Comparison of the model prediction to the measured data can be found in paper III.

Use of an analytical model simulates finger cooling in a large range of individuals at different temperatures and materials. In the theory of heat exchange, this five-element model of the fingertip results in a cooling curve that would be described by a sum of five exponential (Hartog *et al.*, 2000). Usually only the first two can be estimated accurately from curve-fitting methods. The advantage of an analytical model is that it can lead to the identification of parameters that are important in the process that it describes, and thus, to a better understanding of the process (i.e. contact cooling). In this way, the reliability of extrapolations can be largely improved. However, it is still impossible to identify a single set of parameter values to create a unique model with which all conditions can be simulated. For an optimal fit of the simulation to the cooling curves, the parameters had to be adapted to each condition (material and temperature). Still, this method served as an aid to describe the most important features of contact cooling at different temperatures and materials, without actually measuring all of them.

3.1.2 Hand gripping cold objects

Some hand gripping operations like handling machines, touching the handles, using tools as well as carrying objects, etc. in the cold are portion of daily work of outdoor operators. During the operation in the cold environments, the temperature of the hands is reduced due to exposure in the cold air or contact with cold objects. The previous work mainly has concerned the hand cooling due to the influence of cold air (Tanaka *et al.*, 1983; Rogers *et al.*, 1984; Daanen, 1993). It is also of importance to investigate hand-cooling response during gripping on different cold surfaces, particularly in terms of the risk of tissue damage. Thus, the hand cooling response during gripping different cold rods with bare hands in the cold.

In the study, four rods (∅40×400 mm) of different materials (steel, aluminium, stone and nylon) were selected as the gripping objects. Ten subjects (5 females and 5 males, average age of 27 year) dressed the suitable winter clothing and exposed the whole body in a cold climate chamber, which were adjusted from –20 to +1 °C to maintain equilibrium with the T_S of the rods tested. During gripping, subject rated the sensations of thermal, pain, and numbness in hand and the values were recorded consecutively. The T_C was measured at the points of the little finger and palm of the dominant hand. The gripping time depended on either extensive pain or T_C (stopped when $T_C < 1$ °C).

Statistical analysis

Hand cooling on the cold rods can be affected by 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 statistically significant effects on the final T_C, gripping time and subjective sensation among the others a multiply-factor analysis of variance (ANOVA) was utilised. The main independent variables involved the individual subject and experimental condition (type and temperature of the material). In addition, the hand skin temperature ($T_{hsk}0$) and thermal sensation (TS_h0) before gripping were selected as covariates for the ANOVA. The results of the ANOVA for each response are summarised in Table 2.

Table 2. Results of the ANOVA analysis (Samples number: 90)

10 or 5 subjects × 10 conditions				
Responses	**Main effects**		**Covariates**	
	Subject	**Conditions**	**TS_h0**	**$T_{hsk}0$**
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*	NS*
Pain at end of gripping	$p<0.001$	$p<0.001$	NS*	NS*
Numbness at end of gripping	$p<0.001$	NS*	NS*	NS*

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

The ANOVA results show that the subject factor has a significant impact on the gripping duration and subjective sensations (thermal, pain and numbness) at 95% confidence level except on the T_C at the end of gripping**.** As expected, the exposure conditions affected significantly the cold gripping duration, T_C and the subjective sensation score (thermal and pain) at the end of gripping. Also, the hand skin temperature before gripping ($T_{hsk}0$) as a covariate factor was statistically associated with T_C at the end of gripping. However, the grip duration was not significantly associated with $T_{hsk}0$. The TS_h0 did not influence any dependent variables of subjective sensation scores at the end of gripping.

Figure 4 shows a plot of gripping duration versus the experimental conditions (material type and T_S). The duration of gripping the cold aluminium and steel at –10 °C or the cold stone at –20 °C is significantly shorter, compared to that of other conditions. The shortest time for gripping was 330 seconds when gripping the cold aluminium rod at –10 °C. The longest time was 1200 seconds for the cases of cold nylon at –10 °C and the metals at +1 °C.

It was indicated that T_C at the end of gripping was significantly lower when gripping the aluminium and steel rods at –10 °C or the stone rod at –20 °C. The mean T_C was 5.4 °C for the cold aluminium at -10 °C, 9.3 °C for the cold steel at –10 °C, and 7.8 °C for the cold stone at –20°C. The mean T_C at the end of gripping the cold nylon was 15.2 °C at –20 °C and 18.2 °C at -10 °C (Table 3).

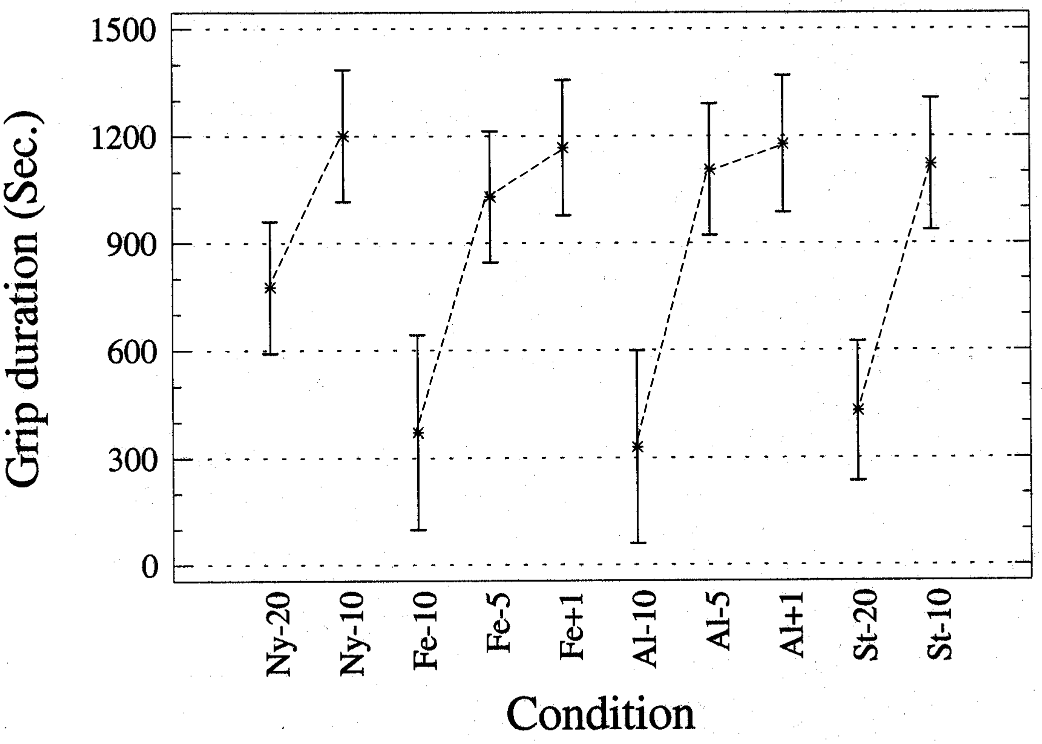

Figure 4. Mean difference of gripping duration under various conditions.

Hand cooling curves

Figure 5 indicates that T_C dropped rapidly and then reduced gradually when gripping the very cold metallic surfaces (aluminium or steel). However, a gradual decrease of T_C with gripping time occurred as the cold surface of non-metallic material (nylon) was gripped. It is indicated that the amount of the heat transfer is related to the ambient temperature (or T_S). The T_S of material is an important factor affecting the hand cooling in gripping the cold surface. A rapid heat transfer from the hand to the cold surface occurred at lower T_S. This effect is significant for various materials. It is well known that a metallic surface subjectively feels “colder” than a non-metallic surface at the same T_S. This is because people do not respond directly to the temperature of the cold surfaces, but to the temperature that the cold surfaces induces in hand skin, namely, the contact interface temperature.

Furthermore, a temporary increase in T_C occurred during gripping the cold rods. The reason may be the occurrence of CIVD. Havenith *et al.* (1995) indicated that when the hand is exposed to cold, blood flow is regulated by opening and closing of the arteriovenous anastomoses (AVA’s). The AVA’s open and blood flow through the hand increases, resulting in a temporary increase of hand temperature. Once hand temperature increases, vasoconstriction starts again with subsequently cooling of the hand. Therefore, CIVD may have a protective function against cold.

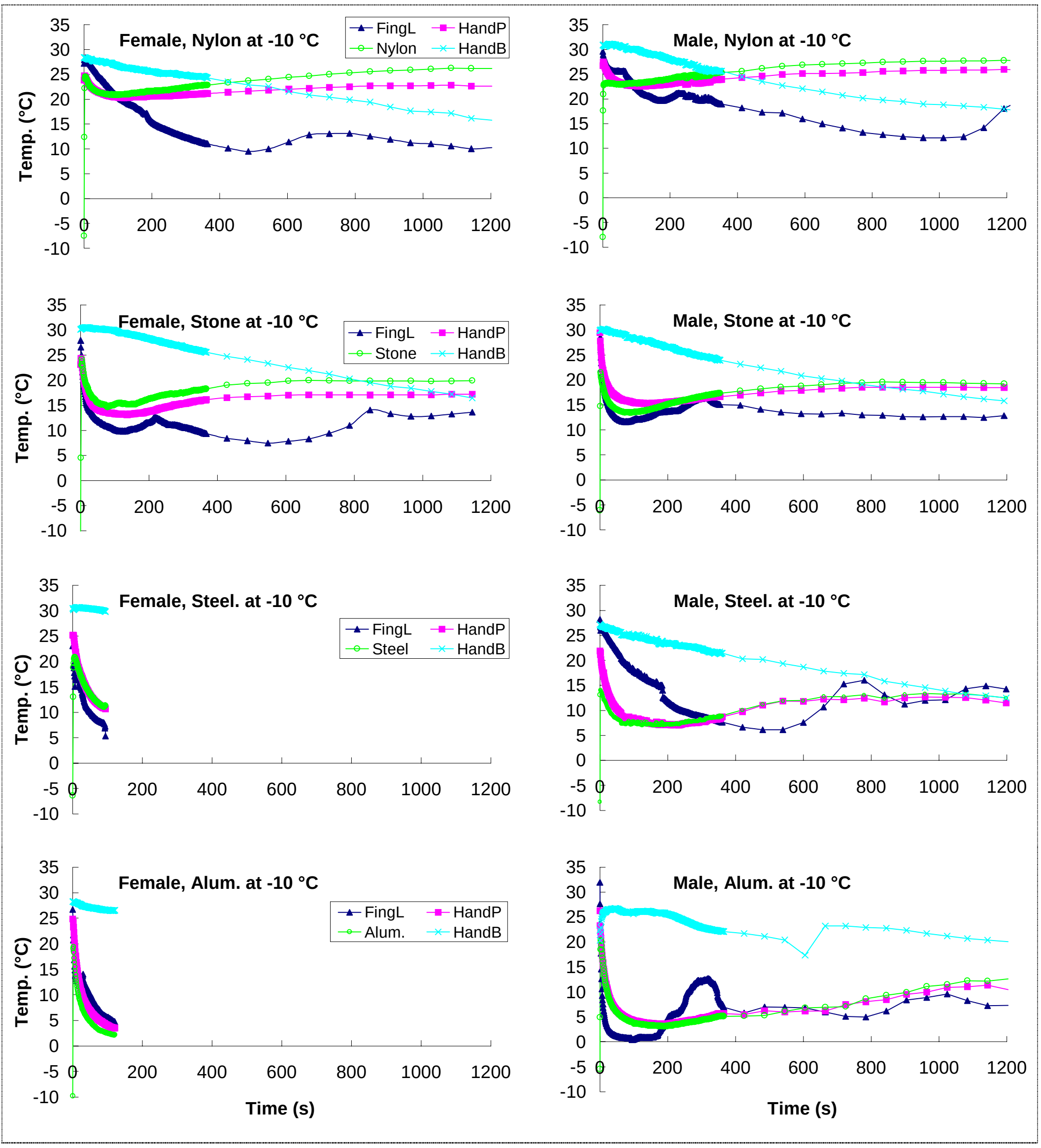

Figure 5. Contact temperature versus gripping time on various cold rods at –10 °C.

Model for hand cooling during gripping

Lotens' model (1992) was used as a basis for modelling of hand cooling during gripping. 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 experimental data and the material characteristic's data.

Furthermore, the effect of changing two parameters in the model was tested. The first parameter was hand thickness, the second vasoconstriction. In the original model the hand thickness used was 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. Figures 21-22 of paper III showed the results when simulations are compared with data for the mean contact temperature. The lowest curve (thin, vasoconstricted hand), follows the fastest cooling curves quite well, including the curve for nylon. 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 get close to the median in the data, except for nylon. Interestingly, in the original validation of the model by Lotens (1992), the simulation results for nylon were also the most deviating. Currently no cause or solution to this problem has been identified.

The present model for hand gripping cooling can be used to predict the worst mean cooling responses observed at the coldest hand locations. The model tends to follow the mean response rather than the ‘worst’ responses.

3.1.3 Comparison between conductive and convective cooling

There are two major ways of cooling the bare hands in cold operations, namely, 1) conductive cooling through contact with cold solid surfaces (the cooling of the hand is unequal); and 2) convective cooling in cold air (the heat loss of the hand to the cold air). In addition, radiation by heat emission to the colder objects affects hand cooling. Appraisement of the risk of cold injury caused by both forms of hand cooling is considered essential and necessary. Accordingly, the responses of human hand cooling either by cold solid contact or in cold air should be understood for protective purposes. Figure 5 illustrates that the T_C at the contact points (FingL and HandP) was much lower for all the cases, compared to the skin temperature of hand back (HandB). This reflects a significant difference of the skin temperature between convective and contact hand cooling.

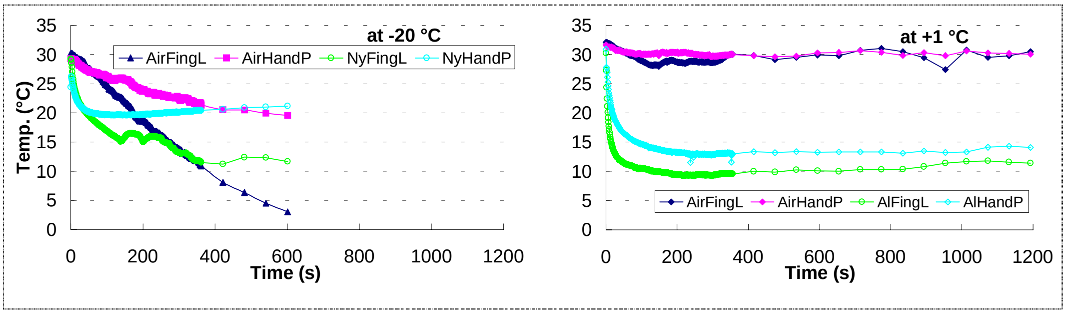

Figure 6. Comparison of hand contact and convective cooling at various surface temperatures.

A comparison of hand contact and convective cooling at various surface temperatures is shown in Figure 6. It is seen that the T_C on the cold rods is much lower than the T_C in cold air. The T_C reduced quickly when gripping the cold rods (conductive or contact cooling) rather than when gripping in air (convective cooling). This difference, however, becomes insignificant after a longer cold exposure at lower environmental temperatures, especially at –20 °C. It is also interesting to see that in the case of nylon at –20 °C the T_C became higher for gripping of the cold rods than that in the cold air after a certain exposure. This may be because the cold non-metallic material with a lower contact factor was warmed by hand, and the contact area of the warmed rod became insulating to the cold environment. T_S of the rods were close to (or even higher than) the T_C of the HandP after gripping the cold rods for about 2 minutes, especially in the case of nylon (Figure 5). Evaluation of this hand cooling should consider both the material characteristics and the cold environments as well. Cooling in contact differs from cooling in air. Hand contact cooling takes place when gripping a cold material. Heat transfers from the warmer hand skin to the cooler material. The hand in contact with the cold material may not be uniform. This may cause uneven cooling patterns over the hands and fingers, resulting in localised cooling. Obviously, the emission of heat from the hand skin to the cold rod in gripping is much higher, compared to that in air. When hand is exposed to the cold air, the deep tissues of the hand are cooled down more slowly. When gripping a cold surface, however, the heat transfer through the skin-surface interface will be more expeditious and the internal tissue of the finger is readily cooled.

3.1.4 Subjective responses to conductive hand cooling

Finger touching

The thermal and pain sensations versus T_C for the aluminium at –15 °C and for the nylon at –20 °C are shown in Figure 7. A rapid decrease in finger skin temperature leads to cold and pain sensations. A longer exposure time caused a colder and more painful sensation. Sensation of cold began to be experienced at the finger T_C of about 15 °C for nylon and at about 17 °C for aluminium. Local cold sensation becomes more intense with increasing the exposure duration. Conditions were experienced slightly painful (1) at a T_C of 15 °C for nylon at –20 °C. Painful (2) was rated when T_C was below 14 °C for aluminium at –15 °C. These findings are consistent with some previous experimental observations (Chatonnet and Cabanac, 1965; Hellström, 1965; Havenith *et al.*, 1992). In these cases, onset of very cold pain sensation occurred when T_C was 5-7 °C. The critical temperature for freezing of finger skin should be about 0 °C. The individual variation in sensation was considerable. Some subjects felt extremely cold (-4) at T_C of 7 °C whereas some felt cold (-2) at T_C of –3 °C. Different tissue properties, temperature at the onset of contact and heat input can explain some of this variation. People also differ according to their previous experiences of cold and pain. Enander (1984) has indicated a psychological adaptation among cold-accustomed individuals, resulting in reduced pain and cold sensations.

Moreover, the effect of pressure on the subjective responses for thermal and pain sensations as well as T_C on the cold aluminium at –15 °C and on the cold nylon at –20 °C is shown in Figure 7. In the case of cold nylon at –20 °C, variation of the both sensations with pressure is not notable and T_C varies trivially with pressure. The cold (-2) and slight pain (1) sensation as touching cold aluminium at –15 °C under lower pressures (< 2.94 N) occurred, when T_C reached 15 °C. The subjects seemed to have lesser sensitivity for cold pain at a higher pressure of 9.81 N. A very cold sensation (-4) occurred at a T_C of 10 °C for 0.98 N, at 8 °C for 2.94

N and at 7 °C for 9.81 N, when aluminium was touched. The intolerable pain sensation (4) for aluminium occurred at a T_C of 8 °C for 0.98 N, at 7 °C for 2.94 N and at 5 °C for 9.81 N. Cold sensation depends both on the size of the local area cooled and on the amount of finger cooling. The finger skin might become numb before the perception of cold and pain. This phenomenon indicated that the critical value of T_{fsk}, for finger protection should not be derived from data obtained at high pressures (> 9.81 N). Finger blood flow reduces or even stops with a higher pressure and the reaction time for cold pain is not long enough. In some cases, the subjects sometimes could not accurately describe their feelings. The subjects could not distinguish slight pain from very cold sensation due to the confusion between cold and pain sensations. During a rapid cooling, the initial warning of cold pain is often missing and the development of frostbite is often not noticed by the affected person (Killian and Graf-Baumann, 1981). Temperature limits for finger cooling based on subjective criteria is thus suggested to be based on judgements under a low pressure (< 3.0 N).

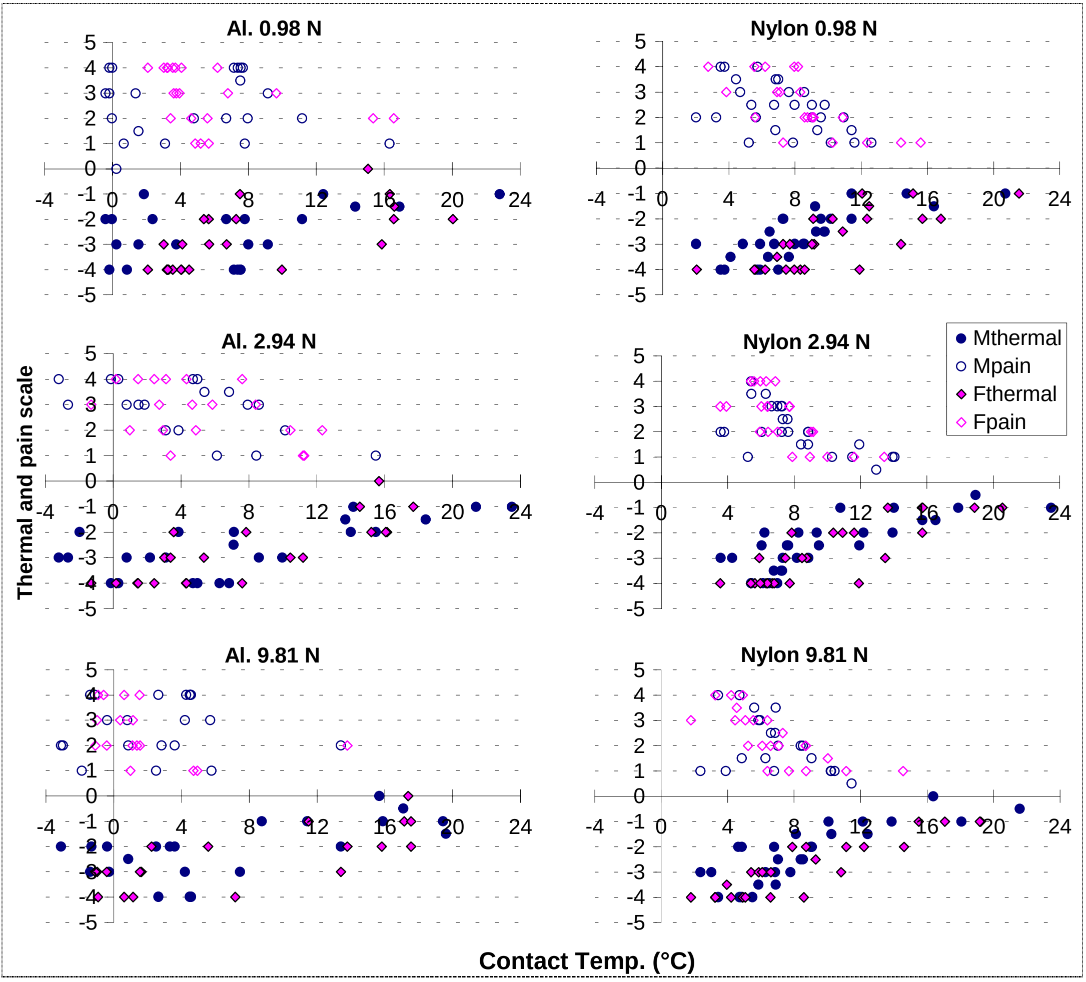

Figure 7. Subjective responses for thermal and pain sensations versus contact temperature at different pressures on cold aluminium at –15 °C and on cold nylon at –20 °C (**M**: Males, **F**: Females). *(Scales for pain: 0: No pain, 1: Slightly painful, 2: Painful, 3: Very painful, 4: Intolerable pain; for thermal: 0 Neutral, -1: Slightly cold, -2: Cold, -3: Very cold, -4: Extremely cold).*

Hand gripping

In order to investigate the inferences on subjective thermal and pain sensations at the end of hand gripping, Table 3 shows the results under different experimental conditions. Subjects felt colder and more painful when gripping the cold aluminium and steel at –10 °C or the cold stone at –20 °C. This was in agreement with the results from the objective measurement of T_C. The more painful sensation was found for the cases of aluminium or steel at –10 °C rather than from other conditions. The mean value of the vote slightly painful (1) was observed when T_C dropped from 18 to 12 °C, depending on various type and T_S of the material gripped. The mean thermal sensation of cold (-2) is related to a T_C, which falls in the same range (18 – 12 °C) as the slightly painful voting occurred. The results indicated that the thermal and pain sensations could be affected by the local contact skin temperature, temperatures of ambient and contacted object surfaces as well as the duration of the cold exposure.

Table 3. Subjective responses on thermal and pain sensations at the end of hand gripping

Condition (Ts, °C)	Grip duration (s)	T_C (°C)	Thermal	Pain
Alum at +1	1177.9±83.1	13.3±0.9	-1.4±0.3	0.6±0.3
Steel at +1	1167.7±82.2	13.9±0.9	-1.1±0.3	0.7±0.3
Steel at -5	1029.9±79.8	11.6±0.9	-1.7±0.3	1.0±0.3
Nylon at -10	1200±79.8	18.2±0.9	-2.0±0.3	1.1±0.3
Alum at -5	1106.4±79.8	12.8±0.9	-1.8±0.3	1.2±0.3
Stone at -10	1121.8±80.1	13.4±0.9	-2.4±0.3	1.6±0.3
Nylon at -20	776.4±79.9	15.2±0.9	-2.1±0.3	2.2±0.3
Stone at -20	430.2±84.3	7.8±0.9	-2.6±0.3	2.5±0.3
Steel at -10	371.5±117.7	9.3±1.4	-2.4±0.5	2.8±0.4
Alum at -10	329.4±116.8	5.4±1.3	-3.3±0.4	2.9±0.4

A relationship between subjective response on cold/pain sensations and contact hand skin temperature was found from hand gripping cold rods under different cold conditions (Havenith *et al.* 1992). The slightly painful condition was associated with a contact skin temperature of 19 °C. The pain level appeared to be inversely related to cooling speed. Also, a rapid decrease of the T_{hsk} complicated detailed comparisons of discrete values of temperature and sensations. Individual variation was considerable.

3.1.5 Development/application of an artificial finger (Paper V)

Change in the T_C of finger touching different cold surfaces was studied with human subjects experimentally. However, it is not acceptable for ethical reasons, to expose human subjects to cold metallic surfaces with extremely low temperatures below –20 °C. Therefore, an instrument in the form of an artificial finger was developed to use for the measurement of T_C when touching very cold metallic surfaces (Figure 8). The instrument consists of an artificial finger, a digital meter named “SWEMA Air 300” for measuring T_{sk} and T_C, and a console with a power supply/control circuitry and a digital display.

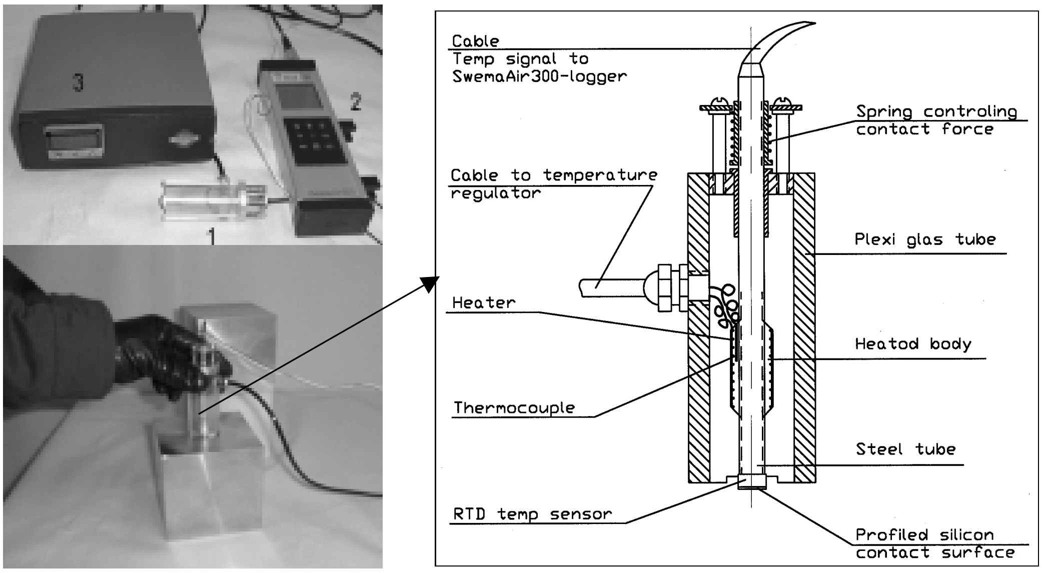

Figure 8. Instrumentation (1: artificial finger, 2: digital meter, 3: power supply console) and schematic drawing of the artificial finger.

In the experiment, the blocks were put in the cold chamber for a sufficiently long time to allow them to equilibrate with the chamber temperature. The artificial finger was heated for about 20 minutes to gain a constant temperature of the probe body/surface. The temperature of the probe body was controlled at 32 °C and the surface temperature of the fingertip was maintained at around 25 °C, corresponding to the skin temperature of a human fingertip in a cold environment. The tested cold surface was touched by the artificial finger, and T_C was displayed and recorded with the digital meter. The sampling frequency was 10 Hz. The values of T_C were collected and then computed after the measurements. The experiments with human fingers were also concerned.

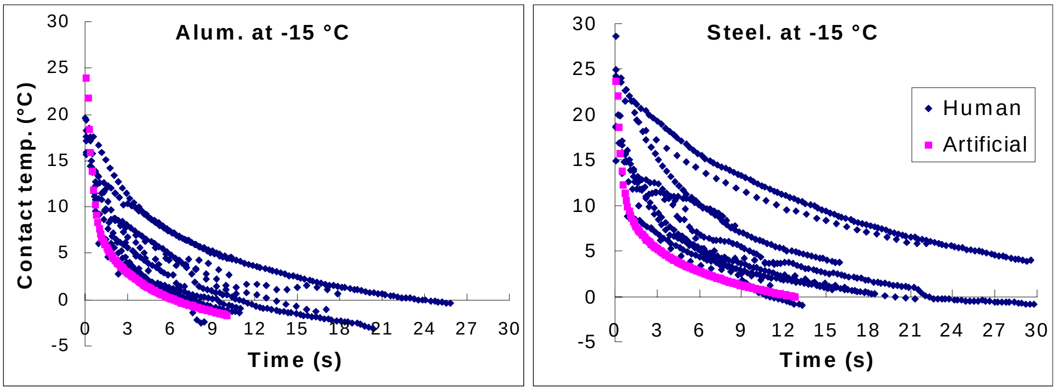

Figure 9. Comparison of cooling curves obtained with the instrument and with human fingers touching cold metallic surfaces at –15 °C.

The artificial finger was utilised to measure T_C for metals (aluminium and steel) in very cold situations (below – 20 °C). The results showed a difference of T_C between the two metals at very low temperatures. A more rapid reduction of T_C occurred when the finger touched aluminium below –20 °C, compared to steel.

Clearly, this resultant difference is because aluminium possesses a higher thermal penetration coefficient, compared to steel. The cooling response on the surface of the artificial finger is clearly related to the materials' contact coefficients. Also, measurements with the artificial finger were compared with those from human fingers in contact with the metallic surfaces at –15 °C. The results are shown in Figure 9. The cooling curve obtained from the artificial finger was calibrated to cover the lowest cooling curves from human fingers. This reflects that the results with the artificial finger can be considered as lowest temperature limits for the protection of human fingers in the cold. The cooling behaviour of the artificial finger follows a similar pattern as that of human fingers. The observed cooling curves from the artificial finger were found to follow most closely the Newtonian cooling law. This electrically heated artificial finger model can be used to simulate the cooling behaviour of human fingers in contact with extremely cold surfaces under various conditions such as type of metallic material, structure of surface and contact force.

3.1.6 Determination of criteria for touchable cold surfaces (Paper III)

The occurrence of contact cold injury depends on T_C and the contact time for T_C to reach a critical temperature. T_C and contact time have been studied experimentally. It has been suggested from the experiments that critical levels of T_C would be 0 °C corresponding to a freezing risk (freezing), 5-7 °C (sensation of numbness) and 15 °C (sensation of pain). In the work site, the determination of contact time could be more convenient, compared to the measurement of T_C as contacting cold surfaces. From the ergonomic point of view, the estimate of the cold risk is possible through measuring T_S of the cold object and the contact time to reach a criterion. The duration limit of contacting various cold surfaces to reach the critical T_C can be regarded as secure time threshold. The time limits can be directly obtained from human finger cooling curves on cold surfaces under selected conditions.

Contact time of finger touching cold metallic surfaces for critical T_C (7 and 0 °C)

Recommended safety contact time for T_C to reach different criteria of finger contact cooling has been statistically derived from the experimental data of finger touching. Table 4 shows the contact duration for T_C on steel and aluminium under various conditions such as the type of the material (steel and aluminium), T_S (2 to –20 °C), and the pressure (0.98, 2.94 and 9.80 N). It is seen that the time for T_C to reach the critical temperature are notably more expeditious in the cases of finger touching at lower T_S. The time to reach the critical temperatures when touching the cold metallic surfaces was notably shorter at higher pressures. Also, the results show the effect of gender on the duration to reach the critical temperatures for touching on the cold metallic surfaces.

Table 4. Contact time for T_C reach to 7 and 0 °C while touching cold metallic surfaces

Material	T_C. (°C)	Gender	Time to reach 7 °C (Sec.)			Time to reach 0 °C (Sec.)		
			0.98 N	2.94 N	9.81N	0.98 N	2.94 N	9.81 N
Aluminium	+ 2	F	43.92	32.93	14.99			
		M	141.68	107.31	66.35			
	- 4	F	22.83	11.56	6.25	440.40*	169.24	60.05
		M	69.96	50.48	15.38	799.19*	293.91*	86.56
	- 10	F	11.89	7.14	3.51	196.78*	71.44*	29.82
		M	6.22	6.59	2.43	148.45*	72.62*	14.60
	- 15	F	6.06	4.35	2.11	74.39*	28.35	11.65
		M	4.90	4.96	2.92	41.97*	55.53*	21.00
Steel	+ 2	F	86.44	78.18	45.48			
		M	217.07*	153.65	116.55			
	- 4	F	12.71	10.43	8.44	272.83*	132.36	85.93
		M	34.45	36.90	34.95	248.07*	266.13*	198.17*
	- 10	F	25.43	10.57	8.62	253.21*	82.66*	46.68*
		M	21.56	15.58	13.24	242.12*	139.28*	103.08*
	- 15	F	16.75	2.95	4.73	252.84*	86.25*	20.38
		M	19.64	13.28	8.78	189.76*	100.74*	48.89*

*Extended values obtained from regression of cooling curves by empirical models (see Paper I)

When bare fingers touching cold aluminum with 9.81 N, numbness would occur at +2 °C after 15 seconds, at –4 °C after 6 seconds and at –10 or –15 °C after 2 seconds. The extended contact on the cold metallic surfaces at temperature below – 4 °C at 9.8 N may result in the cold injury. The results may give the time limit of finger touching cold metals (aluminum and steel) if a special manual work is required at +2 °C or lower. In Table 4, the bare fingers with 9.8 N touching the metallic surfaces at –4 °C for 60 seconds, at –10 °C for 15 seconds and at –15 °C for 12 seconds should be avoided due to the occurrence of possible cold injury.

The results also indicated that time to reach the critical temperature had a large variation among individuals. The individual variance should be considered when the contact time for the critical temperature is determined. To avoid the complexity caused by individuals and secure the manual or finger protection on the touchable cold metallic surfaces, it is suggested that the contact time for the critical T_C could be determined by using the lower predicted limits of the empirical mean curve at 95% confidence level.

Contact duration to reach freezing criterion with the artificial finger

One function of the artificial finger is to predict the contact time to reach a freezing criterion on extremely cold metallic surfaces. Cold temperature of 0 °C is assumed to be a risk level for acquiring a cold injury (frostnip). Figure 10 illustrates the contact time for T_C to reach 0 °C at various surface temperatures measured by the artificial finger. The contact time for the critical T_C limit reduces with decreasing T_S of the materials. The experimental data with the artificial finger indicated that cold freezing injury would take place if the finger touched the cold aluminium surface at –40 °C for only 0.6 seconds, at –30 °C for about 1.2 seconds and at –20 °C for about 5.3 seconds.

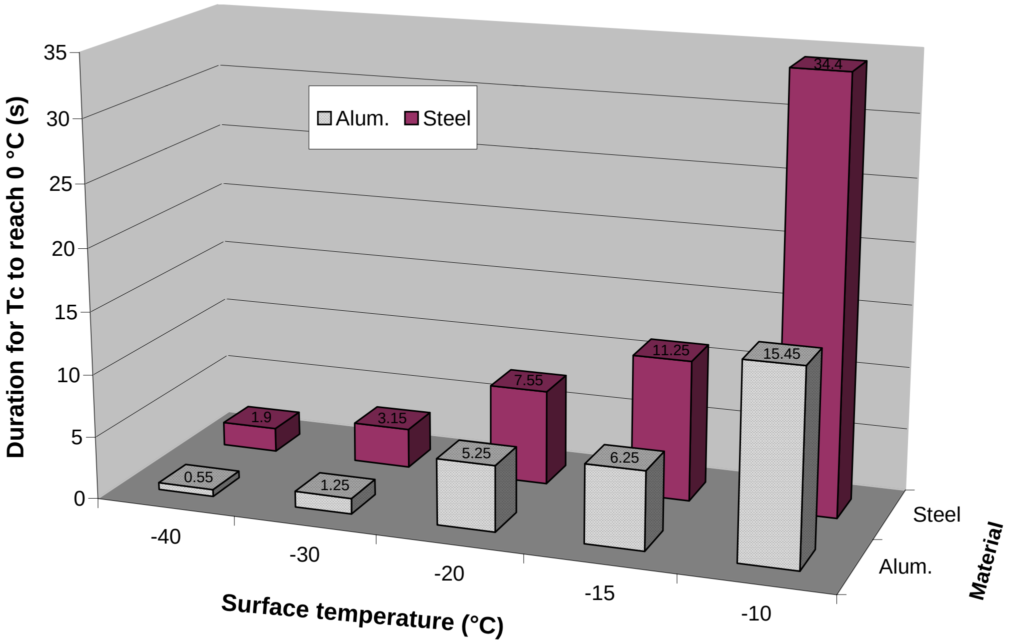

Figure 10. Contact duration for T_C to reach a 0 °C when contact with various cold metallic surfaces by the artificial finger.

Gripping time at the critical T_C=15 °C

Cold discomfort of finger was encountered as T_C fell to 15 °C. Non-freezing cold injuries may occur when the tissue temperature is below 10-15 °C for a longer cold exposure (Holmér, 1997). Thus, the critical T_C for hand gripping could be 15 °C. Figure 11 shows the contact time for the critical T_C at the points of finger and hand palm to reach 15 °C as gripping the cold surfaces. In general, the gripping time for T_C at the finger point is shorter than that at the hand palm point for most of the cases. This reflects that the heat emission from the finger to the cold surfaces is more prompt due to reduced heat input by circulation, a small local metabolic heat production and small finger mass. The time of gripping the cold metallic rods at the finger point is about 3 seconds at –10 °C, which is much shorter than that of the cold stone rod. As mentioned, the metallic objects have higher thermal conductivity. It is also demonstrated that the gripping time for T_C to reach the critical temperature at the palm side was short (about 10 seconds) for the cold metallic surfaces. It is noticed from hand cooling curves that the hand warmed up after gripping at higher ambient temperatures (over –5 °C), but not at –20 °C. The critical gripping time for a T_C of 15 °C is suggested to be <10 seconds at –10 °C for metal and at –20 °C for stone as well as to be <100 seconds for nylon at –20 °C.

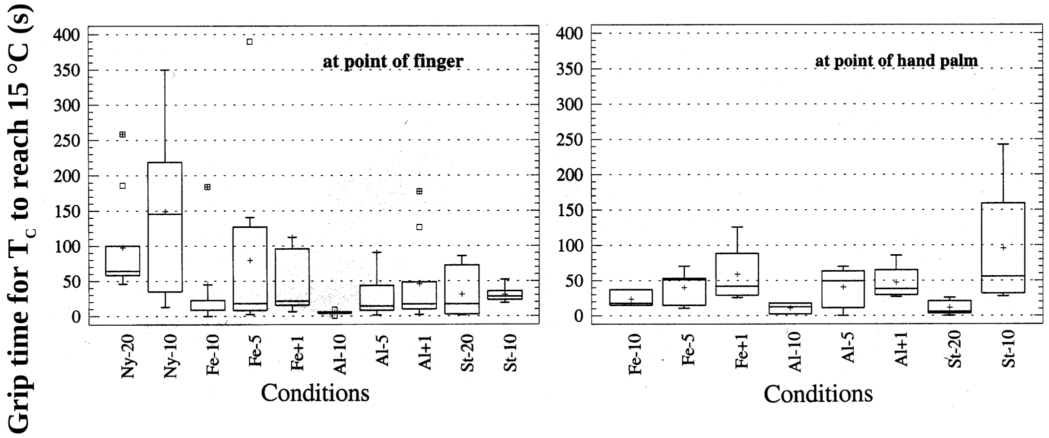

Figure 11. Gripping time for T_C (fingertip and hand palm) to reach 15 °C under various conditions.

3.1.7 Establishment of a database and proposal for a standard (Paper III)

Database

A database, which contains experimental data of finger touching and hand gripping the cold surfaces has been compiled based on pooled data from human subjects and the artificial finger (Holmér *et al.* 2000). Experiments on various materials (wood, nylon, stone, steel and aluminium) at temperature of -40 to +5 °C were included. The database for the finger touching and hand gripping experiments includes the following essential information:

1) characteristics of the subject (age, weight, height, hand surface, hand volume, contact area);
2) experimental set-up (T_S, exposure hand into a cold box or whole body in a cold climatic chamber);
3) parameters (duration of the resting period in the climatic room, skin temperature before contacting, thermal, pain and numbness sensation were determined before each test);
4) criteria used to stop the test risk of frostbite, pain or time limit reached, duration of the test, skin temperature, thermal, pain and numbness sensation were determined after each test;
5) contact time, the thermal, the pain and the numbness sensations were measured during each test;
6) characterisation and evolution of the skin temperature with time (to reach the T_C of 15 °C, 7 °C and 0 °C) and
7) characterisation of the material (thermal conductivity, specific heat, density and contact factor).

Each individual curve of T_C versus contact time in the cold was subsequently plotted from all the records. In the database, the contact time for the critical T_C was determined by using the lower quartile (25%) in order to secure hand/finger protection for 75 % of the population on the touchable cold surfaces. The contact time for critical T_C (15, 7 and 0 °C) for each cooling curve was obtained by inter- or extrapolations. The contact time (t) for critical T_C on were empirically correlated with major factors such as contact factor (F_C) and surface temperature (T_S) of the material, respectively. The following relation were found:

at T_C = 15 °C for steel, aluminium and nylon:

$$t = 13.2 \times F_c^{(-1.0)} \times e^{(0.10T_S)}, \ (R^2=0.94) \qquad (1)$$

at T_C = 7 °C for steel, aluminium, nylon and wood:

$$t = 169.0 \times F_c^{(0.05T_S - 0.70)} \times e^{(0.05T_S)}, \ (R^2=0.85) \qquad (2)$$

at T_C = 0 °C for steel, aluminium, and nylon:

$$t = 406.8 \times F_c^{(0.05T_S - 0.25)} \times e^{(0.05T_S)}, \ (R^2 = 0.84) \qquad (3)$$

Figure 12 shows the predicted contact duration for T_C to reach each critical temperature (15 °C or 7 °C or 0 °C) at various T_S. The time is notably shorter at lower T_S. For instance, when the finger touching cold aluminium, cold injury might occur after 18 seconds at –4 °C, after 6 seconds at –10 °C and about 2 seconds at –15 °C.

Proposed standard (Annex in Paper III)

Results from the database have been compiled in a document that can serve as a proposal for an international standard. This document provides ergonomic data to establish temperature limit values for cold solid surfaces. The values established could be used in the development of special standards, where surface temperature limit values are required. The threshold data of this standard will be applicable to all fields where cold solid surfaces cause a risk of hand/finger contact cold injury (frostbite and non-freezing). The standard is applicable to the healthy hand/finger palm skin of adults (females and males).

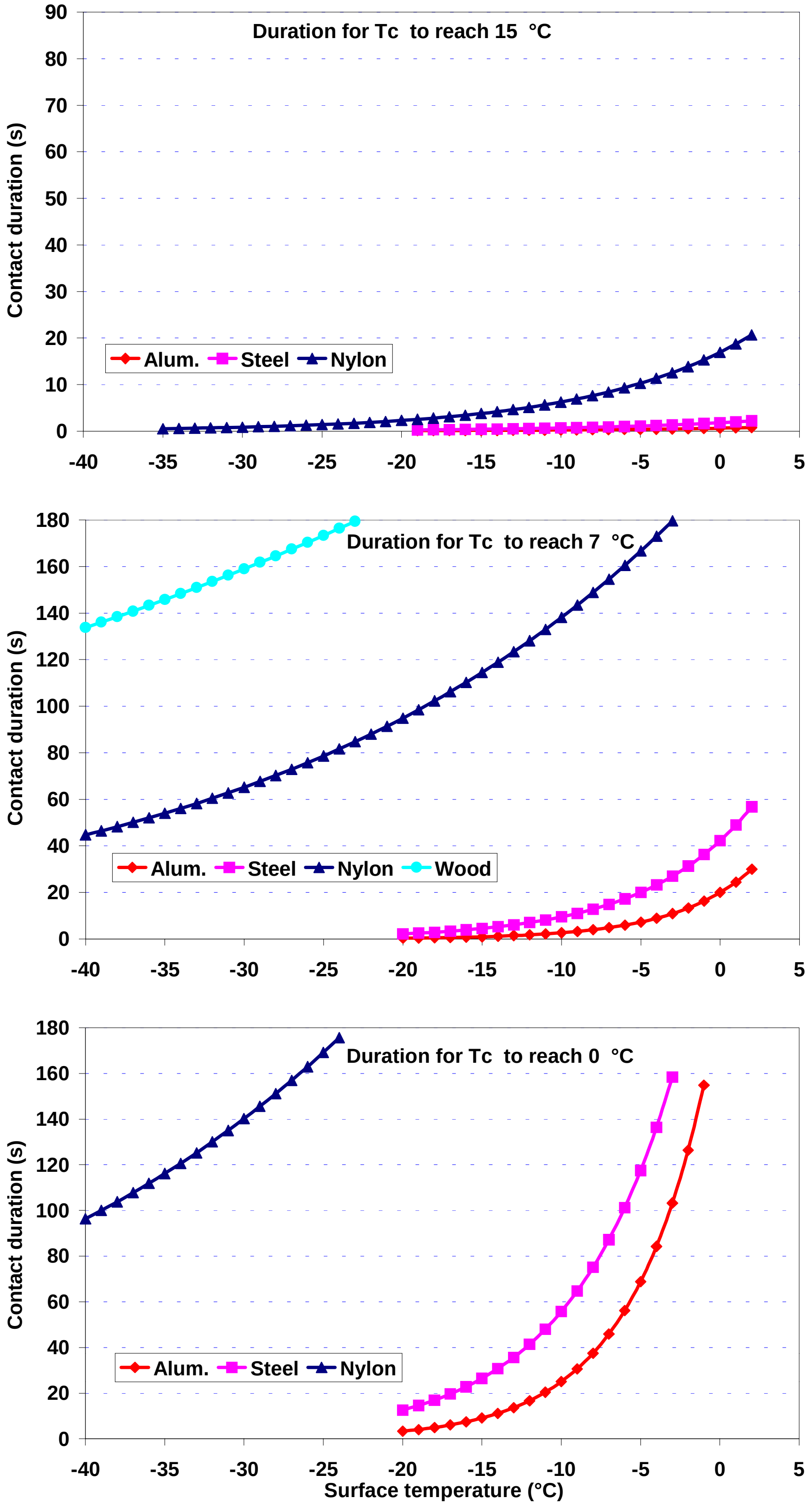

Figure 12. Contact durations for T_c to reach 15, 7 or 0 °C on cold surfaces with human fingers.

3.2 Hand protection with gloves against cold

3.2.1 Thermal insulation measurement of gloves

In the study, five different industrial protective gloves (type A, B, C, D and E), which are commercially available and commonly used in cold operations (such as outdoor building and delivering), were investigated (Figure 13). Detailed information about the gloves can be found in Paper VII.

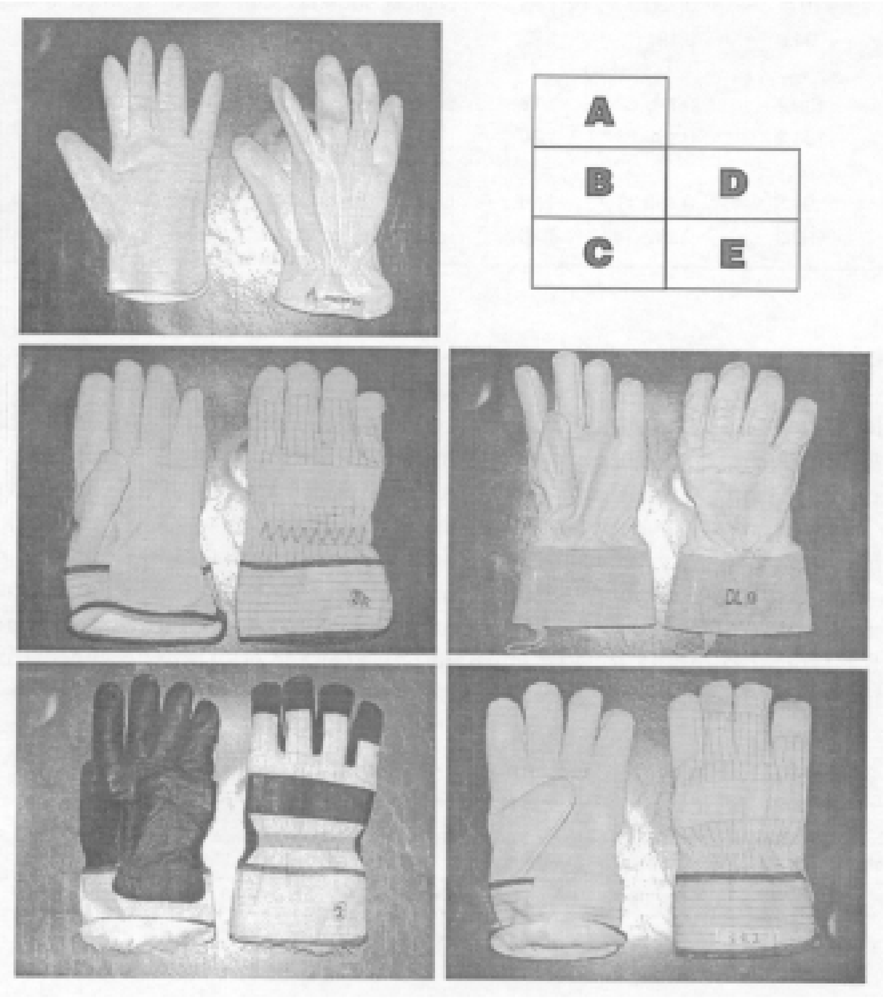

Figure 13. Configuration of gloves used in the investigation.

The thermal insulation value of the five gloves and the combinations of outer gloves B, C, D and E with an inner glove A were measured with an electrical hand model (Figure 14) according to a European Standard method (En 511:1994). The results are shown in Table 5.

Figure 14. An electrical hand model for measurement of thermal insulation.

Table 5. Thermal insulation of the gloves and their combinations with glove A

Glove Number	Weight (g)	Thickness (mm)	Material	Thermal $(m^{2o}C/W)$	Insulation Clo	Perf. Lev.*
A	15.0	1.0	Cotton/Rubber	0.064	0.41	0
B	59.4	2.7	Leather (pig)/Cotton	0.116	0.75	1
C	79.0	3.8	Leather (goat)/Cotton	0.190	1.23	2
D	139.2	4.8	Leather (goat)	0.175	1.13	2
E	94.3	3.7	Leather (pig)/Cotton	0.199	1.28	2
B+A	74.4	3.7		0.135	0.87	1
C+A	94.0	3.8		0.194	1.25	2
D+A	154.2	5.8		0.186	1.20	2
E+A	109.3	4.7		0.202	1.30	2

* Performance level is classed by EN 511

3.2.2 Hand protection with gloves in gripping cold rods (Paper IV)

Hand wear can dramatically reduce the risk of skin freezing during cold air exposure and contact with cold objects. Figure 15 shows T_C at the end of hand gripping cold metallic and non-metallic rods without and with gloves. It is seen that hand cooling is related to material of the rod, ambient temperature as well as type of gloving. Statistically significant temperature differences at 95 % confidence level were found for bare hands and gloved hands and for glove types, when gripping the metallic rods at –10 °C. Clearly, a thicker glove type 2 (glove B) with higher thermal insulation value gives a higher T_C (>21 °C), compared to a thinner glove type 1 (glove A) (<14 °C) or no glove (<9 °C). Gloves lead to a decreased rate of heat transfer from hand to the cold surfaces during gripping. In addition, the results show a significant glove effect on T_C at the end of gripping the cold nylon rod at –20 °C. T_C was significantly lower at the end of gripping without gloves. This emphasises that hands must be protected with gloves during gripping cold non-metallic materials like nylon at a cold temperature below –20 °C. However, there exists no statistically significant variation on T_C between glove types 1 and 2 in this case.

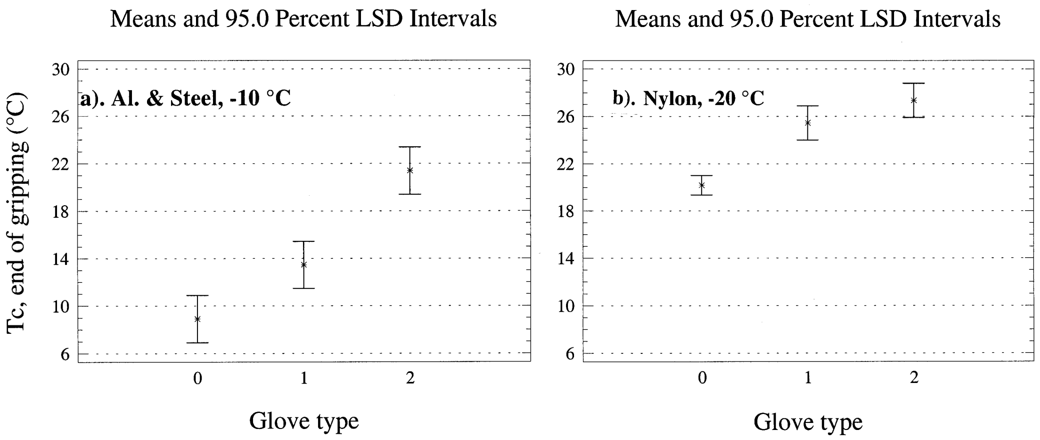

Figure 15. Mean T_C at the end of gripping difference cold rods with bare hand (0), gloves A (1) and B (2): a) for aluminium and steel at-10 °C and b) for nylon at –20 °C.

It is noticed that the variation of T_C appeared to be significantly related to the presence of hand protection. Averaged for all conditions, the presence of a glove increased the hand contact temperature by 4-12 °C for gripping the cold rods, compared to bare hands.

3.2.3 A study of an electrically heated glove

More secure protection with a glove against cold, especially in severe cold, is traditionally connected with an increase in glove thickness. However, this causes a corresponding decrease in manual performance. The development/application of a glove acceptable for performance and comfort is therefore important. Electrical heating is a possible means to keep hands warm. The possibility of utilising electrical heating in the glove can decrease the glove thickness, which allows a better manual performance with gloved hands.

A prototype of an electrically heated glove, which was developed and designed by Eurex AB, Sweden, was examined using both the hand model (Figure 14) and human subjects. The location of regulation sensors for the electrically heated glove was determined. The heated glove was evaluated from the points of view of thermal protection, comfort, fit and performance. The electrically heated glove is expected to keep the power supply at minimum and simultaneously hold the hand temperatures at acceptable comfort and performance levels.

The electrically heated glove (glove H, 0.47 clo) was a thin cotton glove with a heating element, which was tested either as a single gloving or as an inner glove in a double (inner-outer) gloves system. The heating element was located on the dorsal side of hand and fingers. The power supply (from 0 to 10 Watts) of the heated glove was adjusted according to the cold response of gloved hands. The double gloving was tested in combination with two outer gloves (B and E). Glove B is a thin outer glove used at an ambient temperature of –10 °C, and glove E is a thick outer glove used at –20 °C. Glove A was used as an inner glove without any heating to compare the heating effect.

The study was carried out on 2 subjects (1 male and 1 female) in a cold climatic chamber. The skin temperature sensors were taped to finger tops of thumb, index (IFing), middle (Mfing) and little fingers (Lfing), first phalanx of outside little finger (LfingO), hand back, forearm and shoulder. The manual pick-up task (five steel balls of sizes 20, 15, 10, 7 and 5 mm) was performed during the cold exposure. The total time for completing the task was recorded. The subjects also rated their thermal and pain sensations during the test.

Single gloving at –10 °C

The results with single heated and unheated gloves during a cold exposure of 60 minutes at –10 °C showed that the tips of little fingers appeared the lowest skin temperatures This value should be a criterion to adjust the power supply for the control of heat input. The skin temperature of the little finger in the unheated glove (NLFing) dropped to 3 °C, while in the heated glove the lowest temperature (HLFing) was around 12 °C. Thermal and pain sensations for the NLFing were assessed as very cold and very painful. The responses for the HLFing were cool and slightly painful.

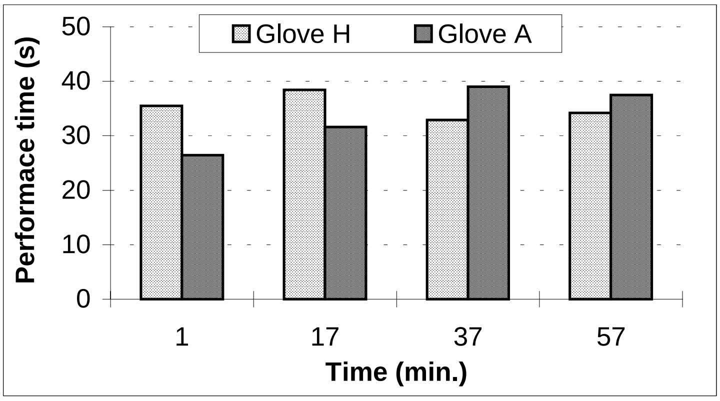

Figure 16. Performance time vs. duration of cold exposure at -10 °C (right hand with glove A and left hand with glove H)

In this case, cooling of hands had a significant effect on the manual task. The time for completing the task increased significantly with decreasing of the finger temperature, although the subject was right handed (Figure 16). This result could be related to a fact that cold climate influences the manual performance as the finger skin temperature of the subject drops below 15 °C.

Double gloving

The use of a double gloving (an outer glove with the electrically heated inner glove) was examined for a cold operation at ambient temperatures below -10 °C. The power supply to heat the glove was 3 W. After exposure for 40 – 50 minutes, It was increased to 6 W if the top of the skin temperature of the LFing (H+B) dropped to 15 °C.

The mean hand and finger skin temperatures with the heated gloves (H+B) and unheated gloves (A+B) during cold exposure for 60 minutes at –10 °C are shown in Figure 17. The skin temperature of the LFing (H+B) is 4-5 °C higher than that of the LFing (A+B). The results show a considerably increase in skin temperatures with double gloving compared to single gloving.

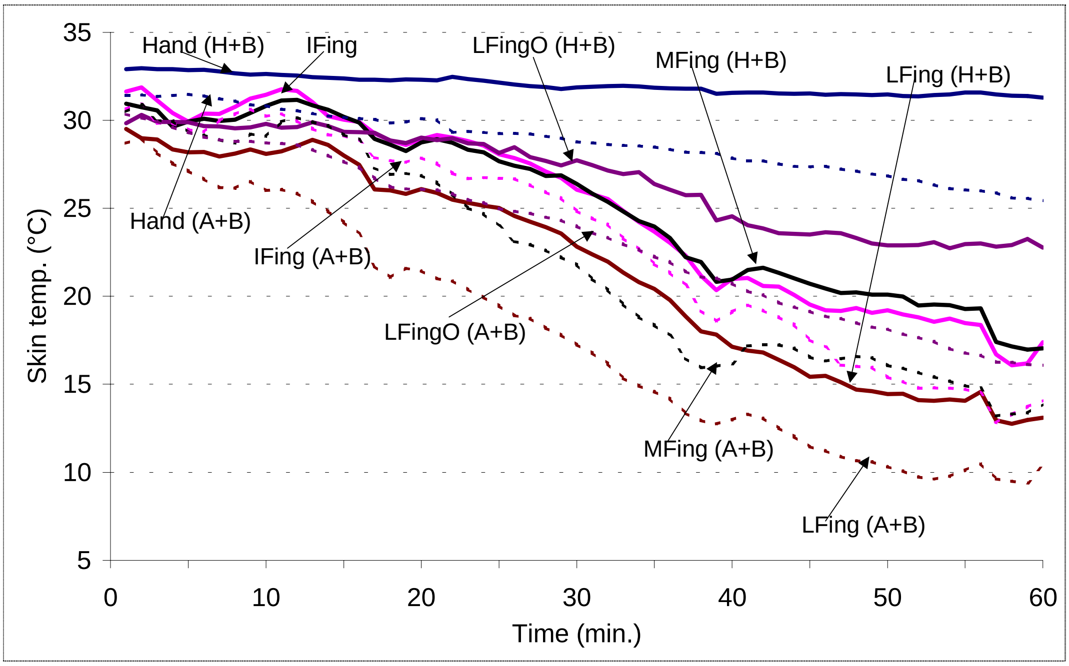

Figure 17. Means of hand/finger skin temperatures with the electrical heated (H+B) and unheated (A+B) gloves at -10 °C

Thermal and pain sensation were related to the change in skin temperatures with and without the heated gloves (Figure 18). The thermal and pain sensation in the fingers for the unheated gloves (A+B) were cold and slight pain, while the responses for the heated gloves (H+B) were cool and no pain.

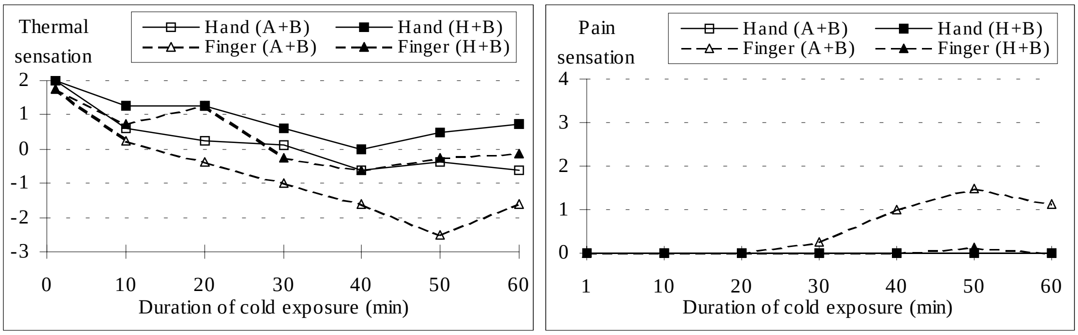

Figure 18. Thermal and pain sensation with gloves (A+B) or (H+B) vs. duration of cold exposure at -10 °C.

The result of using an outer glove B with the heated inner glove at a power supply of 3 W indicated that skin temperature of the LFing (H+B) was kept above 15 °C for 48 minutes (Figure 17). Hence, it is recommended that the electrical heated inner glove at 3 W with an outer glove (B) in double gloving can be used in a cold environment at –10 °C for about 50 minutes. It was also found that a combination of an outer glove E with the electrical heated inner glove of 3 W kept skin temperature of the LFing (H+E) above 15 °C for 60 minutes at –20 °C. Clearly, the use of outer gloves combined with the heated inner glove is advantageous since precision manual tasks can be improved and warm hands maintained in gloves with a higher insulation.

It could be concluded from the results above that an electrically heated glove can be efficient in both keeping hand's thermal comfort and empowering a good manual performance in cold operations, compared to the unheated gloves of the same type.

3.2.4 Prediction of T_{fsk} with hand wears by modelling

Goldman (1994) has proposed an empirical model to estimate finger cooling behaviour with various hand wear in cold. He considered that the insulation of hand wear for little finger is the critical value and is not necessarily correlated with overall glove insulation for the prediction by the model. In this case, the model for prediction of $T_{fsk}(t)$ against exposure time t in still cold air can be expressed as:

$$T_{fsk}(t) = T_{eq} + (T_{fsk0} - T_{eq}) \times e^{-(\frac{t}{100clo-a})} \tag{4}$$

Where: a is the time constant, T_{fsk0} is the initial T_{fsk} and T_{eq} is the equilibrium temperature ($T_{eq}=T_a+0.155\times q\times clo$, where T_a is the air temperature, q is the extremity circulatory heat input, W/m^2 and clo is the insulation value of hand wear).

Figure 19 shows the predicted and measured T_{fsk} of the little finger with two gloves (C: 1.03 clo and D: 0.96 clo for little finger part) at –25 °C. The predicted T_{fsk} follows closely the measured average values from eight subjects for 40 minutes, especially for the case of wearing glove D. However, the measured T_{fsk} is significantly higher than the calculated T_{fsk} after 30 minutes. The resultant difference may be mainly due to various intermittent activity levels. During the cold exposure, the subjects stood firstly for 20 minutes, walked secondly on a treadmill at a speed of 5 km/h (metabolic rate about 160 W/m^2) between 20th and 30th minute and then sat for the last 10 minutes. The measured values with subjects produced considerable heat from walking after 25 minutes. The circulatory heat input to fingers would be higher than 84 W/m^2, used for q in the prediction. It is concluded that the model developed by Goldman could be used to predict finger cooling behaviour for cold exposures with different hand wear insulation.

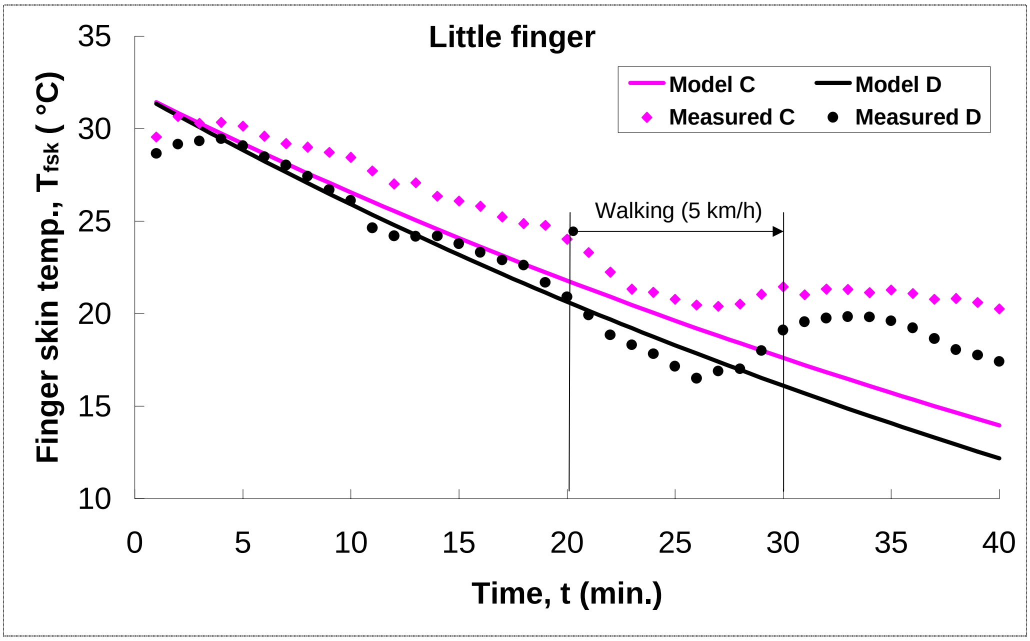

Figure 19. Comparison of predicted and measured T_{fsk} of the little finger with two gloves (clo values: 0.96 and 1.03) at –25 °C.

3.3 Manual performance with and without gloves

3.3.1 After bare hand gripping cold objects

As known, the manual performance in the cold operations can be affected by hand cooling (Holmér, 1994). Majority of this aspect has been focused on effect of cold air on the decrements in manual performance (Mills, 1957; Morton *et al.*, 1960; Tanaka *et al.*, 1983; Rogers *et al.*, 1984; Daanen, 1993). There is not much research work concerning the influence of contact cooling on the manual performance in the cold.

To evaluate and compare the manual performance before and after hand gripping the cold objects, tactile sensitivity and finger dexterity tests were carried out. Tactile sensitivity test was performed using Semmes-Weinstein Pressure (SWP) filaments, which were touched on the distal extremity under index and little finger's metacarpus and pad of the middle finger. The filament size 2.36 represents a press force of 15 mg and was used as the lightest force in all tests (Tomancik, 1987). In a finger dexterity test (O'Connor), a subject was required to fill the first line with 3 pins per hole from left to right as quickly as possible. As a result, the time needed to complete the task (O'Ctime) and counts of mistakes were recorded. A statistical method of t-distribution was utilised to judge the significance of the observed differences of manual performance before and after hand gripping the cold bars in the quantities.

Figure 20 shows the results of manual performance before and after hand gripping the cold bars in Box-and-Whisker plots. There is a statistically significant difference between the means of SWP force for tactile sensitivity before and after gripping the cold rods at 99 % confidence level. The result of the finger dexterity test also shows that the performance time after gripping was significantly longer than that before gripping. Loss of manual performance after gripping the cold rods is considerable from the results of both SWP sensitivity and O'Conner finger dexterity tests.

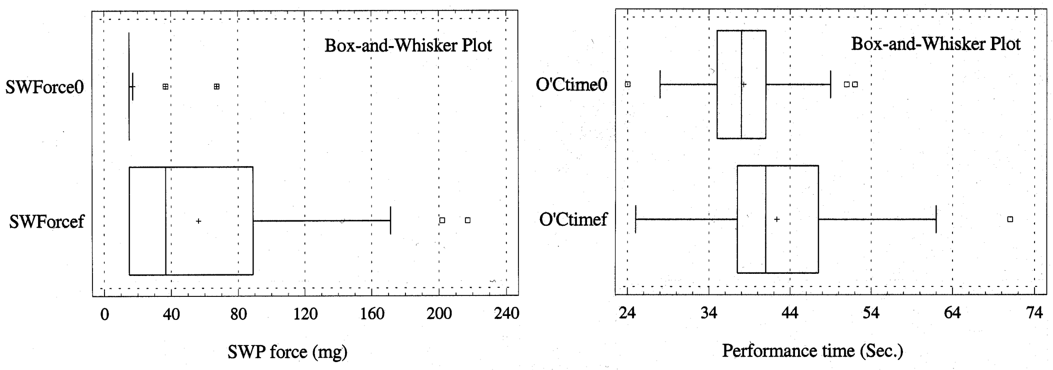

Figure 20. Comparison of hand SWP sensitivity and finger dexterity before (0) and after (f) gripping.

According to some earlier work (Leblanc, 1956; Daanen, 1993), a decrease of the hand skin temperature causes dexterity loss. This may be caused by the influence of cooling on muscles and joints of the finger/hand. Lower core temperature of the finger/hand leads to lower finger/hand skin temperature and then to a significant loss in dexterity. It was also found that finger dexterity decreased sharply when the finger skin temperature fell below 15 °C. Loss of tactile sensitivity of finger after gripping the cold surfaces occurred. The main reasons for this loss are due to the changes in the properties of the finger skin and/or the effects on biochemical processes at nerve or receptor level (Mills, 1957; Stevens *et al.*, 1977). In addition, some previous work has been done on the sensory thresholds of tactile and thermal sensors in relation to manual dexterity (Mackworth, 1953; Morton and Provins, 1960; Mills, 1956). These results indicated that the skin temperatures of 6 to 8 °C appear to be rather critical with sensitivity dropping off very rapidly. When the skin temperature of the fingers reaches 8 °C, a decrement in manual dexterity due to a loss in sensibility has to be expected.

3.3.2 With gloved hands (Papers VI, VII and VIII)

The problems of developing or selecting a hand wear in cold operation which both maintains local thermal comfort and permits the retention of enough manual precision for safe and efficient work have not been completely solved. The main reason is that the use of protective gloves to minimise heat loss can impair manual functions. No studies were found to determine hand performance relative to the use of double gloving during cold exposure. Therefore, investigating the existing work gloves and selecting an approach to use double gloves in cold operations were considered to be a necessity.

All experiments on manual performance with the five different industrial protective gloves (A, B, C, D and E, see Figure 13 and Table 5) were carried out with subjects seated in a cold climatic chamber at -10 °C, -12°C and –25 °C. The skin temperatures of the subject were recorded using thermistors and a data logger.

Manual dexterity (Paper VI)
To evaluate the manual dexterity of gloved hands of subjects (six male, ages: 27 to 43 years), a bolt-nut task and a pick-up task were designed (Geng, 1998). A board with four sizes of bolt-nut (6, 8, 10 and 12 mm) was utilised in a bolt-nut task and two containers with steel balls of five sizes (5, 7, 10, 15 and 20 mm) were used in a pick-up task. The tasks included loosening, grasping, positioning and tightening. In bolt-nut task, the subject with each type of glove was asked to unscrew/screw the bolt-nut, respectively. The pick-up task was designed to study hand ability with gloves in picking up balls with different sizes. Each subject was asked to pick up five balls of the same size from a bowl to a box. A randomised block multiple-factorial experimental design in statistics was employed. The independent variables were temperature, subject, glove type, and task type as well as object size. The response or the dependent variable was the duration of the performance, i.e., the time required to perform the task. During the manual dexterity tests, each subject performed these tasks with gloved hands, while wearing one of the four different types of gloves or while wearing the double gloves combinations, i.e., one of four outer gloves (B, C, D and E) with the same inner glove A at both neutral (+19 °C) and cold (-10 °C) temperature conditions. The time required to perform the tasks was recorded during the experiment. In addition, subjects were required to rate how difficult they found the tasks to be on a five point scale ranging from very easy (0) to very difficult (4) for a subjective assessment of the gloves used after the tasks.

Different gloves: Figure 21 (A) shows the mean time required to complete the bolt-nut and the pick-up tasks with four different types of gloves at –10 °C. The differences of the hand performance are statistically significant between gloves E and B and between gloves E and C in the bolt-nut task. In this task, glove E gave a significant impairment of manual dexterity compared with the other gloves. This may be due to that glove E consists of hard thick pigskin leather on the surface and cotton with mohair or velvet inside. This type of glove with a high insulation value of 1.28 clo is the thickest among the others. However, glove B is made of materials of thinner soft leather of pigskin on the surface and cotton inside. Its insulation value is 0.75 clo. Wearing glove B took a shorter time of manual performance in the bolt-nut task, compared to glove E. This illustrates a well-known fact that the relative superiority of the glove materials can enhance general efficiencies of gloved hands. Difference of the thickness may be an another contribution to the performance improvement. On the other hand, subject's hands and fingers with a softer glove moved intensively when screwing and unscrewing bolt/nuts in the cold. The movement of hands and fingers may increase the blood flow to capillaries and raise the hand skin temperature in certain duration of cold exposure. This may result in an improvement on the performance of hands with glove B. Glove C is made of leather of goatskin on the surface and cotton or mohair inside. This glove with an insulation value of 1.23 clo felt soft and warm. These characteristics seemed to contribute most directly to the overall manual performance improvement in the cold operations, e. g., the bolt-nut and pick-up tasks.

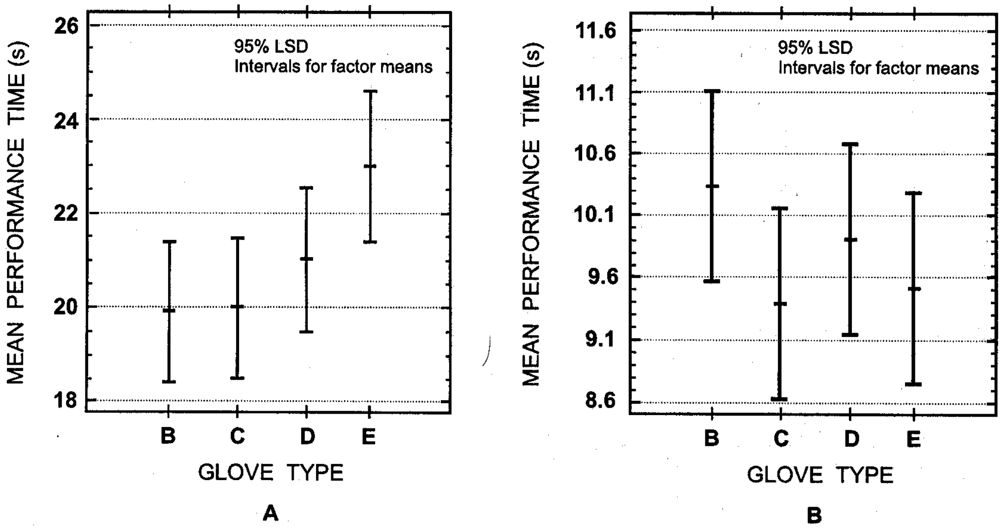

Figure 21. Mean time differences with 4 gloves in the bolt-nuts (A) and pick-up (B) tasks at -10°C.

The results with 95 % LSD for mean performance time with different gloves indicated that there was no significant difference between gloves in the pick-up task, as shown in Figure 21 (B). Therefore, it could be concluded that all the gloves studied gave the similar pick-up performance at –10 °C. The reason for this conclusion may be related to the thermal insulation effect of gloves on finger dexterity in pick-up task. According to Holmér (1994), the gloves used in the study belong to the same thermal performance level 2 (1.0 to 1.5 clo) except glove B. This may lead to an insignificant variance on the performance time with various gloves in the pick-up task, which performs with a little movement with gloved hands in the cold.

The results indicated a relationship between the gloves and the sizes of bolt-nut task in some detail. It is obvious that a smaller bolt-nut takes longer time with all the gloves used in the task. It means that mean time required performing the bolt-nut task increased with decreasing the size of object measured. This result is consistent with an earlier study by Sperling *et al.* (1980). Glove B and C gave a better hand dexterity for smaller sizes of 6 mm and 8 mm bolt-nut. It may be suggested from these results that glove C could be used in some cases of more precision work in the cold environment.

The comfort levels of the gloved conditions were also evaluated subjectively. Glove C was considered to be the most comfortable, as compared with the others (gloves B, D as well as E). Glove D was also regarded as comfortable work glove in most of the cases. A comparison of subjective assessment was not statistically analysed since this subjective evaluation was based only on six subjects. However, the results from the subjective evaluation of the comfort level of the gloves were in agreement with that from the objective task performance studies.

Double gloving: In the study, double, outer and inner gloving were compared in the both tasks. The results indicated that there was no significant difference between double and outer gloving use in the cold for bolt-nut task. Thus, double gloving may be recommended to be utilised in the cold for bolt-nut operations. This combination of using gloves may both maintain local hand thermal comfort and permit the retention of manual precision for efficient work such as bolt-nut task.

In the pick-up task, however, the results obtained showed that a difference between double and outer gloving is statistically significant. Also, it is interesting to see that the results obtained from task performance are in agreement with those from studies of subjective responses (Figure 7 in Paper VI). The improvement in the pick-up performance with outer-inner combination gloving observed was present. However, intuitively, wearing more gloves against cold should reduce hand dexterity. Our results seem rather difficult to explain why hand dexterity could be improved with one more inner glove in addition to the outer glove. One reason for this may be explained through a comparison of hand and glove size measurement. This assumed that although each subject tried to wear a fit glove the sizes of gloves used in this study were still larger, especially the finger diameter, and the lengths of three gloves (glove B, D and E) were too big to fit subject's fingers. This assumption may relate to an interaction effect between the subject and the glove (Table 3 in Paper VI). Wearing double gloves might meet the fitting requirement for the fingers through adding an inner glove due to their increased internal friction. Another reason may be that using available fit double gloving could increase the thermal insulation of gloves against cold.

Also, in some cases where people in the cold operations need to perform some precision tasks such as pick-up small objects with an inner glove or exchange a sweaty inner glove for a dry one, the way of double gloving can make these exchanges process more easy and convenient, and then enhance work efficiencies.

Furthermore, there are significant differences between inner and outer gloving as well as between inner and double gloving in the both tasks. The inner gloving gave a better hand dexterity compared with others due to its thinner thickness of glove material. The thickness of glove can affect the manual dexterity at –10 °C. However, it is important to note that due to the effect of hand cooling, the inner glove can not be used alone for a long duration in the cold (Fig. 3 of Paper VIII). Thumb/little finger skin temperature with the inner glove A at –10 °C was below the critical limit (13 °C) after 40/25 minutes, Also, it is easy to see from these curves that the finger skin temperature with the combination of inner glove A and outer glove B is higher than that with inner glove A. This combination shows a better thermal performance at –10 °C, since double gloving increases the thermal insulation of gloves against cold.

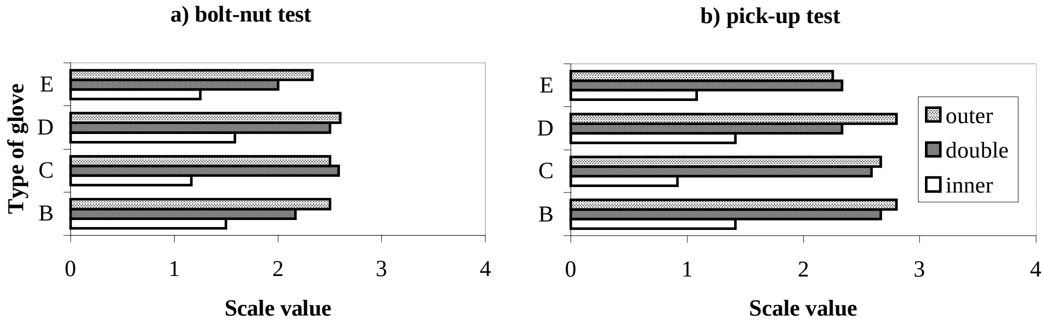

Figure 22. Subjective responses to the tasks performance with three types of gloving (outer, double and inner) at –10 °C. *(Note of scale: 0-Very easy; 1-Easy; 2-Neutral; 3-difficult; 4-Very difficult.).*

In addition to the measurements of task performance, the subjects also rated how difficult they found the tasks. Figure 22 shows these subjective responses for the tasks with three types of gloving (outer, double and inner). The mean response from six subjects with inner gloving appears between easy (1) and neutral (2); with double and outer gloving it was between neutral (2) and difficult (3), while that with outer gloving became more difficult (3). In all cases, it did not appear to become very difficult (4). As discussed above, an explanation for the results is due to the effect of thickness of glove on hand dexterity.

Tactile sensitivity (Paper VII)

Tactile sensitivity of gloved hands of subjects (eight males, ages: 25 to 42 years) has been studied by a designed identification test. This test investigates tactual performance of subject’s fingers through touching activities at work with a ”handing-up” using the different shapes (balls, cylinders, cubes and cap screws) and dimensions (5, 8, 10 and 15 mm) of the objects, which has been described in Paper VII. The experiments were designed based on different ambient temperatures. The experiments at –12 °C were run with 8 subjects by the five glove types (A, B, C, D and E); the experiments at –25 °C were conducted with 8 subjects by the three glove types (C, D and E). The subject performed the identification task twice for each trial: 1) after ten minutes standing in the cold and 2) after fifty minutes cold exposure. During the test, a subject with gloved hands identified the objects in a box through touching them and giving the answer according to the illustrations outside the box. Numbers of failed identification of the objects were counted during the test. As a result, the percentage of total misjudgement of the objects for each size was calculated. Also, subject rated both the thermal sensation (scale was ranged from 4 to -4, where 4 was defined as "very hot”, 0 as "neither warm nor cold” and -4 as "very cold”) and pain sensation (scale was ranged from 0 to 4, where 0 was defined as "no pain” and 4 as "very very painful”).

Analysis of variance (ANOVA): Table 6 shows the results of the ANOVA at both -12 °C and –25 °C, respectively. It can be seen that the probability for all null hypothesis that all the independent variables (glove type, object size, time of cold exposure and subject) have no effect which equals to or approaches zero for the case of -12 °C. This indicates that the independent variables all had a significant impact on the fail percentage of the total objects in the identification task at ambient temperature -12 °C. In addition, an interaction effect between glove type and subject at -12 °C may not be ignored at a significance level of 0.0076.

Table 6. Results of ANOVA for fail percentage of identification task at -12°C and -25°C

Temp. (°C)*	Source of variance	Sum Squares	d.f.	Mean square	F-ratio	Sig. level
-12	*Main effects*					
	A: Gloves	0.72	4	0.18	4.88	0.0009
	B: Object sizes	2.47	3	0.82	22.22	0.0000
	C: Subjects	2.11	7	0.30	8.12	0.0000
	D: Time in cold	0.49	1	0.49	13.18	0.0003
-25	*Main effects*					
	A: Gloves	0.04	2	0.02	0.48	0.6182
	B: Object sizes	1.33	3	0.44	10.25	0.0000
	C: Subjects	2.89	7	0.41	9.56	0.0000
	D: Time in cold	0.81	1	0.81	18.59	0.0000

*: Ambient temperature (°C)

In Table 6, it is interesting to see that all independent variables dominate the tactile discrimination except the type of glove at –25 °C. The probability for the glove type is 61.82 %. This means that the use of different types of gloves (C, D and E) under a very cold condition of –25 °C has not demonstrated to significantly affect the tactile sensitivity from a statistical point of view. For the case of –25 °C, all two-factor interaction effects, as shown in Table 6, are highly significant for the null hypotheses to be true and they will not be considered in the analysis.

Cold exposure: The tactual performance at -12 °C and –25 °C was investigated. It was demonstrated that the mean fail percentage of identification during an extended cold exposure for 50 minutes is significantly higher than that of a short cold exposure for 10 minutes. It is known that the finger skin temperature decreases with an increment in duration of the cold exposure, which leads to an impairment of tactile sensitivity with gloved hands. Clarke *et al.* (1958) found that when the hand and arm are cooled in the long cold exposure time, a number of physiological changes affecting the performance ability occur, for instance, vasoconstriction diminishes the flow of blood to the fingers, the duration of sustained muscular construction is affected at low muscle temperatures, the viscosity of the synovial fluid in the joints increases and diminishes the freedom of the fingers. Figure 23 shows that variation in the mean finger skin temperature during the cold exposure at –12 °C and –25 °C, respectively. In the both cases, an extended cold exposure results in a decrease in the finger skin temperature. Specially, the curves in Figure 23(b) illustrated that the finger skin temperature with the gloves during the deep cold (- 25 °C) exposure is below a critical limit which losses the sensitivity. The results (Morton and Provins, 1960; Holmér, 1994) indicated that tactile sensitivity shows a L-shaped response with little effect from moderate cooling and a sharp drop at the hand skin temperature of 6-12 °C.

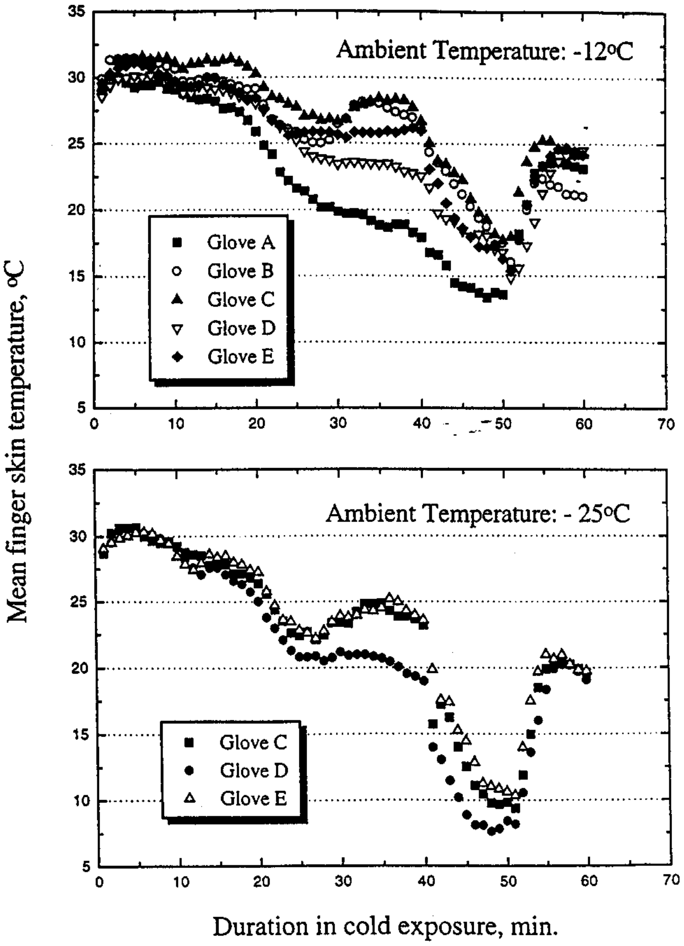

Figure 23. Mean skin temperature during cold exposure of 60 minutes (detailed procedure of the cold exposure is described in paper VII).
a): with 5 gloves at –12 °C; b): with 3 gloves at –25 °C.

Different gloves: The plots of fail percentage of identification for each type of glove at –12 °C and –25 °C are shown in Figure 24. It is seen in Figure 24(a) that at –12 °C the glove type A gives a superior tactile sensitivity, compared with the glove types B, C and D. This may be mainly contributed to the thickness of glove material. Obviously, Glove A is the thinnest among the others. The thickness of glove can favour the tactile discrimination during the cold exposure at –12 °C. The curves illustrated that the finger skin temperature of gloved hands during the cold exposure has not reached the sharp critical limit (6-12 °C) at which the fingers lose their sensitivity.

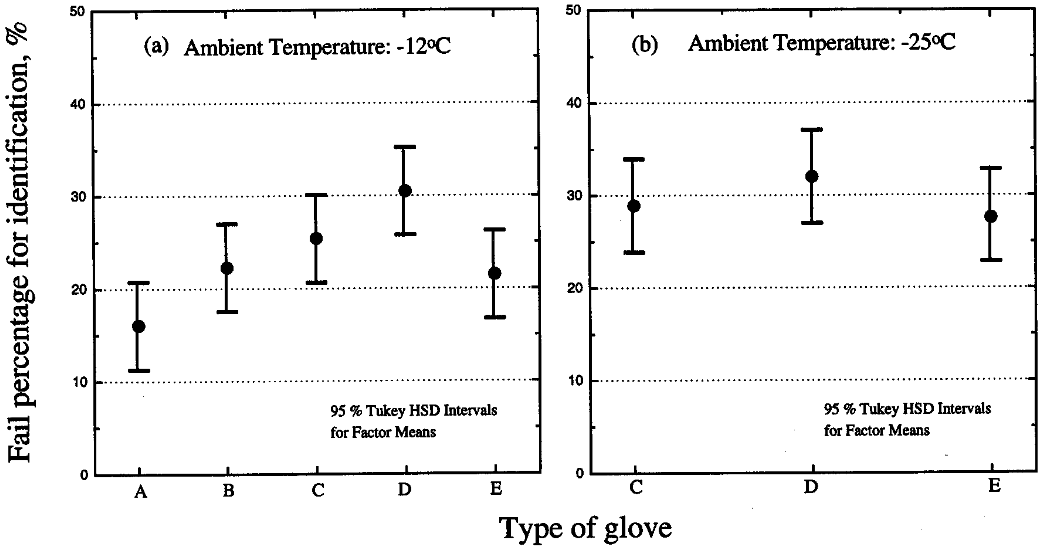

Figure 24. Mean fail percentage of identification for the cases: (a) with 5 gloves at –12 °C; (b): with 3 gloves at –25 °C.

In Figure 24(b), there are no statistically significant differences among the three types of gloves (C, D and E) at –25 °C. It is obvious that while there appears to be a strong relationship between ambient temperature and finger numbness, it is ultimately the temperature of the extremity itself which affects tactile discrimination. From a practical viewpoint, this means that since the hand is likely to be covered with these gloves, it is better to consider the finger skin temperature as the primary effect in loss of tactile sensitivity at such a cold climate. Figure 23 shows that the finger skin temperature with the gloves during the very cold exposure is below the critical limit (6-12 °C) at 45 minutes. In other words, the elimination of glove type effect on the tactual performance is due to the loss of tactile sensitivity of gloved hands at –25 °C

Subjective assessment: The results showed the subjective response of thermal sensation with various gloves during the cold exposure at –12 °C and –25 °C, respectively. In the case of –12 °C, subjects rated the lowest value when wearing glove A with the lowest insulation value. The thermal sensation with gloved hands is almost dependent on the insulation value of gloves used during the cold exposure at –12 °C. However, at –25 °C such a dependence with different gloves (C, D and E) disappears after the cold exposure of 50 minutes. The reason for this may be that the gloved hands were exposed for a long duration. A complete loss of hand comfort with gloves occurs during the extended cold exposure. This result can also be illustrated by pain sensation in Figure 8 of Paper VII. The same conclusion can be drawn from the subjective response for pain sensation at both –12 °C and –25 °C. The results from subjective response of thermal and pain sensations were in agreement with that from the objective task performance and hand/fingers skin temperature measurements studies.

In addition, Figure 25 shows empirical relations between T_{fsk} and the thermal or pain sensations in convective cooling at –12 and –25 °C for the cases of wearing glove D. It is seen that thermal sensation from cold in finger tip correlated linearly with mean T_{fsk} ($R^2 > 0.93$). It has been shown (Enander *et al.*, 1982; Chen, 1997) that subjective sensation is strongly correlated to finger skin temperature during hand convective cooling, in spite of considerable individual variation. The pain sensation in finger had a logarithmic correlation with mean T_{fsk} ($R^2 = 0.96$). This regression was associated with an earlier observation that onset of cold pain in the hand has been reported at hand skin temperature below 16 °C (Chatonnet, 1965).

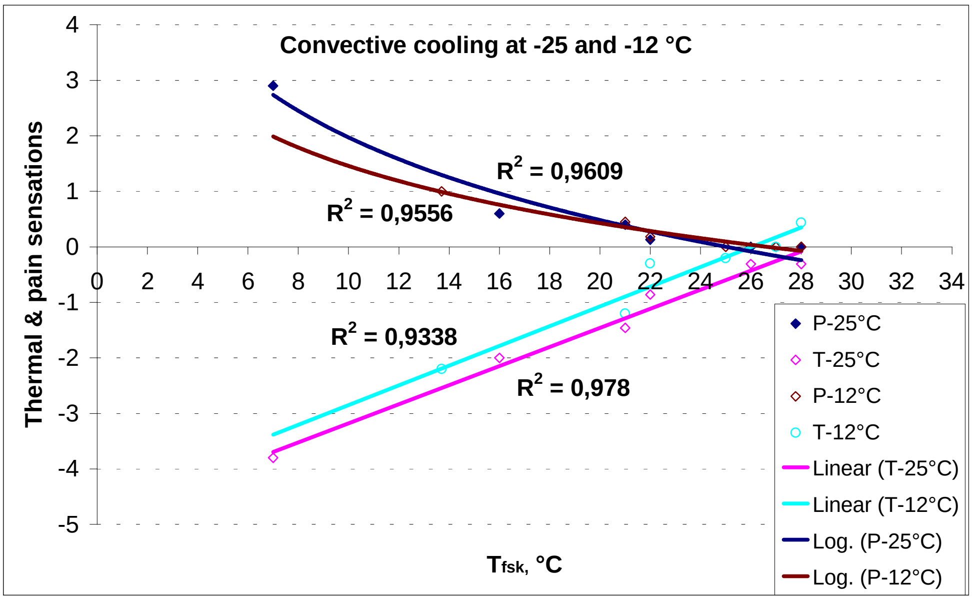

Figure 25. Relations between T_{fsk} and the thermal and pain sensations in convective cooling at –12 and –25 °C for the cases of wearing glove D.

The results showed that there are slight differences in subjective responses to both cold and pain between the two ambient temperatures. The subjects felt colder and more painful when T_{fsk} dropped below 18 °C at –25 °C than at –12 °C. Tochihara *et al.* (1995) and Chen (1997) mentioned in their studies of repeated exposures in cold air that a close relationship between T_{fsk} and pain sensation of the finger under various conditions was significant. However, Enander (1986) concluded that the relationship between hand skin temperature and thermal and pain sensations did not vary at ambient temperatures above –5 °C. The differences appeared because the subjective sensations were influenced by rate of cooling. The quicker cooling, the stronger responses to cold and pain.

4. Conclusions

1) A more rapid reduction of T_C occurred in conductive hand/finger cooling on cold metallic surfaces, compared to non-metallic surfaces. The conductive cooling diminishes T_C rather than the convective cooling in cold air.
2) Finger cooling on metallic surfaces is affected by pressure. This effect becomes less significant with a decrease in T_S. A T_S < -15 °C dominates over the effect of pressure for finger cooling on metallic surfaces. Since the subjects have less sensitivity for cold and pain at high pressures (> 9.81 N) in extremely cold situations, the temperature limit for finger protection in the cold is suggested to be determined with the data obtained at low pressures (< 3.0 N).
3) A temporary increase in T_C occurred during hand gripping cold objects due to a possible effect of the CIVD. Considerable performance (press tactile sensitivity and finger dexterity) loss after hand gripping the cold rods was found. A decrease of the hand skin temperature causes the loss of performance.
4) Cooling response of an electrically heated artificial finger on cold metallic surfaces, which follows most closely the Newtonian cooling law, is similar to that of human fingers. The cooling behaviour of human finger on extremely cold surfaces (< –20 °C) can be simulated by the artificial finger model.
5) Thermal and pain sensations vary linearly as an inverse function of the skin temperature in convective cooling. In conductive cooling, the rate of cooling has a considerable effect on the cold and pain responses.
6) Subjective thermal sensation is affected by rate of cooling, local skin temperature, duration and location of the cold exposure, pre-existing thermal state of the body, ambient temperature and type of the cooling, as well.
7) Besides the physiological state, psychological effects (i.e., motivation and emotional state) influence subjective sensations. This contributes to the inter-individual variation.
8) An ergonomic database for touchable cold surfaces based on the experimental data has been established for the protection of hand/finger in cold operations. The database, which is applicable for safety design of workstations, manual material handling jobs and tools design in the cold, has been prepared for a European standard.
9) The safety criteria for T_C are suggested to be 0 °C for risk of frostnip cold injury, 7 °C for numbness and 15 °C for pain sensation.
10) The duration of permissible cold contact is found to correlate with T_S and the thermal penetration coefficient of the material. Determined contact time for the critical T_C has been derived statistically from the database.

11) A significant impairment in dexterity and tactile performance occurred due to wearing gloves in the cold. In very cold environments (i.e., –25 °C), the effect of gloves on the tactile performance could not be separated from the effect of the cold fingers.

12) The use of a double (outer-inner) gloving system solves some problems of performing precision manual tasks for cold work of short duration. An inner glove is used for precision tasks at -10°C for 30 minutes. An electrically heated glove may be recommended to use as an inner glove for a prolonged cold operation (60 minutes at –20 °C).

13) The relationship between physical parameters, subjective responses and performance of manual tasks has proven to be a complex process, requiring further studies with the knowledge of ergonomics.

5. Further research needs

- Cold injury caused by wet hand/finger skin sticking on extremely cold surfaces is a common phenomenon during occupational and leisure actions, such as transferring some cold objects from freezer with wet hands. Although the problem is well known, the information about quantitative measures of this phenomenon is lacking and no published data is available to our knowledge. Thus, a study on this topic is needed to prevent the cold injury due to sticking effects.
- The human finger cooling behaviour on extremely cold metallic surfaces (lower than -20 °C) can be simulated by a recently developed artificial finger model. Further development of the instrument is needed for the cases of touching non-metals at T_S below -20 °C.
- Effect of wind chill on hand cooling is often encountered in cold operations. An investigation on the effect of wind chill on hand cooling response and performance with and without gloves in cold climate is suggested.
- Present criteria concerned cold smooth surfaces of non-coated material. It is known that the texture of the surface can affect the nature of contact cooling. Additional cooling threshold values for coated/rough metallic surfaces at extremely cold conditions could be studied by using artificial finger.
- Investigations of the effects of different protective gloves on hand performance, especially in work sites, are suggested.
- Present work only concerned one test order of double-single gloving. A further study will deal with a single-double gloving order to compare and evaluate the order effect of experiments.
- Prolonged exposure to the cold results in more reduction of the hand/finger skin temperature, even with protective gloves. Further studies on design of an electrically heated hand-wear to maintain sufficient thermal comfort and optimise manual dexterity will be expected, particularly for specific tasks.
- The present design of an electrically heated inner glove impairs more or less the manual performance and touchable comfort due to the elements between the hand skin and the glove. Therefore, it is desired to devise a satisfactory combination of an electrically heated outer mitten (finger part of the mitten can be opened) with a thin inner glove.
- Experiments are needed to test the advanced material, shape, size, thermal performance and even appearance of working gloves, which are related to practical task requirements as well as individual users in the cold climate.

6. Summary

Qiuqing Geng. *Hand Cooling, Protection and Performance in Cold Environments.* Arbete och Hälsa 2001:4.

This dissertation presents experimental data on hand/finger cooling responses and performance with and without gloves in cold environments.

The first part concerned studies of hand/finger cooling behaviors under various cold conditions. It included 1) literature study; 2) experimental studies with human subjects; 3) development of an instrumentation for predicting contact temperature (T_C) limits; 4) establishment of a database and 5) the preparation of a standard for touchable cold surfaces. The experimental results with human subjects indicate that a more rapid reduction of T_C occurred when finger/hand contacted metallic surfaces, compared to non-metallic surfaces. A reduction in T_C is a function of skin and material's surface temperature (T_S), thermal properties of the materials and the nature of the contact as well. Manual performance (tactile sensitivity/finger dexterity) reduced after gripping the cold objects for 10-20 minutes. A decrease of the hand skin temperature causes performance loss. The safety criteria for T_C are suggested to be 0 °C (freezing), 7 °C (numbness) and 15 °C (pain sensation). An electrically heated finger model was developed and used to derive additional cooling information for extremely cold metallic surfaces (<–20 °C). All results were utilized to establish relations between contact temperature, contact time and material used and compiled in an ergonomic database. The information can be used for risk assessment and for setting temperature limit values for products in appropriate standards for cold work. The data are applicable for all fields where cold surfaces cause a risk of hand/finger contact cooling.

The second part presented studies of manual performance such as dexterity and tactile sensitivity of gloved hand in cold operations. The relation between physical properties of protective gloves and hand performance were evaluated objectively and subjectively. Human subjects wearing four different work gloves and three different types of gloving (outer, inner and double) participated in the experimental studies during cold exposure. It is indicated that wearing various work gloves gives impairment in both manual dexterity and tactile sensitivity in cold operations. The performance was affected both by glove design and by hand/finger cooling. In extremely cold exposures hand cooling overrides the effect of glove on tactile performance. Use of double gloving (outer-inner combination) is recommended to be an appropriate approach to use protective gloves in the cold, while inner glove can be used to perform some precision works. The inner glove may be used at –12 °C for 30 minutes since the finger skin temperature did not fall down to 15 °C. An electrically heated glove that improved maintenance of warmth could be considered for hand protection in a prolonged cold operation.

7. Summary in Swedish

Qiuqing Geng. *Hand Cooling, Protection and Performance in Cold Environments.* Arbete och Hälsa 2001:4.

Denna avhandling presenterar experimentella data på hand - och fingernedkylning och funktionsförmåga hos handen med och utan handskar i kyla.

Den första delen omfattar hand och fingernedkylning under olika kalla betingelser. Den innefattar 1) litteraturgenomgång, 2) experimentella studier med mätningar på människor, 3) utveckling av ett mätinstrument för bestämning av kontakttemperatur, 4) skapandet av en databas och 5) framtagandet av förslag till en standard för bestämning av temperaturgränsvärden för kontakt med kalla ytor. Resultaten med försökspersoner visade en snabbare minskning av kontakttemperaturen när finger/hand kom i kontakt med kalla metallytor jämfört med andra ytor. Temperaturminskning var en funktion av hud - och materialytornas initialtemperatur, materialens termiska egenskaper samt kontaktbetingelserna. Händernas känsel och fingermotorik försämrades efter
10-20 minuters grepp om en kall cylinder. En nedgång av hudtemperaturen är huvudorsaken 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 uppvärmd fingermodell har tillverkats för att härleda ytterligare information om nedkylningsreaktionen vid kontakt med extremt kalla metallytor (<-20 °C). Med hjälp av dessa resultat har generella samband mellan kontakttemperatur, kontakttid och material tagits fram och samlats i en ergonomisk databas. Informationen kan användas för riskbedömningar och för att sätta temperaturgränser för produkter i lämpliga standarder gällande kallt arbete. Dessa data är tillämpliga på alla områden där kalla ytor utgör en risk för hand /finger nedkylning.

I den andra delen har fingerfärdighet och känsel med handskar utforskats under kallt arbete. Sambanden mellan olika fysiska egenskaper hos skyddshandskar och betydelse för handfunktion utvärderades objektivt och subjektivt. Försökspersoner bar fyra olika skyddshandskar med i tre olika kombination (ytter, inner - och dubbel) och exponerades för omgivningstemperaturer mellan –10 och –25 °C. Resultaten visade att alla arbetshandskar minskade både fingerfärdighet och känsel vid kallt arbete. Handfunktionen påverkades av såväl handskkonstruktion som hudtemperatur. I extrem kyla överskuggade handnedkylningen effekten av handske på känseln. Dubbla handskar (ytter och innerhandskar) rekommenderas i kallt klimat. Innerhandsken kan då användas för att genomföra vissa precisionsuppgifter. Innerhandsken kan användas vid –12 °C under 30 minuter utan att handens kyls ner till 15 °C. En elektriskt uppvärmd handske förbättrade värmbalansen och kan användas för att skydda händerna under långvarigt manuellt arbete i kyla.

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