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# **Contact Cooling and its Effects on Manual Dexterity**


**By S. L. Powell**

**A Doctoral thesis**

**Submitted in partial fulfilment of the requirements for the award of  
Doctor of Philosophy of Loughborough University**

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## **Abstract**

In industry, it is common for workers to be exposed to a variety of cold surfaces including machinery parts, walls and tools that have cooled to ambient conditions or are cooled by the production process. Although there is legislation and there are guidelines to protect workers and minimise safety risks in environments where there may be hot surfaces (Skin Burns; EN 563:1994), this is not the case for environments containing cold surfaces.

It was hence decided by the European standardisation organisation CEN that a standard should exist to outline the risks associated with contact with a cold material in terms of skin damages, discomfort and effects on manual dexterity.

Data was collected for the development of a cold surfaces standard (European Union project SMT4- CT97-2149). The standard should provide information on the relationship between contact material type, surface temperature and the subsequent risk of pain, frostbite and manual dexterity deficits after prolonged exposure.

Further research, related to this standard was performed and is described in this thesis. It was found that the draft standard did not identify the full range and aspects of manual dexterity affected by contact cooling. It was determined using data collected for the standard, that people would withstand longer durations of contact with materials with low contact coefficients such as wood or plastic than they could when in contact with materials with higher contact coefficients such as metals, even when the latter were at much higher temperatures. It was thought this could have a direct effect on manual dexterity after contact with the low contact coefficient materials resulting in different aspects of manual dexterity being affected when compared to the effects of contact with a high contact coefficient material.

To study this further, four tests were identified through a literature review and were chosen on their ability to discriminate different aspects of manual dexterity, on their validity and their reliability. These four tests, A strength test, a tactile sensitivity test, a speed test and a nut and bolt test, were then used to determine any manual dexterity deficits occurring as a result of contact cooling with materials from both ends of the contact coefficient scale. This was important due to the uneven and unique properties of contact cooling when compared to cooling by air or water. It was observed that different aspects of manual dexterity were affected as a result of contact with materials of differing contact coefficients and that strength and speed were affected the most in both fast and slow cooling conditions.

All the experimental work for the standard was based on the dominant hand of individuals. As both hands are used in day to day activities it was felt necessary to ensure that the standard would indeed protect against the worst case scenario, and that contact cooling did not appear to be significantly worse in the non dominant hand when compared to the dominant hand. In terms of manual dexterity deficits, strength was the only aspect that was significantly decreased in the non dominant hand when compared to the dominant hand. It was found that pain was no worse for the non dominant than the dominant hand in the tested population.

Again to ensure the protection of the majority of the population it was necessary to consider factors such as the effect of blood flow. Many common events can affect blood

flow to the hands, including tight clothing, injury through vibration and disorders such as Raynauds Phenomenon or body cooling proceeding the contact exposure. As differing effects of contact cooling had already been identified as a result of contact with different materials, it was decided to investigate the effect of blood flow on contact cooling, similar to studies mentioned above, with materials from both ends of the contact coefficient scale. It was determined that for the non metals (nylon, wood) blood flow (high versus none) had a significant effect on cooling speed but in the condition with metals where cooling was faster, there was no significant effect of blood flow on cooling.

As blood flow was identified as having a significant effect on cooling as a result of contact with a cold material, it was decided to investigate if there was in fact any difference in blood flow between the dominant and dominant hand. Although there were no differences in terms of manual dexterity deficits between the dominant and non dominant hand the possibility of differences occurring in cooling speed was not investigated. Again this was done to ensure the standard had suitably protected against worst case scenarios. It was found that there was no significant difference in resting blood flow between the dominant and non dominant hand.

The ergonomic implications for the findings of this research are: 1) The standard as it stands should protect 75% of the population in accordance with its objective, however, special attention should be paid to workers with circulatory disorders or who are exposed to conditions that affect blood flow. 2) The effects of contact cooling on manual dexterity are more pronounced than accounted for in the standard for longer term contact with materials with low contact coefficients. For cases of contact with a material with a high contact coefficient, on the other hand, skin damage would usually result before manual dexterity is severely affected, so the standards safety limit for frostbite is sufficient for safety and no separate manual dexterity criterion is required.

Keywords: manual dexterity, contact cooling, blood flow, hands, cold pain, cold injury

# STATEMENT

The work presented in this thesis was part funded by the science faculty of Loughborough University and part funded by the European Union project SMT4-CT97-2149. The data collected for this project by the Author (Chapter 3) was used in part to develop a standard for "temperature limits for cold touchable surface" by the European standards committee: CEN TC122/WG3.

The study described in Chapter 6 represents work conducted jointly by the Author and Ms. L. Cobb. The Author was responsible for assisting with the supervision of Ms. L Cobb during this, her BSc dissertation work. The Author designed the experiment and re-analysed the raw data obtained in this study for inclusion in this thesis.

The study described in Chapter 7 represents work conducted jointly by the Author and Ms. J. Edwards. The author was responsible for the design of the experiment and assisting with the supervision of Ms. J. Edwards during this, her BSc dissertation work. The Author reanalysed the raw data obtained in this study for inclusion in this thesis.

# **1 General Introduction**

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## **1.1 Chapter Summary**

This chapter introduces the research issues covered in this thesis. It considers the background to the research and issues involved in contact cooling. It also shows the need for empirical research to provide better understanding of how people react to such environments.

## **1.2 Introduction**

Many studies into the physiological responses of humans to the cold have been completed. The benefits of this work are obvious as a cold environment can present many hazards including excessive heat loss from the body, pain and decreases in manual performance. By knowing the responses of man to a cold environment, it is possible to predict the level of discomfort and the likely effects of being exposed to such an environment. This will enable the effective reduction of the effect of cold on man by providing adequate protection to compensate for the cold (i.e. gloves). Alternatively, it will allow the prediction of the point (in terms of time and/or temperature) at which the cold will become detrimental to the performance of and/or the safety of the human.

There is very little work to date however that deals with the specific problems associated with contact cooling. Contact cooling may occur where machinery is operated in cold conditions, for example, by the accidental touching of machinery surfaces in cold environments, or by the sustained gripping of cold tools (e.g. a hammer or a gun). If the

contact is accidental, it is likely that the contact will only occur for a very short time because behavioural reactions such as removing the hand will break the contact with the cold surface. Contact for a short duration with a cold object may result in surface tissue cooling, which in turn may lead to tissue freezing. If, however, the contact is as a result of handling a tool then the contact can be for much longer periods of time resulting in deeper tissue damage, whole hand frostbite and numbness which will effect the manual dexterity of the person.

A research group was formed in response to this identified lack of information for contact cooling with the aim of completing a guideline document that will form the basis for the development of a European Standard. It was thought that this aim could be realised by reviewing the work done to date in this area, conducting experiments and forming databases from the information gathered in these experiments. It was then intended that mathematical modelling could be used to predict the physiological responses of people after the point where it would no longer be ethical to use 'real' subjects.

Five institutes across Europe were involved in this project, they were: Loughborough University, England, The National Institute for Working Life, Solna, Sweden, Institute of Perception Research, Soesterburg, The Netherlands, The Regional Institute of Occupational Health, Oulu, Finland and Louvain Catholic University, Brussels, Belgium.

This thesis will represent partly work done for this project, but also builds on the original project work. It describes a number of investigations on the effects of long term exposure (>5 minutes) to cold surfaces and the effects that this has on manual dexterity and subjective sensations.

### **1.3 International and European Standards Relating to Work in the Cold**

There are several International Standards that deal with working in the cold. These standards include ISO/DIS 12894 -Ergonomics of the thermal environment - Medical supervision of individuals exposed to extreme hot or cold environments and ISO TR11079 Evaluation of cold environments - Determination of required clothing insulation. Neither of the above two standards however adequately deal with the specific problems posed by contact with cold surfaces. ISO/DIS 12894 states that frostnip leading to frostbite may

occur as a result of contact with a cold surface. The standard then gives a description of the appearance of frostnip and frostbite, and the first aid treatment that should be given, but doesn't give any information as to the avoidance of such injuries or 'safe' contact temperatures and durations. ISO TR 11079 doesn't deal with the issues arising from contact with cold surfaces. The British Occupational Hygiene society's (BOHS) Technical Guide Number 8 states that special attention should be paid to keeping worker's hands warm if they are working in conditions below  $-16^{\circ}\text{C}$  for more than twenty minutes at a time. It then goes on to state that metal handles and tools should be covered by thermal insulating material for work at temperatures below  $-1^{\circ}\text{C}$ . The report however doesn't state any research or data that would validate this statement. The report however does advise that gloves should be worn by people when fine manual dexterity is not required for sedentary work where the air temperature is below  $6^{\circ}\text{C}$ , below  $4^{\circ}\text{C}$  for light work situations ( $120 \text{ Wm}^{-2}$ ), and at air temperatures below  $-7^{\circ}$  for moderate work ( $170 \text{ Wm}^{-2}$ ). The report also states that anti-contact gloves should be worn to prevent contact frostbite when cold surfaces below  $-7^{\circ}\text{C}$  are within reach. Again the data or research for the basis of these assumptions has not been stated, and it is thought that the following experiment will show that this report does not advise adequate protection for the worker.

The Health and Safety (HSE) information sheet for Workroom Temperatures in Places where Food is Handled has no advice for 'safe' contact temperatures.

There is obviously a real need for information in this area.

#### **1.4 Conduction, Convection and Radiation between Materials**

For the following studies, the majority of heat transferred is by conduction, from the hand to the bars of material, although heat will also be transferred by radiation and convection. Heat will always flow from higher temperatures to lower temperatures. This is known as heat transfer. The rate of heat flow is dependent upon several factors including the conductivity of the material, and always follows the laws of thermodynamics.

The first law states that 'the change in the internal energy of a system is equal to the heat added to the system minus the work done by the system, that is, there is conservation of energy. The amount of heat given up by one system, which is interacting, with another

system, is equal to the amount taken up by the second system.' (Parsons 1993). The second law of thermodynamics states that heat flows from a hot body to a cooler body, but not vice versa. Conduction (the transmission of heat through a substance from a high temperature to a low temperature) occurs in one of two ways depending upon the state of the material. In gases and most liquids the heat energy is transmitted mainly by collisions between atoms and molecules with those possessing lower kinetic energy. In solid and liquid metals, heat is primarily transferred by the migration of fast moving electrons, followed by a collision between these electrons and ions.

The conductivity of a material is a measure of the material's ability to conduct heat. All objects that have a temperature above 0 Kelvin give off thermal radiation. Heat transfer occurs as a result of energy travelling in the form of electromagnetic waves or photons from a hot 'body' to a cooler object. Convection is a process by which heat is transferred from one part of a fluid or gas to another by the movement of the fluid itself. Natural convection occurs as a result of gravity, where the hotter part of the fluid expands and becomes less dense. This hotter fluid is then displaced by the colder, denser fluid, which then sinks below it. Convection also occurs in air although the effect is usually less pronounced (ASHRAE 1993).

In summary, to determine the reaction of the skin surface when in contact with a cold surface, it is important to determine the 'type' of contact. Heat will always flow from the warmer finger to the cooler bar surface. However, the rate at which this will occur depend upon several factors, including the properties of the two surfaces, the contact time, the surface area of the skin exposed to the cooler object and how 'perfect' the contact with the block is. The latter factor is related to the amount of pressure that the finger is exerting onto the block. The greater the pressure, the 'better the fit'.

## **1.5 Earlier Studies on Contact Cooling**

### **1.5.1 Gripping**

Havenith, Heus and van de Linde (1992) studied the cooling rates and resulting comfort and pain levels for twelve subjects, touching six different materials (polyurethane foam, wood, nylon, rust proof steel, aluminium and a water perfused aluminium tube with an infinite heat capacity, at four different temperatures (10 °C, 0°C and -10°C). The subjects

were asked to grip a cylinder of material applying just enough pressure to lift the cylinder, which was suspended by a cable. It is good that the experimenters attempted to control the amount of pressure that the subjects applied to the bar, although different pressures could have been tested. The subjects were exposed to the bars either after rest or exercise. All trials were done with and then without gloves. The cooling curves were analysed as Newtonian cooling curves, which appeared to be significantly related to the material's contact coefficient, the presence of hand protection, the preceding exercise and the interaction between the contact coefficient and the presence of protective hand-wear. It was also found that thermal sensation and pain could be described in terms of local skin temperature, ambient temperature and hand protection. The pain and thermal sensations reported for the contact area of the hand was the same as those reported for the back of the hand for the lower temperatures. It was found that when the subjects reported that they were 'slightly painful' a skin temperature of 16°C for the back of the hand and 19°C for the palm of the hand was common. The presence of pain and its level appeared to be inversely proportional to the cooling speed of the hand and skin freezing occurred at lower skin temperatures when touching cold objects than it did when the skin was merely exposed to air. This was as a result of supercooling. It was possible for the experimenters to produce calculations for the safety limit for hand cooling whilst in contact with a cold material. However, Chen (1994), points out, that some subjects suffered from frostnip because the temperatures of the subject's hands were average temperatures for the whole hand. Contact cooling does not result in a uniform cooling, so some spots were colder than others were. For this reason more thermocouples should be used and each individual temperature should be considered.

### **1.5.2 Touching**

Chen, Nilsson and Holmer (1994) examined the change in finger skin temperature for twenty subjects touching aluminium at -7°C, 0°C and +7°C, with a pressure of 0.1N, 5.9N and 9.8N. Two aluminium blocks were used that had two different masses, 3559g and 108g. The subjects were asked to place their left hand into a small chamber and touch the block in the chamber with the first section of their index finger. It was found that all the factors listed above had significant effects on the contact skin temperature with time. The study also confirmed that the contact temperature change over time could be successfully described using a modified Newtonian model though these authors used a double

exponential curve. The results of this study also indicated that metal surfaces in contact with bare hands should not be below 4°C. If surfaces with lower surface temperatures than this are present, then users should wear protective gloves. Chen also conducted several other experiments of a similar nature to the one detailed above. They all confirmed that cooling curves could be analysed as a Modified Newtonian curve with two time constants. The first time constant describes the initial sharp decrease in contact temperature upon initial contact with the cold surface and the second time constant describes the slower decrease in contact temperature that subsequently follows.

Geng *et al.* (2000) investigated the effects of material and contact pressure, and Rintamäki (1997) investigated the effects of contact area on contact cooling. Little work has been carried out though in an extensive or exhaustive manner to fully identify effects of contact cooling on physiological and psychological responses. Below is a table taken from Holmer and Geng (2000), describing the types of contact cooling that may occur and some typical actions leading to the contact.

**Table 1.1. Examples of Typical Contact cooling Durations (Holmér and Geng, 2000)**

Contact Duration	Examples for contact with cold surface	
	Intentional	Unintentional
1 second		Touching of a metallic surface (-15°C or below) and quick removal following pain sensation
3 seconds	Activation of a pressing, switching a button or removing a small spare part by the fingertips	Touching of a cold surface for extended reaction time (on metal of -15°C and below) has numbness sensation and even may result in cold injury
10 seconds	Prolonged activation of a slight adjustment of a switch, handle, hand-wheel, valve or spare part etc. with finger touching	Falling against a cold surface without recovery
100 seconds	Turning of a hand-wheel, handle valve or crew bolt-nut etc. possibly with finger touching	After slipping and falling accidents on cold surfaces, victim unable to get up

## 1.6 General Overview of the Thermoregulatory System

### 1.6.1 Environmental Parameters Affecting Body Temperature

Humans are homeotherms, this means that they need to maintain an internal temperature of approximately 36.9°C to maintain well being. To do this, internal temperature is

maintained through heat balance. This means that the amount of heat produced within the body should equal the amount of heat transferred away from the body. The following equation represents the heat balance that occurs in the human body.

$$(M - W) = E + R + C + K + S$$

Where

M = Metabolic rate of the body

W = Energy used to produce mechanical work

Heat transfer can occur in the following ways

E = Evaporation

R = Radiation

C = Convection

K = Conduction

S = Heat storage of the body

For heat balance,  $S = 0$

If S is greater than 0 then heat is stored and body temperature will rise, if S is less than 0 then heat is lost to the environment and body temperature will decrease.

## 1.7 Environmental Parameters

There are four basic environmental parameters that affect human response to the thermal environment. These are air temperature, radiant temperature, humidity and air velocity. Air temperature could be defined as the temperature of the air surrounding the body. Heat exchange may take place between the body and the surrounding air (e.g. if the air is cooler than the body, then heat may pass from the body to the surrounding air although air close to the body is generally warmer than the prevalent air temperature). Heat is given off and absorbed by all bodies via radiation. In many situations, there is a radiant source, e.g. an electric heater in a room, or the sun. In this instance, the radiant temperature may be significantly different to the air temperature in that same room. If however, there is no radiant source, then the air and radiant temperature will be very similar. As the subject's hand will be at a warmer temperature than the air in the freezer, a small amount of heat will be exchanged in the following experiments by the net heat flow of heat from a hot (hand) body to a cooler environment (the air in the freezer).

Air movement over the body can affect body temperature in terms of draughts and evaporation of sweat. Differences in air speeds will obviously affect the body temperature to a varying degree. Humidity is also an important factor when considering the factors that can affect a human's temperature. If sweat is heated by the body and evaporated into a vapour, which passes into the air, for example, then heat is lost to the surrounding air cooling the human. The sweat is evaporated because of the difference in mass per unit volume of moist air between the skin surface and that of the surrounding environment. The higher the air temperature, the more water vapour can be held in suspension in the air. As the air temperature in the freezer will be very low (the lowest air temperature to be used will be  $-35^{\circ}\text{C}$ ) the air will have a very low partial vapour pressure.

## **1.8 Personal Parameters**

In addition to these environmental parameters there are also two personal parameters which are metabolic heat production (activity levels) and the amount of clothing worn by the person. The amount of heat produced as a by-product of metabolic activity varies as a result of activity level. If a human is undertaking hard exercise, then the human will feel a lot hotter than if the same human in the same environment is sat down reading a paper. Clothing also affects the temperature of the human wearing it, as the more clothing worn (in the same environment); the warmer the human will become. Clothing properties should also be taken into account. Clothing was standardised for all subjects in the following experiments.

The interaction of these six parameters determines how a subject will respond to a given thermal environment. For example, air movement combined with air temperature will affect the rate of evaporation and therefore the rate of body cooling.

## **1.9 Behavioural Responses**

Behavioural responses can also affect the temperature of a human. The behavioural responses to a thermal environment often occur if a person is rapidly heated or cooled. The perception of change in the thermal environment may provoke a behavioural response in the form of the subject removing clothing (in the case of a cold environment turning warm) thus exposing a greater area of body to the external environment. Standing next to a heater or wrapping arms around the body (in the case of a warm environment turning cold) would also be examples of behavioural thermoregulation. If the thermal stimulus is more intense

than a warm environment turning cool, then a more severe reaction is sometimes observed. This reaction is often not voluntary. An example of this would occur if a person touched a very cold material. The natural reaction of this person would probably be to withdraw their hand from the painful stimulus as quickly as possible. However, in some situations, subjects are also exposed to longer contact exposures, where contact with a cold material didn't occur by accident but by design (as in the case of a person using tools etc.).

### **1.10 Physiological Responses**

Physiological responses are involuntary responses caused by a change in internal temperature. Examples would include sweating, vasoconstriction, piloerection, vasodilation or shivering.

Temperature sensors are located in both the skin and the hypothalamus. The skin thermoregulators, are actually free nerve endings that can be divided into two types: warm or cold. These thermosensors are connected to the hypothalamus by nervous pathways. The anterior hypothalamus and preoptic region control heat loss and the posterior hypothalamus is involved with vasoconstriction and shivering.

Sweating aids heat loss by secretion of a liquid onto the skin's surface which is heated by the skin and eventually evaporated under the appropriate conditions. In a hot environment the evaporation of sweat is the dominant method for maintaining a stable core temperature.

Vasoconstriction and vasodilation are discussed in more depth later, however a brief overview shall be given here. During vasodilation, venous blood returns near to the skin's surface. This increases the amount of heat at skin level able to be lost to the environment. In vasoconstriction the constriction of superficial veins results in cool blood from the skin returning along the venae comitans close to the artery. This means that heat is gained on its return to the body core.

Piloerection occurs when the skin decreases in temperature and the arrector anterior pili muscles contract. This results in the tiny hairs on the skin's surface standing on end and trapping a boundary layer of air between the skin and the environment. Whilst this

boundary layer or air is effective in insulating animals with more hair, due to the sparse nature of hair on the human, this is generally considered to be an ineffective method of thermoregulation (Parsons 1993).

Bligh (1985) described shivering as "simultaneous asynchronous contraction of muscle fibres in both the flexor and extensor muscles". If the body temperature starts to fall, then the metabolic rate starts to increase initially as a result of increased muscle tone, then as a result of shivering.

### **1.11 Thermal Comfort and Subjective Scales**

Thermal comfort is defined as 'that condition of mind that expresses satisfaction with the thermal environment' (ISO 7730, 1994). The subjective measurements are in the form of scales such as the Bedford Comfort Scale (1936) or the ASHRAE sensation scales (1996). The ASHRAE scale is more commonly used as it can be easily compared to the Predicted Mean Vote (PMV) thermal comfort index (Fanger 1970). Fanger hypothesised that the degree of thermal discomfort was a function of thermal load and physical activity. Fanger (1970), Nevins *et al.* (1966) and McNall *et al.* (1968) provided the data on which the PMV was based. Fanger's PMV index gives the mean vote of a large number of people at known environmental conditions as if they had rated their thermal comfort on the ASHRAE scale which is numbered from +3 (hot) to -3 (cold). The PMV can be estimated when clothing and activity are established and the six parameters (described above) are measured. The PMV is based on heat balance. Man is in heat balance when the internal heat produced is equal to the loss of heat to the environment. The Fanger model is used in an international standard to assess moderate thermal environments 'ISO 7730 (1994) - Determination of the PMV and PPD indices and specification of conditions for thermal comfort'.

#### **1.11.1 Thermal Sensation**

Thermal sensation is related to mean skin temperature (Gagge *et al.* 1967). Havenith (1992) found that subjective temperature scores were related to the local skin temperature of the hand during contact cooling. Havenith (1995) also found that central body temperature had no influence on thermal or pain sensations.

The skin acts as the thermal interface of the body with temperature receptors distributed over the body. Different areas of the body have different concentrations of temperature receptors, the majority of which are in the fingers and toes, with lesser numbers on the hands and feet (Clark and Edholm 1985). Enander (1982) showed a correlation between the temperature of the hand in air and thermal sensation across several temperatures. She also found that the thumb showed the best correlation. It was determined that a hand skin temperature below 20°C resulted in the thermal sensation of cold, with the first sensations of cold starting to be experienced around 28°C.

### **1.11.2 Pain**

Eide (1965) describes cold pain as being caused by "...local vasoconstriction giving rise to pain and the pain elicits the pressure reaction and cardio-acceleration mediated by some complex central mechanism". Cold pain has been reported as being experienced over a range of temperatures. Havenith *et al.* (1992) determined that the sensation of pain (slightly painful) began at temperatures of 12-20°C for the back of the hand and 14-23°C for the contact palmar aspect. Enander (1982) determined that no pain was experienced at temperatures in excess of 20°C. Havenith *et al.* (1992) therefore concluded, that as neither pain nor thermal sensations were affected by ambient air temperature, then they must be affected by the actual hand temperature independent upon the rate of cooling.

The methods by which the sensation of pain can be assessed were reviewed by Merksey (1973). It was noted that complaints of pain were resultant upon a range of physiological factors and that there is much inter individual differences. It was also noted that sex, ethnic origin and moods affected pain complaints.

The following methods for assessing pain can be used; threshold of pain complaint, maximum tolerance, duration of pain to a fixed stimulant, verbal visual or auditory ratings and dosage of drug required to abate pain.

## **1.12 Manual Performance in the Cold**

Manual dexterity can be defined as a motor skill that is determined by a range of motion of arm, hand and fingers and the possibility to manipulate with hands and fingers (Havenith *et al.* 1995).

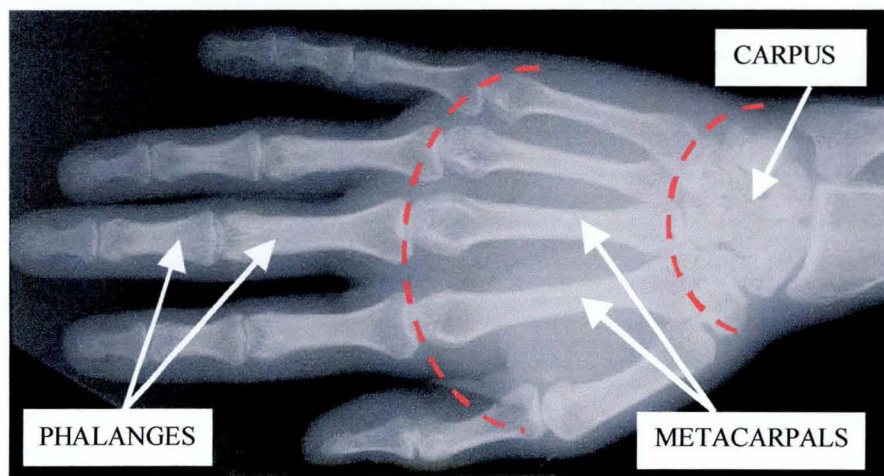
Manual dexterity can be divided into five factors that constitute overall dexterity (Fleischman and Hempel (1954): 1) finger dexterity (ability to manipulate and co-ordinate finger movements when performing tasks requiring fine manipulation), 2) manual dexterity (the ability to make skilful arm movements and hand movements without using the fingers), 3) wrist finger speed (ability to make rapid wrist flexing and finger movements) 4) aiming (ability to perform quickly and accurately a series of movements requiring hand eye co-ordination and 5) positioning (less well understood, but is different from aiming and involves a movement of the hand from one location/position to another). Factors like tactile sensitivity and force capability and sustainability also influence manual dexterity however.

The effects of cold on manual dexterity (i.e. cold is detrimental to manual performance unless adequate protection is worn) have been known for many years now. An example cited in 'The Impact of Environmental Conditions on Human Performance' illustrates for example, that Osbourne and Vernon (1922) showed that at cooler temperatures, the likelihood of industrial accident increased significantly.

There are many different tests to determine the different aspects of losses in manual dexterity. These tests include the Purdue Pegboard, O'Connor Dexterity test, The Minnesota Rate of Manipulation, The Plate tapping test and the Macworth V test.

### **1.13 Structure of the Hand**

The hand consists of twenty-seven bones. These form the carpus, metacarpals and phalanges. Figure 1.1. shows the bones of the human hand from the dorsal aspect.



*Figure 1.1. The bones of the Human Hand (Dorsal aspect) (Eaton 1997)*

The wrist (carpus) consists of 8 carpal bones. These bones are arranged in two rows. Each row consists of four bones. The palm of the hand (metacarpus) consists of 5 metacarpal bones. Each bone consists of a base, a shaft and a rounded distal head. The head is rounded for articulation with the base of each proximal phalanx. There are fourteen phalanges that form the skeletal basis of the digits. Each single bone is called a phalanx.

The muscles that allow the hand, wrist and fingers to move are primarily situated along the forearm. These muscles can act on two joints - the elbow and the wrist, or the hand and the digits. The muscles primarily have four actions. These are - supination, pronation, flexion and extension.

**Table 1.2. Intrinsic Muscles of the Hand (taken from Concepts of Anatomy and Physiology - Van De Graff)**

Muscle	Action
Abductor pollicis brevis	abducts the joint of the thumb
Flexor pollicis brevis	flexes the joint of the thumb
Opponens pollicis	opposes joints of thumb
Abductor pollicis (oblique and transverse heads)	adducts joints of thumb
Lumbricales	flexes digit at metacarpophalangeal joints; extends digits at interphalangeal joints
Palmar interossei	adducts fingers toward middle finger at metacarpophalangeal joints
Dorsal interossei	abducts fingers away from middle finger at metacarpophalangeal joints
Abductor digiti minimi	abducts joints of digit v
Flexor digiti minimi	flexes joints of digit v
Opponens digiti minimi	Opposes joints of digit v

## 1.14 Skin

The skin is the largest organ of the body. The skin consists of three distinct layers, the epidermis, dermis and hypodermis. It is of variable thickness approximately 1-2 mm in depth. However some areas of the skin such as the soles of the feet can be up to 6 mm in depth. The structure of the skin is dependent upon its function. The skin consists of two main layers - these are a) the outer epidermis and b) the dermis. The dermis is much thicker than the outer epidermis and consists of two sub-layers. The thinner epidermis consists of four or five sub layers depending upon the location of the skin (5 layers are present for example on the sole of the foot or the palm of the hand as both of these areas are exposed to friction on a regular basis).

### 1.14.1 Epidermis

The main purpose of the epidermis is to provide superficial protection to the underlying tissue. It is composed primarily of stratified squamous epithelium. A thin surface layer is composed of dead cells. The five layers of the epidermis are stratum corneum, stratum lucidum, stratum granulosum, stratum spinosum and stratum basale. The stratum corneum is composed primarily of keratinized dead skin cells that are flattened and non-nucleated, they are cornified. It provides the cells for regeneration of the epidermis. The stratum lucidum is found only in the palms of the hand and the soles of the feet. The stratum granulosum is composed of one or more layers of granular cells that contain fibres of Keratin and shrivelled nuclei. These granular cells contain lipids, which allow the formation of a waterproof barrier. Stratum spinosum lies above the basal layer and is made of several

layers of cells that have spine-like projections from them. Protein synthesis occurs here. The stratum basale contains pigment and produces melanocytes. The cuboidal cells in this layer undergo frequent mitosis.

#### **1.14.2 Dermis**

The two layers of the dermis are named stratum papilliosum and stratum reticularosum. The stratum papilliosum accounts for approximately one fifth of the entire dermis and forms the upper layers of the dermis which 'touches' the epidermis. The thickness of both the epidermal and dermal layer varies on the fingertips. Dermal thickness varies as a result of many factors including age, sex and body region (Tur 1997, Vitello-Zuccarello 1994). This layer contains the vascular network that facilitates blood flow for thermoregulatory purposes. Pain, touch and warmth and cold receptors are also located here. Numerous processes called 'papillae' from this layer protrude into the epidermal layer of skin. The papillae form the base for friction ridges on the fingers and toes (fingerprints). The fibres in the stratum reticularosum are arranged to form a tough flexible network and give the skin its strength and elasticity.

The hypodermis is an attachment layer for the dermis and underlying tissues. The definitive boundary for this area can be difficult to identify due to its irregularity. It consists primarily of adipose and connective tissue.

#### **1.14.3 Calluses**

Calluses are a thickened keratinised layer of the epidermis. The cornified epidermis (Stratum corneum) is the thickest part on the finger pad and often on parts of the palm of the hand. It is also generally thicker on males than females (Fruhstorfer *et al.* 2000). It has been shown (Stoll 1977) that the thickness of the epidermal layer, as a result of callus build up, resulted in significantly thicker fingers in the heavily callused hand of a machine worker compared to a desk worker with minimal calluses. It is thought that this callus layer increased insulation when exposed to thermal stimuli as the machinery workers reported a significant delay in pain when compared to the office workers.

#### **1.14.4 Sensory Receptors in the Skin**

The skin is innervated with approximately one million afferent nerve fibres. The majority of these terminate in the face and extremities; relatively few supply the back. The number of thermoreceptors present on the lips, for example, is 15 to 25 per cm<sup>2</sup>, compared to less

than 1 per cm<sup>2</sup> on the trunk. There are between 3 to 5 cold receptors per cm<sup>2</sup> on the finger (Schmidt and Thews). There are two main types of sensory endings; these are corpuscular and free. Pain receptors are actually free nerve endings. Although nerve endings are specialised to respond to tissue damage, the skin receptors will relay impulses that are interpreted as pain if they are excessively stimulated. There are several million-pain receptors present in the skin and these sensors respond to various tactile, pressure, temperature and pain sensations.

Free nerve endings occur in the superficial dermis and the overlying epidermis. These are the receptors for pain, touch, pressure and temperature. Hair follicles have fine nerve filaments running parallel to and encapsulating the follicles; each group of axons is surrounded by Schwann cells, which mediate touch sensation.

Thermoreceptors are widespread throughout the dermis of the skin. Both thermoreceptors are approximately 1 mm in diameter. The perception of temperature is on a progressive scale (e.g. freezing cold, cold, cool, neutral, warm, hot and burning hot). The perception of these sensations are as a result of a combination of three types of sensory sensors (cold, warm and pain). The three sensors are stimulated to a varying degree dependant upon the temperature of the object being touched. There are two main types of thermoreceptor. These are the organs of Ruffini and the Bulbs of Kraus. The organs of Ruffini are the heat receptors and are located deep within the dermis. The organs of Ruffini are elongated oval structures most sensitive to temperatures in excess of 25°C. Temperatures above 45°C cause impulses through the organs of Ruffini that are perceived as painful, burning sensations.

The bulbs of Kraus are the receptors primarily responsible for the detection of cold sensations. There are many more 'cold receptors' than there are 'heat receptors' (between 3 to 10 times more cold receptors being located across the body). The cold receptors are also much closer to the skin surface. The bulbs of Kraus are most sensitive to temperatures between 15°C and 34°C (Zotterman *et al.* 1959). Temperatures below 10°C can cause the painful 'freezing' sensation.

Although is it believed that both cold and warmth receptors reside in the dermis of the skin, Morin and Bushnell (1998) have suggested cold receptors are actually located deeper than warmth receptors. Further research may be needed in this area.

### 1.14.5 Physical Properties of Skin

Parsons (1993) identified a number of factors that can influence the condition of skin.

- Age
- Gender
- Ethnicity
- States of vasoconstriction/ vasodilation
- State of thermoregulatory sweating
- Circadian Rhythm

Other factors can include occupation, injury and regional differences in epithelial structure and thickness.

*Table 1.3. Shows the properties of Skin on the hand (Parsons, 1993).*

Dimension		Units	Values
<i>Approximate values of physical dimensions</i>			
Mass		Kg	4
Water content		%	70-75
Thickness		mm	0.5-5
<i>Approximate values for thermal properties</i>			
Density ( $\rho$ )		Kg m <sup>-3</sup>	860
Specific heat (c)		J Kg <sup>-1</sup> K <sup>-1</sup>	5021
		<i>Vasoconstricted</i>	<i>Vasodilated</i>
Thermal conductivity (k)	W m <sup>-1</sup> K <sup>-1</sup>	0.2-0.3	0.4-0.9
Thermal diffusivity (a=k/pc)	(m <sup>2</sup> s <sup>-1</sup> )x10 <sup>-8</sup>	4.63-6.95	9.26-20.83
Thermal penetration coefficient [b=(kpc) <sup>1/2</sup> ]	J m <sup>-2</sup> s <sup>-1/2</sup> K <sup>-1</sup>	929-1138	1314-1971

The rate at which heat transfers from the skin to a cold material will affect the skin's response. When skin is exposed to a cold environment, a thermal gradient will be apparent between the skin and the environment resulting in the skin starting to cool. The higher the thermal gradient between the warm hand and cold environment, the quicker the hand will cool down. The gradient of the thermal gradient is dependent upon the difference in temperature between the hand and the environment, the bigger the difference the steeper the gradient. However, as the hand is made up of several different structures and components it is necessary to consider their interaction with each other and the

environment as a whole. Table 1.4 is taken from Sekins and Emery (1982) and shows the differences in density and specific heat capacity of the structures that make up the hand. Parsons (1993) points out with reference to Table 1.3, that because of the dynamic and 'living' nature of skin, it is only possible to provide approximate 'static' values for its properties. This may partly explain the differences in density and specific heat noted between the two tables, as Table 1.3 lists the density of skin as equivalent to the density of pure fat as described in Table 1.4 and as such is unlikely to give an accurate impression of the density of skin on the hand.

**Table 1.4.** *Thermophysical properties of the tissues in the hand (Sekins and Emery 1982)*

Tissue	Qualification	Thermal Conductivity (W m <sup>-1</sup> K <sup>-1</sup> )	Specific heat (J Kg <sup>-1</sup> K <sup>-1</sup> )	Density (Kg m <sup>-3</sup> )
Skin	cold hand	0.335		
	normal hand	0.960	3770	1000
Fat	pure fat	0.190	2300	850
Muscle	living muscle	0.642	3750	1050
Bone	cancellous	0.582	1590	1300
	cortical	2.28	1590	1700
Blood	whole blood	0.549	3640	1050

### 1.15 Individual Differences

Terregino *et al.* (1985) found women to have variable responses to cooling of the hand in air over the phases of the menstrual cycle. Women were found to be least tolerant of cold during the time of menstruation. Havenith *et al.* (1992) found that women on average had lower hand skin temperatures than men and also have smaller hands with consequently smaller contact areas. Havenith found that the slimmest hands had the lowest temperatures with the average hand temperature differing by as much as 5°C. Jay *et al.* (2000) reported that size, structure and shape of the hand influences contact cooling. There is also evidence (Havenith 1992) that body size and aerobic capacity have an effect of human responses to heat stress.

Chen (1997) reported that numerous factors affected the overall response of an individual to cold exposure, for example, body composition, physiology and emotional state. Enander *et al.* (1980) determined cooling amongst occupationally exposed workers was not severe

enough to produce physiological adaptations, although some psychological adaptation was indicated.

Circadian rhythm also influences temperature. Core temperature is at its lowest in the morning, increasing throughout the day until decreasing again in the evening. Generally speaking, a higher core temperature results in a high mean finger skin temperature during the hunting reaction (described later in this chapter). During cold induced vasodilation, circadian rhythm effects in the following ways: 1) The hunting reaction is more pronounced in the afternoon than in the morning or at night (Kramer and Schulze 1948) 2) There is a difference in average maximal finger skin temperature between the summer and winter (Kramer and Schulze 1948), Elkington also showed that finger blood flow during immersion in cold water was less during the Arctic winter than in the summer.

Molnar *et al.* (1973) and Stoll (1977) found that heat exchange at the material skin interface is influenced by thermophysical properties of the skin itself and its state and nature including factors such as wetness and skin thickness.

### **1.16 Cutaneous Sensory System**

The brain receives two types of sensation. These are the superficial sensations, which includes pain temperature and crude touch, and the deeper sensations including sense of position, sense of movement, vibration, and fine touch (Electronic Handbook of Dermatology). Some aspects of superficial and deep sensations have to reach the cortex in order to be detected. These include tactile localisation, tactile discrimination, and the detection of the temperatures that are neither very hot nor very cold and the sense of position and movement.

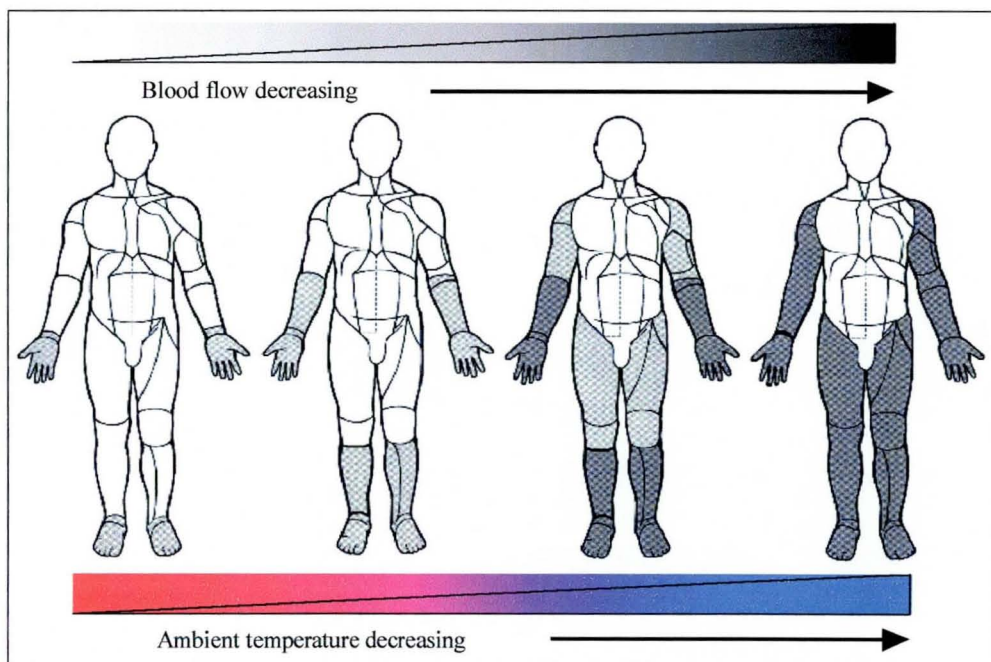
### **1.17 Cutaneous Vascular System**

The circulation of blood through the skin has two major functions: the nutrition of skin tissue and the regulation of body temperature via countercurrent heat exchange and exchange with the external environment.

There is a centre in the anterior hypothalamus of the brain that controls body temperature. When this area is heated, vasodilation of all the skin vessels of the body occurs as does sweating. Similarly, cooling this area results in vasoconstriction of skin vessels and the

cessation of sweating. The hypothalamus controls these reactions by sympathetic nerves and vasoconstrictor reflex centres in the spinal cord. Sympathetic noradrenergic vasoconstrictor fibres supply the vessels of the skin. The system is most prevalent in the hands, feet, lips, ears and nose due to the large numbers of arteriovenous anastomoses (AVA's) found there. At a normal body temperature, the sympathetic vasoconstrictor nerves keeps the AVA's closed, however, when the body become over heated, the sympathetic discharge is significantly reduced resulting in the AVA's dilating. This increases the blood flow to the skin, increasing heat loss from the body. Although the relaxation of the AVA's is the primary reason for vasodilation and therefore enhanced heat loss, it is thought, that sweating may also influence vasodilation. Sweating releases Kallikrein, which is an enzyme that splits the polypeptide bradykinin from a globulin present in the interstitial spaces. Bradykinin is a powerful vasodilator (Electronic textbook of Dermatology).

However, when a person is exposed to an ambient air temperature of approximately 22°C, certain areas of a naked man can start to show differences in skin temperature which vary from one region to another. At room temperature blood supply can be reduced by 20 - 30% in order to conserve heat to the core.



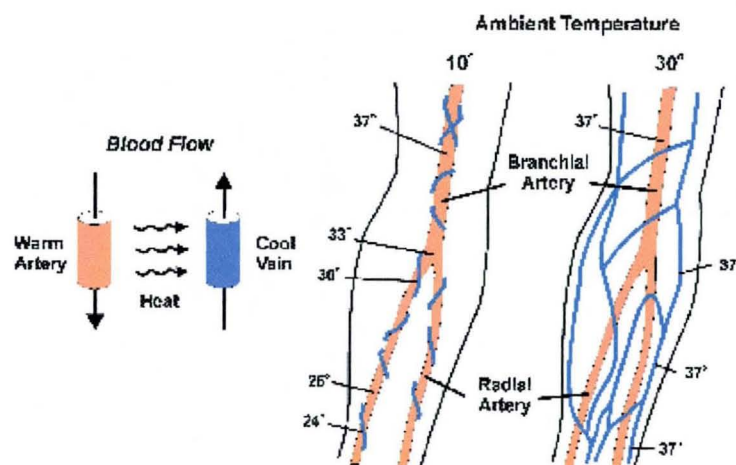
**Figure 1.2.** Taken from (Lehmuskallio 2000) illustrates the blood flow responses to conserve core temperature with decreasing ambient temperature.

### 1.17.1 Physiological Amputation

Physiological amputation occurs as a result of a declining internal temperature. It is a result of severe vasoconstriction of the blood flow to the extremities in order to conserve heat flow to the core (Raman and Roberts, 1989). Vangaard (1990) showed that when participants were exposed to an environmental air temperature of 8°C the effect of blood flow to the hand was identical to that when compared to a completely occluded hand.

### 1.17.2 Counter Current Heat Exchange

As described previously, when the body starts to cool down, skin arteries will respond by regulating the blood flow to the extremities. This is done by the closure of AVA's, which control the amount of blood entering the superficial veins. Blood flow to the hands can be drastically reduced by vasoconstriction. Blood will then return to the core via deep veins located close to the arteries. This mechanism allows counter current heat exchange (CCHE) to occur and transfers heat from the efferent arteries to the afferent veins and thus prevents it from being lost in the extremities. Bazett *et al.* (1948) first described CCHE. CCHE occurs when two adjacent blood vessels with the opposite direction of blood flow (e.g. veins and arteries) exchange heat.



**Figure 1.3.** Shows the process of heat exchange including the temperature gradient through Counter current Heat Exchange

(Taken from TTUHSC, <http://phy025.lubb.ttuhs.edu/Pressley/Course/Temp-Reg.htm>)

However, it should be considered that, in the skin, arterial and venous vessels are small, so almost no CCHE takes place. Jiji *et al.* (1984) determined that the arteries that make a significant contribution to CCHE are located in the deep tissue (deeper than 4 mm under

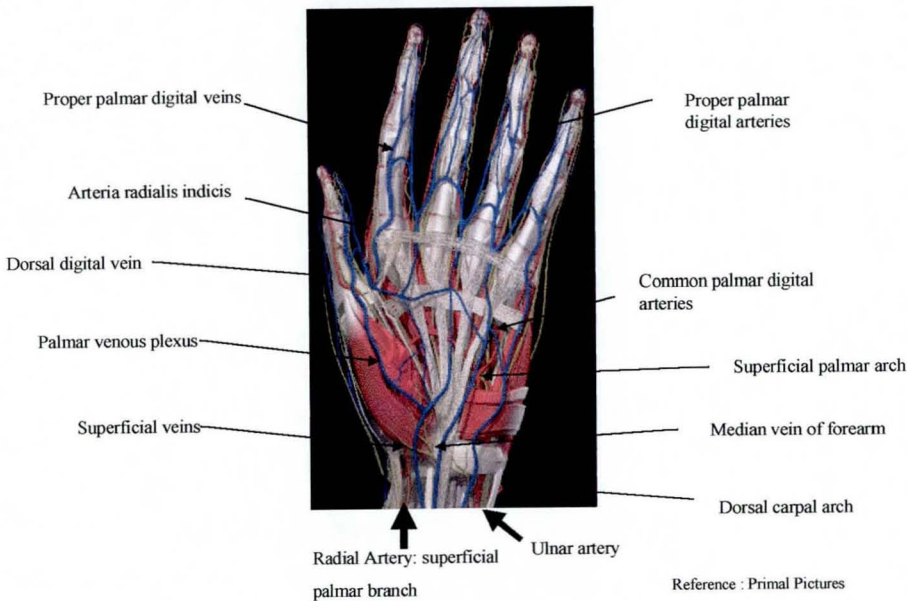
the skin) and have much larger diameters. It was also determined, that to make any significant effect on CCHE the temperature gradient between the two vessels had to be large. This difference can be found with the major blood supply vessels located close to the core. The temperature gradient between the two vessels can differ by as much as 10°C. The blood vessels located closer to the surface can differ by as little as 0.1°C to 0.2°C which would have little impact on CCHE.

Raman and Roberts (1989) calculated that CCHE resulted in a maximum of 30 W heat loss at a hand temperature of 25°C and Tikuisis and Ducharme (1990) calculated a 53 % efficiency for CCHE in the forearm.

### **1.17.3 Blood Supply to the Hands**

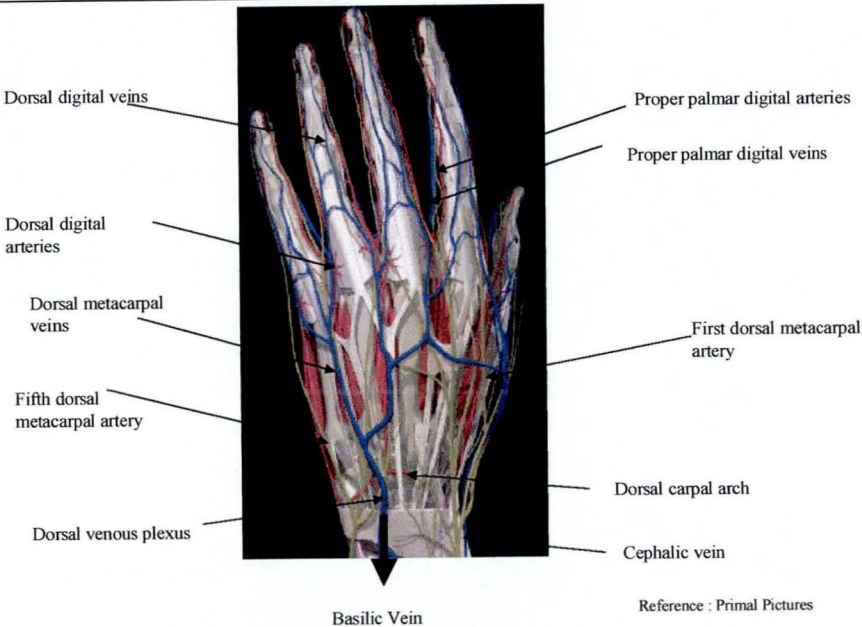
Blood is supplied to the hands via two main arteries, the radial and ulnar artery. These two arteries bifurcate and form the deep palmar arteries and the superficial palmar arch (Gray 1980). The finger arteries are supplied primarily from these two arches. Both dorsal and palmar arteries run parallel to the phalanges on both sides. The palmar digital arteries are the dominant arteries supply most of the blood as the dorsal digital arteries are much smaller in comparison (Smith *et al.* 1991a). Figures 4 and 5 illustrate the blood supply to the hands.

Palmar View of the Left Hand



*Figure 1.4. Illustrates the blood supply to the palmar aspect of the hand*

Dorsal View of the Left Hand



*Figure 1.5. Illustrates the blood supply to the dorsal aspect of the hand*

The blood exits the hands by the superficial and deep veins. The palmar digital veins open into superficial arches and the palmar metacarpal veins open into deep arches. The arterial and venous network is primarily connected by capillaries. Capillaries take blood from arterioles which lead off smaller arteries. In tissues similar to the mesentery of connective tissue, the first part of the capillary has a coat of smooth muscle. This is named a precapillary sphincter, but the existence of these structures is under debate (Currie 1990). Wilkins *et al.* (1939) determined that blood flow to the distal phalanx was greater than that of any other phalanx primarily due to the greater number of AVA's present there.

#### **1.17.4 Cold Induced Vasodilation (CIVD)**

Cold induced vasodilation is "a cyclic vasodilation resulting from the cyclic loss of the responsiveness of the vascular smooth muscle to Noradrenalin that occurs with the lowering of local temperature" (Blatteis 1998). Blood flow therefore temporarily increases resulting in an increase in local temperature until vasoconstriction occurs again. The increased blood flow and resultant increase in local temperature are caused by a relaxation of the smooth muscle cells of the AVA's (Bergersen 1999).

CIVD occurs as a response to extremity being exposed to a cold environment. Initially vasoconstriction occurs to limit heat loss. However, in a severely cold environment after about ten minutes, the vessels dilate again allowing blood to pass through to the skin, thereby decreasing dexterity losses. Lewis (1930) was the first to describe CIVD. He termed the phenomenon of the repeated fluctuations in finger skin temperature 'hunting'.

There are several phases experienced as a result of cold exposure. Initially, vasoconstriction will be experienced, then CIVD as the blood vessels dilate and local skin temperature increases. This phase would occur after approximately ten minutes of exposure to cold water. Vasoconstriction then occurs again, the Hunting reaction then follows as the cycle of vasodilation and vasoconstriction repeat until final vasodilation occurs.

#### **1.18 Cold Acclimatisation**

Cold acclimatisation refers to the ability of the body to adapt physiologically to changes that occur slowly in the environment changing from warm to cold. Cold adaptation however, would appear to be limited when compared to the ability of the body to adapt to heat. The following studies have investigated local cold acclimatisation.

Rintamäki *et al.* (1993) investigated eight subjects not previously acclimatised to the cold over 53 days in the Antarctic. The participants conducted fieldwork requiring the use of bare hands. It was determined that there appeared to be some adaptation to the cold. This was put down to exposure to the outdoor conditions.

LeBlanc *et al.* (1960) determined that cold acclimatisation did occur. A group of Gaspe fishermen used to cold water immersion of their hands was compared to a control group unused to cold water exposure. Higher finger skin temperatures were found amongst the fishermen than the control group. Nelms and Soper (1962) also determined that there were higher finger skin temperatures and an earlier onset of CIVD when British fish filleters were compared to a control group.

However, studies such as Stein *et al.* (1949), Horvath *et al.* (1947) and Miller (1949) found no evidence of acclimatisation to cold existing. However, it is possible certainly in the case of Bridgman (1991) that cold acclimatisation did not occur due to the frequency, duration and severity of exposure. Bridgman investigated cold acclimatisation of divers who were sporadically exposed to the cold. Massey (1959) upon observing a group of new arrivals to Antarctica and comparing them to a group staying for a consecutive second year found an initial difference in finger skin temperatures between the two groups, but found that this difference disappeared within six weeks of arrival. However, the people in their second consecutive year were found to have a greater tolerance to frostbite induced under experimental conditions.

It would appear the majority of findings suggest an earlier onset of CIVD in response to cold acclimatisation (Smith 1961, Purkayastha *et al.* 1992, LeBlanc *et al.* 1960 etc).

However, psychological adaptation to cold sensitivity and cold induced pain has been shown to occur. LeBlanc (1960) found that the Gaspe fishermen complained less about cold. Nelms and Soper (1961) found that several members of the control group (non-acclimatised) actually passed out and became stressed whereas the fish filleters did not. Enander *et al.* (1980) also demonstrated that there were significantly lower pain and cold sensations reported amongst meat cutters regularly exposed to cold and a control group.

LeBlanc and Potvin (1966) suggested the seemingly increased tolerance to cold pain and sensitivity was due to the central nervous becoming accustomed to repeated cold exposure.

### **1.19 Cold Injuries**

Wilson *et al.* (1976) reported that skin begins to freeze at skin temperatures below  $-10^{\circ}\text{C}$ . This however, was thought to be as a result of supercooling of tissue as a result of the low ambient temperature. The freezing point of skin has been found to be much higher during contact with cold bars. Lewis and Love (1926) measured the freezing point of human skin in contact with metal bars and found the freezing point to be approximately  $-2.2^{\circ}\text{C}$ , whilst Keatinge and Cannon (1960) exposed the finger to brine water and found the freezing point to be much higher at approximately  $-0.6^{\circ}\text{C}$ .

When the body becomes cold, vasoconstriction or even physiological amputation may occur. This leads to a decreased amount of blood reaching the hand. The hand is able to produce a very small amount of heat itself due to the small muscle mass there. Raman and Vanhuysse (1975) estimated that the metabolic heat production of the hand under resting conditions was approximately 0.25 W. This means that blood flow is very important for heat input. The decreased amount of blood to the hands leaves them particularly vulnerable to cold injury including frostnip, frostbite and chilblains.

#### **1.19.1 Frostnip**

Fritz and Perrin (1989) described Frostnip as a reversible injury that occurs as a result of an ice crystal formation of the skin's surface. The skin itself does not actually freeze. Typically it develops painlessly, although a sudden blanching of the skin can be observed.

#### **1.19.2 Frostbite**

Asahina (1966) describes frostbite as being caused by the freezing of the fluids around the cells of the body tissue. During prolonged freezing at a relatively low temperature ice crystal begin to form in the extra-cellular electrolytes. This leads to a concentration of electrolytes, which in turn leads to osmosis of the remaining water from the cell eventually leading to cell death. Fast cooling as a result of exposure to a colder environment leads to the tissue freezing more quickly. Ice crystals form immediately both extra and intra-cellularly resulting in immediate cell damage and death (Whittaker 1972). The size of the

ice crystals formed is related to the speed of cooling. The faster the cooling the greater the size of the single crystals (Holden and Saunders 1973).

The symptoms of frostbite include an initial redness and swelling. The person experiences a diffuse numbness that may or may not be preceded by a prickling itchy sensation. If the frostbite is superficial, then pressing on the skin causes a dent as the underlying tissue is hard due to freezing (Fritz and Perrin 1989).

#### **1.19.3 Trench Foot (Immersion Foot)**

Trench Foot occurs as the result of repeated exposure to a wet, cold environment over a period of days or hours at temperatures only slightly above freezing. Damage occurs to the capillaries leading to necrosis or gangrene of the skin, muscles, nerves and soft tissue.

#### **1.19.4 Chilblains**

Chilblains are usually small itchy, red swellings on the skin. These can become increasingly painful, swollen and dry resulting in cracks in the skin which expose the foot to the risk of infection. They occur on the toes, particularly the smaller ones, fingers, the face and the lobes of the ears. They can also occur on areas of the feet exposed to pressure, for instance, on a bunion or where the second toe is squeezed by tight shoes.

### **1.20 Conclusions**

1. At present, there is no standard to address the associated problems of *contact cooling*.
2. Contact cooling may occur where tools or machinery are operated in cold conditions.
3. Contact cooling occurs either accidentally or as a result of sustained contact. If the contact is sustained then tissue damage and manual dexterity deficits may result.
4. Sustained contact with a cold surface would occur where tools are handled in cold environments for example, a hammer or a gun.
5. Heat always transfers from higher to lower temperatures.

6. The majority of heat transferred during contact cooling, occurring as a result of contact with a material with a high contact coefficient, is transferred away from the hand to the cold material by conduction. However, when the hand is in contact with a material of a low contact coefficient at low temperatures (e.g. - 20°C) the majority of heat would be transferred away from the hand by convection although some heat loss through conduction would still occur.
7. A thermal gradient exists between the hand and the cold material. The steeper the gradient, the faster heat is transferred away from the hand.
8. Contact temperature change over time during cold contact has been successfully described using a modified Newtonian model with two time constants.
9. The skin is the largest organ in the body and consists of three layers; the epidermis, dermis and hypodermis.
10. Pain receptors are free nerve endings that respond to tactile pressure, temperature and pain sensations.
11. There is a high concentration of temperature receptors found in the hands and feet compared to the rest of the body.
12. There are many individual differences in responses to cold.
13. Blood is the main source of heat input into the hand. When vasoconstriction occurs as a result to cold exposure, blood flow to the hands is drastically reduced and so the hand cools quickly.
14. Physiological amputation occurs as a result of decreased temperatures. It is a result of severe vasoconstriction of the blood flow to the extremities.

15. Manual dexterity can be divided into five areas; finger dexterity, manual dexterity, wrist finger speed aiming and positioning. Tactile discrimination and strength capability and sustainability also affect manual dexterity.

## **2 Equipment and Methodology**

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### **2.1 Chapter Summary**

This chapter describes the experimental research methods used to investigate the effects of contact cooling. It also describes the construction of the cool box facilities. The aim of this research is to investigate the effect of full hand contact whilst gripping cold materials and any subsequent effects on manual dexterity. This will be done for both short term (approximately 5 minutes) and long term (approximately 20 - 30 minutes) exposure over a range of temperatures (between 0°C and -35°C). In order to achieve and maintain these temperatures equipment design requirements must be determined prior to experimentation. The primary design aim of this equipment was to fulfil the criteria of the EU sponsored cold surfaces project (SMT4-CT97-2149), however a further specification of the equipment was that it should meet any future requirements of cold surfaces related projects in the future.

### **2.2 Design Specification**

#### **2.2.1 Cold Chamber**

The cold chamber must be designed in such a way that temperatures of at least -35°C can be reached and maintained even with the introduction of a participant's hand into the environment. Participants must therefore be able to enter their hand into the environment and at the same time see the correct object to grip. This is a necessity not only to ensure that the correct measurements are recorded, but also for the safety of the participant, (e.g.

contact with the metal pulley system at temperatures of  $-35^{\circ}\text{C}$  would result in skin damage after a very short contact time).

### **2.2.2 Temperatures**

The research will require participants to be exposed to materials ranging in temperature from  $0^{\circ}\text{C}$  to  $-35^{\circ}\text{C}$ . These temperatures must be maintained even with the introduction of the participant's arm to the environment.

### **2.2.3 Materials**

The rate of heat transfer from the participant's hand to the bar is influenced by the thermal properties of the material as well as the temperature gradient (First law of thermodynamics). Therefore, the materials chosen for testing should represent a wide range of potential materials that a worker may be exposed to in the workplace. As the dimensions of the object can also affect the rate of heat exchange, it was decided that all materials shall be of the same shape and dimensions.

### **2.2.4 Lifting Force**

As all the materials are required to be of the same dimensions, the materials will have different masses, for example, aluminium will have a much lower mass than stainless steel. This would result in the participants having to exert differing amounts of pressure and effort in order to lift and keep the bar in the required position. It is also important to ensure that the bar is not so heavy that the participant is unable to maintain the position of the bar in the air for the longer contact durations. The system needs to be able to compensate for these weight differences. The participants must also exert the same amount of pressure in order to lift and hold the bar in the air regardless of the differing masses of the bars.

### **2.2.5 Skin Cooling**

For the safety of the participants and to gather accurate data, the skin /surface of material temperature must be measured (contact temperature). The contact temperature will be taken rather than just skin or material temperature to increase safety for the participant and give a more realistic impression of what is happening at the actual contact site. In conditions where the skin is in contact with a solid, thermally conductive object, it is technically difficult to measure the actual skin temperature. As inserting sensors into the skin was deemed unacceptable, the contact temperature was measured with thermocouples. The contact temperature will give a more accurate reading of what is

actually happening at the site of contact, and the combination of the two temperatures will mean that the skin temperature is actually higher than the recorded temperature. This will increase safety margins for participant withdrawal. The conditions (material \* temperature) chosen for this research will induce two types of cooling. A fast cooling and a slow cooling. It is expected in the fast cooling condition that temperatures will drop rapidly. For this reason a temperature sensor with a rapid response time and sampling rate is required. The temperature sensor must also be able to operate accurately throughout the anticipated temperature range.

### **2.2.6 Data Acquisition and Recording**

Due to the risk of skin damage to the participants a method of data acquisition that also allows the experimenter to monitor the cooling of the participant in real time is required. It is also important that the data be recorded in a format that is compatible with later data analysis.

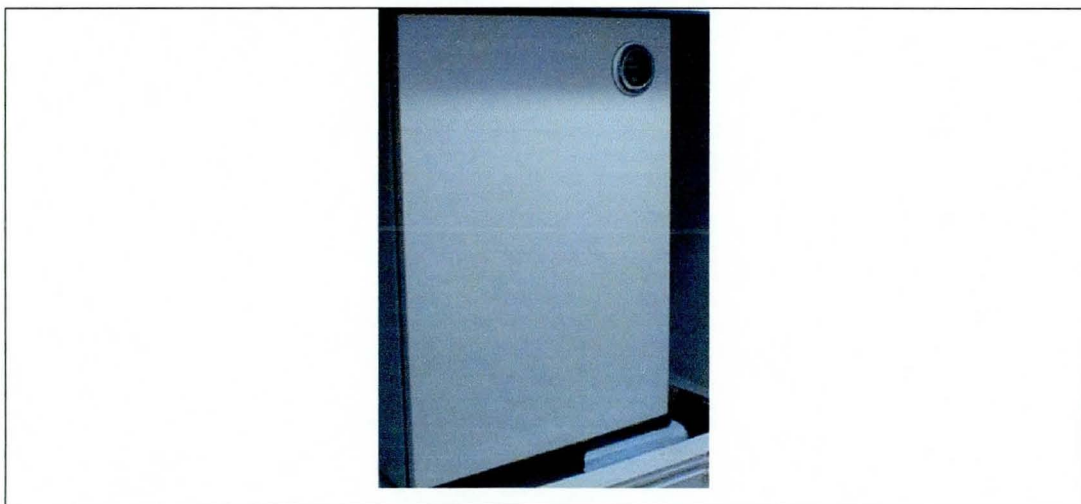
### **2.2.7 Subjective Responses**

Sensations most likely to be affected as a result of whole hand contact cooling should be determined and suitable scales devised and used.

## **2.3 Equipment**

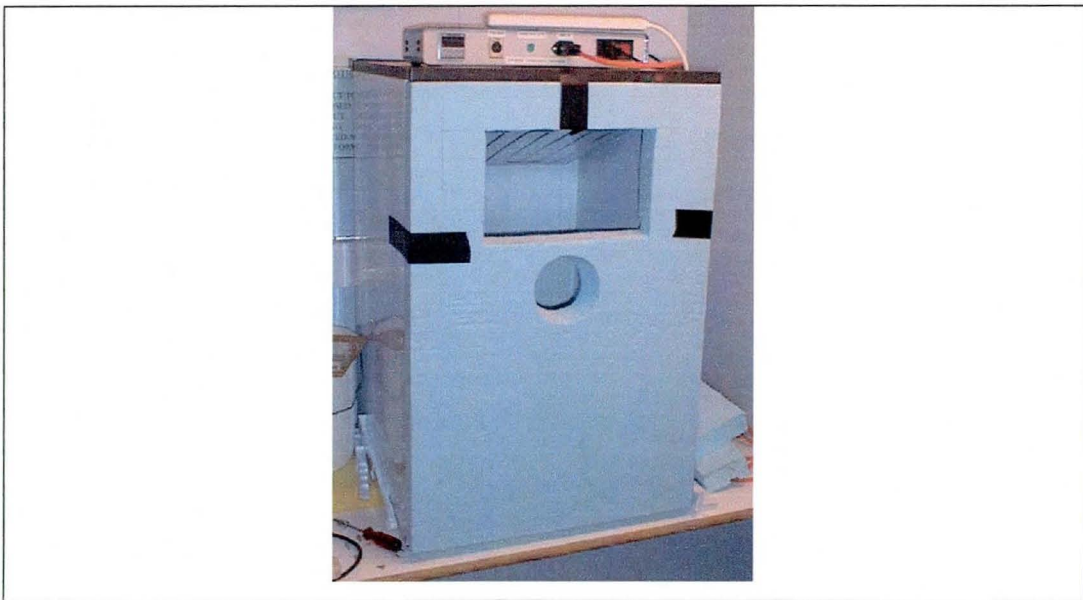
### **2.3.1 Cold Chamber**

The freezer used is a modified Hotpoint Iced Diamond 87610 measuring 51cm x 55 cm x 83.5cm (externally) (see Figure 2.1.).



*Figure 2.1. The freezer before modification*

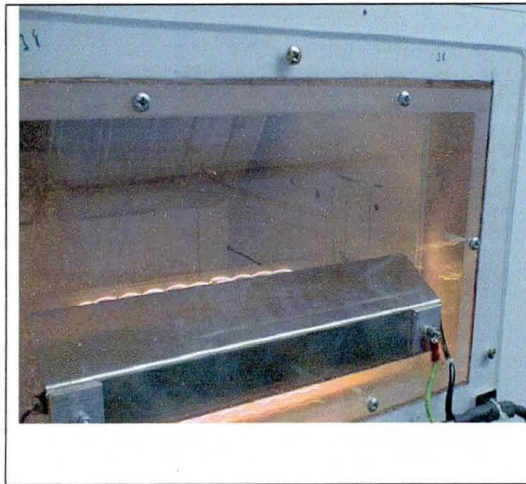
Two adaptations to the external appearance of the freezer were necessary, this was the addition of an area that would allow participants to introduce their hands to the environments, and the addition of a window to allow participants to see the correct area to grip. The following mock up of the freezer was made so that the freezer would meet the requirements of the experiment. Figure 2.2 below shows the freezer with the mock up door in place. The purpose of the mock up was to allow several positions and dimensions of armhole and window to be assessed so the optimum position of both could be determined.



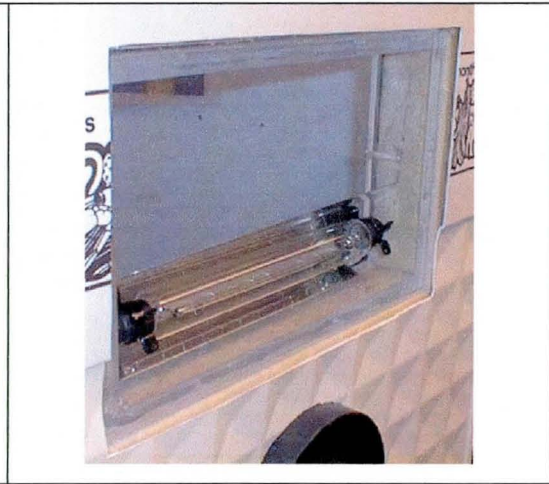
*Figure 2.2. Mock up of Experimental Chamber Door*

For visibility purposes, it was necessary to cut a hole in the door of the freezer to fit a window. The window enabled subjects to see what they were touching in the freezer. The window is made of Perspex that is approximately 1.1cm thick. Four pieces of this Perspex are glued together to form a see through hollow 'box'. Another larger sheet of Perspex is screwed onto the 'box' and then screwed onto the front of the freezer door to minimise any air and therefore heat exchange between the inside of the freezer and the outside environment. Inside the hollow box is a custom made light, with a reflective shield that minimises reflection onto the Perspex and the amount of light that shines directly into the subject's eyes. The light operates on a dimmer so that it can fulfil the dual function of lighting the interior of the freezer when dimmed, and defrosting the Perspex when the light is on full power. When the light is dimmed but still bright enough to illuminate the interior of the freezer, sufficient heat is given off to heat the interior of the freezer slightly. For this

reason the light was only used for illuminating the interior of the freezer when a subject was about to put their hand into it. A small hole in the Perspex box and covering Perspex sheet on the exterior of the freezer is present to allow for the wires of the light. Figures 3 and 4 show the window from outside and inside the freezer.



*Figure 2.3. Outside View of Window*



*Figure 2.4. Inside View of Window*

An armhole (approximately 11.5cm in diameter) was cut into the freezer door below the window. Initially two access points (right and left) were considered. The dual access point was disregarded however as it affected the insulation of the freezer and would have made sustaining temperatures at  $-35^{\circ}\text{C}$  impossible. Plastic tubing was glued inside this hole. The aim of the plastic tubing was to allow the participant to rest their forearm on it comfortably without the pressure of a narrow band affecting either comfort or blood flow. The tube protrudes slightly at both sides of the freezer door. In order to maximise insulation and minimise heat exchange between the internal environment of the freezer and the external environment a 'sleeve' part of an industrial rubber glove was glued to the outside of the tubing on the exterior side of the freezer door. The end of the rubber sleeve was folded over and sewn in place. A length of cord was threaded through this and a spring-loaded toggle attached to the end of the sleeve. When a subject is not using the freezer the rubber sleeve is folded into the freezer and a polystyrene bung is fitted into the hole.



*Figure 2.5 and Figure 2.6 show the armhole from the inside and outside of the freezer door.*

After trial runs, it was noted that there was a 2°C degree difference in temperature between the top and bottom of the freezer. To eliminate this, a fan was fitted to the bottom of the interior side of the freezer door. The fan was used to circulate the air within the freezer. The fan fitted however was too powerful and resulted in the interior of the freezer heating significantly. A smaller computer fan was then fitted. The smaller motor on the fan did not cause the interior of the freezer to heat, but did result in a wind-chill on participant's hands, so this feature was only used prior to the introduction of the participant's hand and after it was removed. It was determined this was effective in eliminating the 2°C heat difference within the freezer.

### **2.3.2 Climate Control**

A thermometer (typePT100 sensor (platinum resistance thermometer)) is placed in close proximity to the bars so that the temperature of the freezer near to the gripping area is measured. A hole has been cut into the right hand side of the freezer close to the bottom to allow for wires including that of the thermometer to exit the freezer. Gaps between the wires and the hole were filled with polystyrene so air exchange between the two environments was at a minimum.

Domestic freezers generally operate at a temperature range of -18°C to -20°C. The freezer purchased operated at a temperature of -19°C ( $\pm 2.0^\circ\text{C}$ ). As this was a much higher temperature than the research required an alternative method of temperature regulation was required. A PID (Proportional Integrative Differential) controller (FUJI Electric) was therefore used to regulate the temperature of the freezer as sensed by the PT100 sensor more accurately than could realistically be expected from a household freezer. A 'normal' household freezer may allow the air temperature within the freezer to vary in excess of 2°C

before the thermostat reacts to the change in temperature. It is not acceptable for the air temperature in the experimental freezer to vary by this much especially before the subject's put their arm into the freezer. One reason for this is that the freezer will inevitably heat up from the warmth of the subject's arm, and an additional two degree difference in temperature would change the environmental conditions significantly, and make the conditions more difficult to control and therefore more difficult to replicate for other subjects (the PID controller keeps the temperature within by  $0.8^{\circ}\text{C}$  either way from the specified temperature) internally in the freezer. The PID controller overrides the existing thermostat. However the P (proportional) and I (integrative) characteristics were not compatible with the freezer's compressor, so an on/off function with a differential of  $0.1^{\circ}\text{C}$  was used.

### **2.3.3 Air Conditioning Unit**

Due to the adaptations made to the freezer (armhole and window) after the introduction of the PID controller, the minimum temperature that the freezer could reach and maintain was approximately  $-28^{\circ}\text{C}$ . As an operating range of  $0^{\circ}\text{C}$  to  $-35^{\circ}\text{C}$  was required for the research this was insufficient. Two main ways of achieving a lower internal temperature were considered feasible. The initial method was to increase the insulation around the freezer. This was tried and resulted in the motor used to power the compressor increasing in temperature and warming up the environment external to the freezer. This resulted in the freezer having to do more work in order to achieve and maintain temperatures which it previously had no problems with. The second method involved lowering the external temperature of the freezer. To do this, the adapted freezer was placed inside an air conditioned unit measuring  $122.5\text{cm} \times 82\text{cm} \times 124\text{cm}$ . The air conditioned unit allowed the freezer to reach lower temperatures by cooling the air that is surrounding the freezer. The hole cut into the front of the air conditioning unit (measuring  $80\text{cm} \times 80\text{cm}$ ), allows the freezer to be placed into and removed from the cool box. The hole is covered by a polystyrene sheet, which insulates the inside of the cool box ( $110\text{cm} \times 69\text{cm} \times 106\text{cm}$ ) from the higher temperature of the prep room. The temperature within the cool box can reach  $0^{\circ}\text{C}$  as measured during trials and as indicated by the presence of frost on the freezer when the polystyrene sheet is removed.

With the air conditioning unit is on and the polystyrene sheet is in place over the opening, it was possible for the freezer to reach temperatures of  $-40^{\circ}\text{C}$  after approximately three and a half hours and a material surface temperature of  $-38^{\circ}\text{C}$  could be achieved after five hours. Upon removal of the polystyrene sheet covering the opening of the air conditioning unit the internal temperature and material temperature could be maintained for a further two and a half hours. Figure 2.7 shows the freezer inside the air conditioning unit.



*Figure 2.7 Freezer inside the air conditioning unit*

#### **2.3.4 Pulley System**

The shelves inside the freezer were removed. A pulley system was incorporated (see Figure 2.8). The metal rods in which the pulley is centrally located is made of aluminium and it is placed approximately 11.5cm from the top of the freezer and is 21cm long. The pulley is 5cm in diameter. The second pulley is located on the outside wall on the left-hand side of the freezer. As the bars were the same size but of different masses compensating weights were required so that the same effort and pressure was applied to the bar in order to lift and hold the bar in the air regardless of material property. The compensating weights for the bars are attached here by an S hook, or in the case of the wooden bar, which was less than 500g; lead was attached to the bottom of the bar with a nail. The compensating weight was hooked onto the pulley system so that it was possible to change weights easily and quickly. The bar itself is inside the freezer suspended by plaited cord from the pulley. The bar inside the freezer was attached to the cord by a hook so that the bars can be changed within the freezer during an experiment. When the bar is not in use, it rests on the

bottom of the freezer in the correct position for gripping. Other bars that are not in use at the time, but will be needed later in the experimental session were placed on the ledge at the back of the freezer.

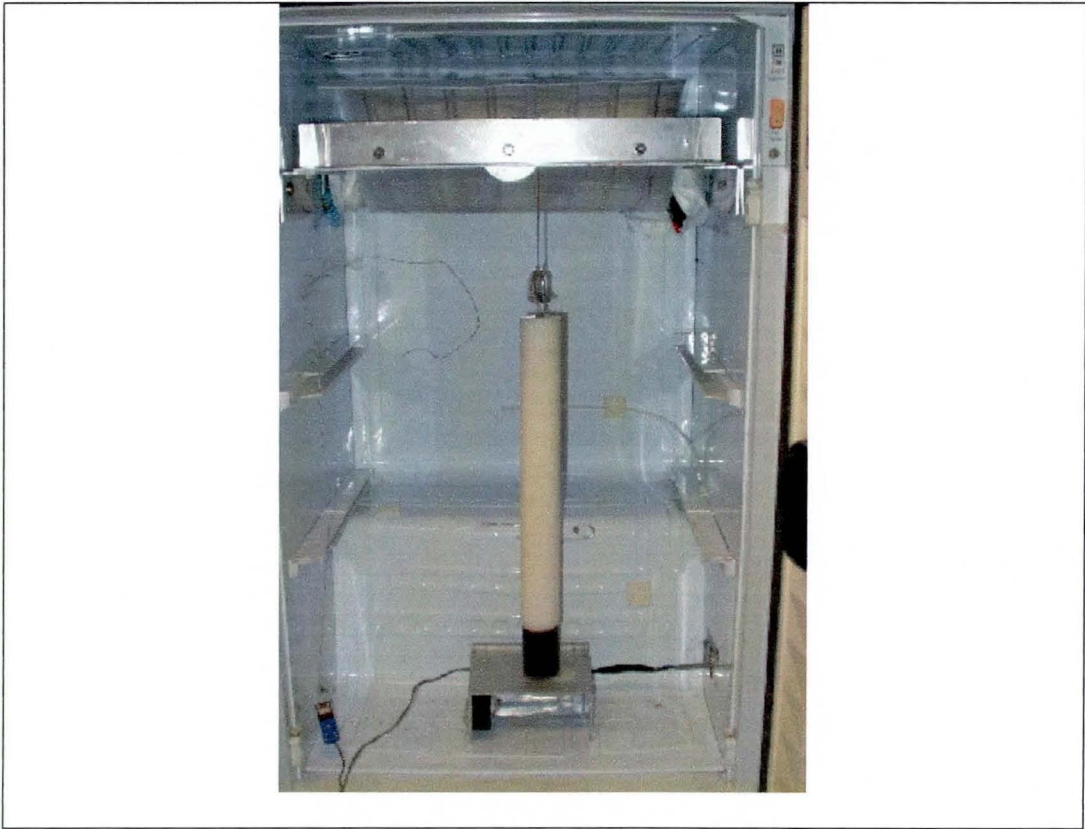


Figure 2.8 shows the freezer set up for experimentation.

Table 2.1 Weights and compensating weights for each material

Material	Mass (in Kg)	Compensating Weight (in Kg)
WOOD	0.269	+ 0.231
NYLON	0.716	- 0.216
ALUMINIUM	1.419	- 0.919
STONE	1.399	- 0.800
STAINLESS STEEL	3.849	-3.349

## 2.4 Materials

### 2.4.1 Contact Properties

This research required a range of contact materials, that would represent a range of thermal properties in order to accurately assess cooling speeds and effects as a result of full hand contact with materials commonly found in the work place. It was decided for contact cooling, that bars of five different materials should be used: wood, nylon, stainless

steel, aluminium and stone. All these materials have different thermal properties as defined by their contact coefficient:

$$\text{Contact Coefficient } \beta = (k\rho c)^{1/2}$$

Where k = thermal conductivity, ρ = density and c = specific heat.

The properties of the materials chosen are given below in Table 2.2.

Table 2.2. Thermal properties of test materials (Tested by VTT, Finland, June 14, 1999)

Material	Density (ρ)	Thermal Conductivity (k)	Specific Heat (mass) (c)	Thermal Diffusivity (a=kρ <sup>-1</sup> c <sup>-1</sup> )	Thermal Penetration coefficient
	Kg m <sup>-3</sup>	W m <sup>-1</sup> K <sup>-1</sup>	J Kg <sup>-1</sup> K <sup>-1</sup>	10 <sup>-6</sup> m <sup>2</sup> s <sup>-1</sup>	Jm <sup>-2</sup> s <sup>-1/2</sup> K <sup>-1</sup>
Aluminium	2770	180	900	28.80	21180
Steel	7750	14.8	461	4.20	7270
Nylon	1200	0.34	1484	0.19	780
Stone	2800	2.07	750	0.99	2084
Wood	560	0.22	2196	0.18	520

Factors other than the thermal properties of the material can affect contact cooling including, surface cleanliness, material mass, material thickness and surface topography.

For these reasons, the bars were cut from the materials mentioned above into bars approximately 400mm in length and 40mm or 42mm (Stone) in diameter. The five materials and air (holding the hand in a gripping position in air of the respective temperature) were only tested at temperatures appropriate to their thermal properties in terms of risk of tissue damage to the subject. The bars had a hole drilled centrally down the length of the bar approximately 20cm long and 8mm in diameter. A thermocouple was inserted into this hole to measure the 'core' temperature of the bar. At least two bars of each material were used. This was found necessary due to time constraints. Although the wooden and nylon bar cooled quickly to the required temperature, 3-4 hours was required for the stainless steel and aluminium bars to reach and stabilise at the required temperatures after contact. By utilising two bars of the same materials participants could complete the experiment on both the dominant and non dominant hand in the same experimental session, meaning participants were more likely to complete all experimental sessions, or four participants could complete an experimental session in a day where it had previously been only two.

## **2.5 Objective Measures**

### **2.5.1 Temperature Sensors**

To measure the contact temperature (the skin-material interface temperature) thermocouples were chosen. The primary reasons for selection of thermocouples as the temperature measuring device was because they will measure contact temperature, have a fast response time (small time constant), are sufficiently sensitive to small changes in temperature and operate in the temperature range expected to be achieved in the experiment and allow the constant on line monitoring of thermal changes.

Initially infra red imaging was considered, but disregarded as it would only measure actual temperature of the material or skin but not the contact temperature and temperature readings would only be intermittent and therefore not in real time.

The contact temperature, the temperature of the bars and the temperature of the subject's hand were measured using T-Type thermocouples (copper constantan). Two different thicknesses of thermocouples were used. The finer thermocouple (0.2mm in diameter) was used on the subject's hand because it responds more quickly to the change in temperature than the thicker thermocouple. This reduces the chance of the subject suffering cold injury and gives a clearer picture as to what happens when with regard to the change in temperature of the subject's hand.

Thermocouples are very delicate and frequently break. If this occurs, then the thermocouple is stripped of the covering plastic and the two wires within the thermocouple are soldered together. It was originally intended that seven thermocouples should be placed on the subject's hand for the touching experiment. Electrical interference between the thermocouples occurred however, so all thermocouples were insulated with a clear varnish to avoid the interference. The thermocouples are plugged into a terminal box, which is directly linked to a Strawberry Tree data shuttle, which in turn is connected to a PC. Interference was also occurring between the channels not used and the channels in use in the data shuttle. To eliminate the interference, unused channels were shorted.

It was necessary to calculate how quickly the thermocouples reacted and to see whether the insulation (clear varnish) sprayed onto the thermocouples altered the overall response

time. To determine the time constants, the thermocouples were kept at a steady temperature (room temperature) and then placed in hot water. When the thermocouple registered a steady temperature the thermocouple was removed from the water. This was repeated three times for each category of thermocouple. After one time constant, the thermocouples have reached 63% of the total temperature difference. Insulated (covered) and not insulated (uncovered) thermocouples were tested. It was determined that although there was a difference in response time between the insulated and not insulated thermocouples, the response time of the thermocouples was still fast enough for this difference not to matter (time constant  $\leq 0.1$  s).

### **2.5.2 Analogue-digital converter**

The thermocouples are plugged into a terminal box which is directly linked to a 16 bit data shuttle (model DS-16-8-TC-AO (Strawberry Tree Inc., Sunnyvale, CA,USA) that incorporates a cold junction compensation block (this means that only the change in current resulting from the specified temperature is measured rather than arbitrary contact points), it allows the sample rate to be set and changed.

### **2.5.3 Data Organisation Software**

The software used with this data shuttle is Workbench PC for windows 3.00.15 and was run under Microsoft Windows 95<sup>TM</sup>. This software allows the user to create a programme that is specific to that user and experiment via an icon list or pull down menu. The functions used will depend upon the type of data collection and how the user wishes to utilise the information. The 'cold' programme written for these experiments uses a sampling rate of five Hertz, that is one reading every 0.2 of a second. It was anticipated that this rate would give a full picture of any changes that may occur rapidly as a result of contact cooling and sufficient to minimise any lag effect that could result in injury to the participant whilst not creating excessively large data files. A graphical output was used to describe the change in contact temperature over time. The temperature axis was in the range of 40°C to -5°C to allow the temperature and risk to a participant to be accurately assessed. A second axis was added to describe the change in environmental and bar temperature with a more appropriate axis. A 'light' on the workbench programme indicates whether the subject is lifting the bar (this is helpful in establishing the exact start time when the subject made contact with the block as not only is it displayed on the screen but is marked in the data).

The data collected is immediately written to the hard drive in ASCII text format where it is stored in a temporary file in the PC. To prevent useless information being recorded between runs, an on/off button has been incorporated into the programme to stop and start recording at any time. A buzzer is also plugged into the data shuttle as a warning signal for low skin temperatures. The programme sets the buzzer off when a set point ( $0^{\circ}\text{C}$ ) of a specified channel(s) is reached. Labelled digital meters were also present on the right hand side of the screen to show exactly what temperatures were being recorded at that time. Subjects were told to withdraw their hand if their skin temperature reached  $0.5^{\circ}\text{C}$ . To remind the experimenters that this time was approaching different colours were used for the screen output to indicate different levels of temperatures. Green was used if the subject's skin temperature was above  $5^{\circ}\text{C}$ , yellow was used to indicate that the subject's skin temperature was between  $1^{\circ}\text{C}$  and  $5^{\circ}\text{C}$ , and red was used to indicate that the subject's skin temperature was approaching  $0^{\circ}\text{C}$ . It was also possible to display the cooling curves on the screen whilst the experiment was being conducted. A constant red line was also produced at  $0.5^{\circ}\text{C}$  to indicate to both the experimenter and the subject that the hand would need to be withdrawn very shortly. Two different axes were on the graph the axis on the right was for skin temperature, and the axis on the left was for the block and environmental temperature.

## **2.6 Subjective Sensations**

Subjective sensations were taken prior to exposure to the bar and then reported verbally every time the sensations changed by the participants. Prior to exposure, a whole body rating of thermal sensation was taken (all subjects started the experiment when they attained and stabilised at a sensation of  $-1$  (slightly cool) on the thermal sensation scale (Fanger 1970)). After this time, as the experiments were related to whole hand cooling, the participant was asked to report any changes in sensation for the hand only.

### **2.6.1 Thermal sensation**

The thermal sensation scale is an adaptation of the Bedford scale and the ASHRAE (American Society of Heating and Refrigeration and Air-conditioning Engineers) scale. The original nine point bi-polar scale was adapted to seven points by omitting the upper two points (hot and very hot). It was felt that it was unlikely due to the nature of this experiment, that participants would attain sensations of this order.

The pain, tingling and numbness scales were based on a four points all ranging from 0 which indicated no sensation to 4 which indicated whether intolerable pain, whole hand numb or whole hand tingling.

The method by which subjects should report changes in any of their sensations was initially deliberated. It was thought that by prompting participants to report changes in sensations at set times every minute or so may result in inaccuracy in the times that the sensations were felt, in that there could be a time lag of 59 sec from the onset of sensations to the actual reporting of. This is obviously unacceptable especially in the fast cooling conditions, where participants were only cooled for up to five minutes. It was determined that participants would report any changes verbally (as they would be unable to write) every time a sensation changed. If the participant did not report any change for a prolonged period of time (determined by the experimenter) then the experimenter could remind the subject to report any changes in sensation.

The sensation scales are shown in chapter 6.

## **2.7 Experimental Space**

An experimental space that had all of the following criteria was designed and built.

- ❖ Space for an air conditioning cabinet
- ❖ A thermal environment, which could be, controlled within the following range  $T_a \approx 15^\circ\text{C}$  to  $30^\circ\text{C}$ ,  $v \leq 0.2 \text{ ms}^{-1}$ ,  $R_h \approx 40 - 60\%$ .
- ❖ Bench space for data acquisition system and PC
- ❖ Sufficient space for a minimum of two participants and one experimenter

## **2.8 Safety**

Due to the materials used and the temperatures and duration that contact would be sustained for, it was anticipated that skin temperatures could fall below  $0^\circ\text{C}$  which could result in tissue damage of participants. To prevent this, several safety precautions were put in place.

Participants were asked to withdraw their hand from the cold chamber if:

- ❖ A contact temperature of  $0.5^\circ\text{C}$  was reached anywhere on the hand

- ❖ Participants were reminded they could withdraw at any time and had to withdraw if they reached 4 on the pain scale (intolerable pain)
- ❖ Prior to the experiment Participants were also instructed to withdraw from the cold chamber if they experienced a sensation similar to an electric shock or severe pins and needles, as both these sensations can be indicative of frost nip.

Extensive pilot studies were conducted at the partner institutes involved the European project (National Institute for Working Life, Stockholm, Sweden; Universite Catholique de Louvain, Belgium; TNO Human Factors Research Institute, The Netherlands and at The Institute for Occupational Health, Finland. The data from these pilot studies, provided information on the expected cooling speeds and safe temperatures for a number of the materials to be tested at. Based on these pilot studies conditions were established for the experiment, which would result in minimal risks of frostnip, as for a normal healthy subject cooling speeds were slow enough that participants could withdraw their hand before damage was sustained.

## **2.9 Ethical Clearance**

Prior to start of experimentation, it was necessary to gain ethical clearance from the Loughborough University Ethical Advisory committee. A generic protocol for human biological investigation was submitted. This was accepted and cleared by the committee in November 1998, research proposal number: G98- P5.

## **2.10 Pre visits**

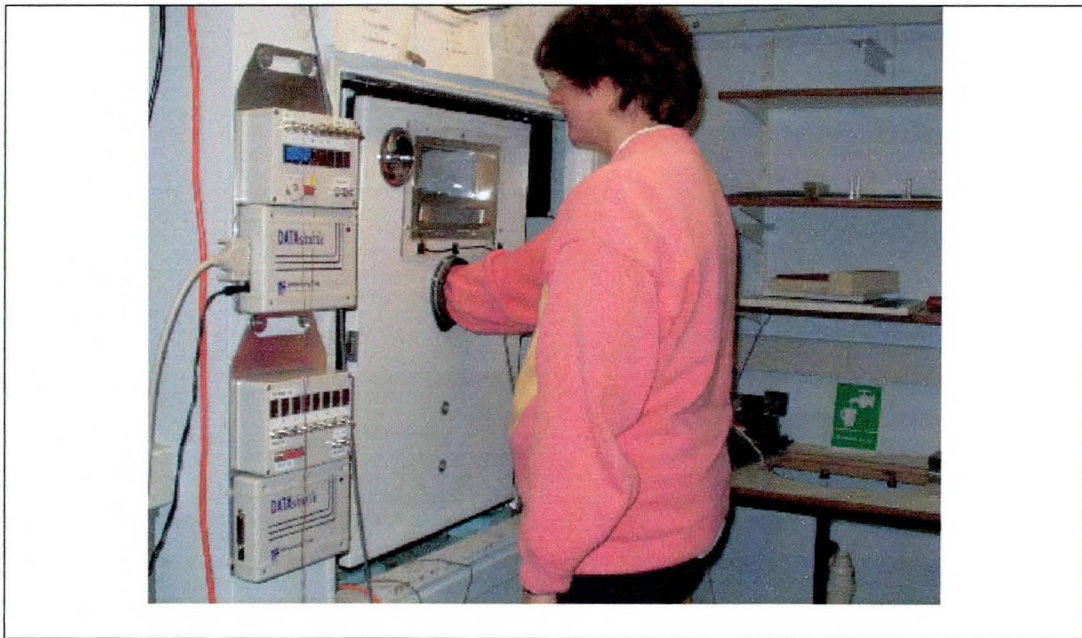
Prior to a participant starting an experiment, they were invited down to the lab to discuss the experiment with the experimenter and to familiarise themselves with the set up. After a discussion of what the experiment entailed and answering any questions that the participant may have, the participant was asked to fill out a health screen questionnaire and an informed consent form (see appendix 1). If the participant passed the health screen and consented to the experiment, then the participant was asked to grip a nylon bar at -18°C for two minutes. This was done so that the experimenter could ensure a normal cooling curve resulted. It was done at this temperature, as it was felt the material and condition would not induce rapid cooling, or if a subject should have a disorder they were unaware of affecting the circulation or cooling of the hands, it would be observed quickly and the

participant released from the experiment without any damage. If the cooling curve was normal the participants hand was rewarmed and the participant was asked to practice any manual dexterity tests that he or she would perform in the experiment. The subject continued practising the test until there was a plateau of performance, or until the subject became fatigued in which case they would have a drink before continuing to practice. It was established through trials, that once the manual dexterity test performance had reached a plateau, that there was no decrease in performance over the duration of the experiment due to time. Physical measurements of the participants were then taken including hand morphology and the size of the area of the hand that would be in contact with the bar.

## **2.11 Generic Experimental procedure**

Participants were asked to arrive five minutes before the experiment was to begin. Each participant was tested at the same time of day on each occasion. All participants were asked to wear similar clothing. This consisted of a T-shirt, jeans, socks, shoes and appropriate underwear. Participants were also asked to abstain from tobacco products and also alcohol for 24 hours prior to the experimental session and otherwise to eat and drink as normal. Participants were then asked to sit in the experimental area until they achieved a sensation of -1 on the thermal sensation scale. Once this was achieved, participants were asked to rest for a further fifteen minutes. Their sensation votes were then taken every five minutes until the start of the experiment. Air conditioning and clothing level was adjusted to accommodate the starting thermal sensation vote accordingly. The environmental data logger started recording at this point. Whilst the participants sat at rest thermocouples were placed on the hand that was being tested in that experiment. Thermocouple location and the number of thermocouples depended upon the experiment. The experimenter then started the Workbench for Windows programme. The environmental conditions and material for that experimental session were then checked to ensure they were at the correct temperature, and the bar was removed from the back of the freezer and attached to the pulley system. A step was supplied depending upon the participants height, they could access the armhole with the minimum of discomfort. For the occlusion experiments however, due to the increased risk of fainting, all participants were asked to be seated and the seat height was adjusted accordingly. A skin temperature of a minimum of 25°C was required at all thermocouple sites prior to entry of the hand into the freezer. Once this was

achieved and the participant had remained at PMV-1 for fifteen minutes the data acquisition programme was set to write to the PC hard drive, and the participant was asked to remove the polystyrene bung in the armhole opening. Participants then gave their sensation votes (thermal sensation, pain, numbness and tingling for the hand only and the experimenter instructed the participant “3.... 2.....1.... go” at which point the participant entered their hand into the freezer and picked up the bar and suspended it in the air. Upon the word go, the experimenter started a stopwatch. The participants were again asked to give their sensation votes immediately upon contact with the bar. It was desired that all participants gripped the bar in the same way. To this end red tape was placed on the bar to be used and the participant was asked to grip the bar in such a manner that the ‘v’ between the thumb and first phalanx was directly above the strip of tape placed on the bar for easy identification of hand placement. Upon gripping of the bar, participants were asked to report any changes in sensation as and when they occurred.



*Figure 2.9 A participant entering their hand into the freezer*



*Figure 2.2.10 shows the correct position for gripping a bar.*

The experimenter constantly monitored the cooling of the participant's hand, and the experiment was immediately stopped if any of the criteria given earlier were reached, or:

- ❖ The participant wished to withdraw at any time for any reason

Upon completion of the exposure time (this was dependant upon the experiment and the speed of cooling) the participant was asked to withdraw their hand and replace the polystyrene bung. The participant's hand was then monitored until it returned to a temperature of 25°C. The participant placing their hand under their armpit speeded this up. When a temperature of 25°C was attained participants were asked to repeat their sensations, if there was no abnormal sensations recorded, then the participant repeated the test with their other hand, or left the laboratory.

If a manual dexterity test was used in an experiment, participants completed the manual dexterity test just prior to entry of their hand into the freezer, with all the thermocouples in place. The participants then repeated the manual dexterity experiment at the end of the contact period. The manual dexterity tests will be discussed in detail in chapter 4.

## **2.12 Arm Blood Flow Occlusion Procedure**

A pressure cuff (105cm) was wrapped round the participants forearm with the widest part of the material in contact with the participants skin. The cuff was situated proximal to the

condoloids on the dominant arm. Care was taken to avoid any bony prominence (condoloids) when attaching the cuff to avoid potential nerve damage. The valve for pressure release in the cuff was closed and the cuff was inflated rapidly to 200mmHg. After the occlusion period, pressure was released from the pressure cuff slowly by opening the pressure release valve. Figure 2.11 shows the occlusion cuff in the correct position and ready for inflation



*Figure 2.11 Correct position of the Occlusion Cuff*

### **2.13 Plethysmography procedure**

The widest part of the participants forearm was measured using a tape measure. An EC4 Hokanson SGP mercury strain gauge was then selected that was 2 cm shorter than circumference of the widest part of the participants forearm. The strain gauge was then placed around the participants arm at the widest part and the lead was secured using a small piece of '3M Blenderm' tape. The tape was arranged in such a way, that at no point was either the tape or the loop of the mercury strain gauge touching any other part. The strain gauge was then plugged into the plethysmograph.

The equipment used to collect and record the data was a 16- bit Strawberry Tree DATAshuttle, model DS-16-8-TC-AO, and it was linked to a Pentium II, 300MHz, 32Mb

PC with Workbench for Windows software. The customised programme also controlled the inflation and deflation of the blood pressure cuff via a solenoid power unit.

The Participants arm was then placed into a made to measure sling, which supported the arm at heart level at the wrist with the palm facing upwards. The arm was straight at this point. The participants were then asked to find a comfortable position they felt they would be able to hold for five minutes and asked not to talk from that point on. The WorkBench programme was then started and five blood flow measurements were taken over a five minute period. Only three of these measurements were required, but due to the sensitive nature of this equipment typically at least one of the five measurements was affected by participants shifting position or moving their hands. The solenoid power unit then inflated the blood pressure cuff to a pressure of approximately 50mmHg. This pressure was determined as optimal as it prevents venous outflow but allows the inflow of blood through the arteries. This results in an increase in the diameter of the arm, which is subsequently measured by the strain gauge plethysmograph. For the purpose of calibration and to give a baseline reading from which the final blood flow measurement can be calculated, a 'spike' representing 1% increase in blood flow was produced by the calibration switch before and after each blood flow measurement. The analysis of the volume curve is detailed in chapter 8.

## **2.14 Participant Selection**

All participants were volunteers with no history of frostbite, cold related injuries or vascular disease. In the case of the occlusion experiment, all participants had to have no history of fractures in their dominant arm. Both male and female participants were used for the majority of the studies, as this was felt to be more representative of the working population. Females however where used were controlled for menstrual effects. Prior to the experiment, all participants were given an information sheet. The time and place of each experiment was controlled and kept constant. All participants completed a medical screening form and an informed consent form. All procedures conducted at the laboratory were first cleared by Loughborough University Ethical Committee.

## **2.15 Statistical Analysis**

All data was analysed in Systat 9 (SPSS Inc.).

## **3 The Effects of Contact Cooling on Manual Dexterity and Cooling of the Hand**

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### **3.1 Chapter Summary**

Two main types of cooling were found to occur as a result of contact cooling (on the continuous spectrum of cooling); slow cooling and fast cooling. It was concluded, for materials with high contact coefficients, tissue damage would usually result before manual dexterity is severely affected. However for materials with lower contact coefficients it is possible that severe decreases in dexterity would be experienced before tissue damage. It was also felt that the O'Connor dexterity test did not reflect the full range of manual dexterity decrements occurring as a result of contact cooling.

### **3.2 Background**

At present there is no international standard that addresses the specific safety problems associated with contact cooling. Contact cooling, in this sense, occurs when contact with a material that is colder than the skin is made. Heat flows away from the warmer skin to the cooler material. Contact cooling differs from cooling by air or water, as the hand may not be in uniform contact with the material. This may lead to uneven cooling patterns throughout the hands and fingers, resulting in very localised cooling (Chen, F. et al., 1996.). It is therefore important to determine safe contact times for different materials at different temperatures in terms of the risk of tissue damage *and* the effects on manual dexterity. The majority of research investigating the effects of cold on manual dexterity has

focused on the effect of air and water cooling on extremities, for both whole body and local cooling (Provins and Morton 1960, Clark and Cohen 1960). To date very little research has been conducted into the effects of contact cooling on performance, although it is thought that factors such as the thermal properties and the surface topography of the material will affect physiological responses including manual dexterity (Chen et al. 1994). Contact cooling may occur where machinery is operated in cold conditions, for example, by accidental touching of machinery surfaces in cold environments, or by the intentional sustained gripping of cold tools (e.g. a hammer or a gun). If the contact is as a result of handling a tool and therefore for a prolonged period of time, deep tissue damage, whole hand frostbite and/or numbness may result (Chen et al. 1994). This will be detrimental to manual dexterity.

### **3.2.1 Hand Skin Contact with Cold Solid Surfaces**

The contact of skin with a cold solid surface may result in an increased cooling speed of the skin when compared to that, that would be found if the skin was exposed to ambient air at the same temperature. When the skin is exposed to ambient air, the majority of cooling occurs by convection. When a hand is in contact with a cold solid surface of a material with a high contact coefficient, the majority of cooling occurs by conduction. However, when the hand is in contact with a material with insulating properties (i.e. a material with a low contact coefficient) at low temperatures (e.g. -20°C) heat from the hand will also be conducted by convection to the surrounding air. The steeper the temperature gradient between the material and the skin, the faster heat will be transferred from the skin to the material. The more rapid the cooling, the more increased is the risk of the initial pain associated with the onset of frostbite being missed before the development of frostbite begins and is therefore noticed (Killian and Graf-Baumann 1981). As well as the temperature gradient, the speed of cooling and resultant transfer of heat from the skin to the cold solid surface depends upon a number of factors: a) Pathak *et al.* 1987, Havenith *et al.* 1992, Chen *et al.* 1994 and Rintamaki 1997 agreed that properties of the surface of the material that the skin is in contact with affected cooling, b) human hand skin and individual differences were also found to affect contact cooling (Hellstom 1965, Burse *et al.* 1979, Havenith *et al.* 1992, Rintamaki *et al.* 1997) and finally c) the constitution (including factors like pressure) of contact was found to affect contact cooling (Imamura *et al.* 1996, Rintamaki *et al.* 1997, Chen *et al.* 1994).

### 3.2.2 Contact Material Properties

Thermal properties of the material including specific heat capacity and thermal conductivity have a direct relationship with the heat exchange that occurs between the human skin and the material (Holman 1989). Havenith *et al.* 1992, Chen *et al.* 1992, both use the thermal penetration coefficient of the material to characterise its properties, and is expressed as the following (BSI 1978).

$$b = (k \cdot \rho \cdot c)^{1/2} \quad (\text{units} = \text{Jm}^{-2}\text{s}^{-1/2}\text{K}^{-1})$$

Where:  $b$  is the thermal penetration coefficient,  $k$  is thermal conductivity ( $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ ),  $\rho$  is density ( $\text{Kg}\cdot\text{m}^{-3}$ ) and  $c$  is the specific heat ( $\text{J}\cdot\text{Kg}^{-1}\cdot\text{K}^{-1}$ )

A table of thermal properties of the materials used in the following experiments can be found in Chapter 2.

### 3.2.3 Hand Skin and Individual differences

Differences in human skin between individuals was discussed in chapter one. Reasons for differences can include callus presence, gender differences and variations in thermal body state and blood flow of the micro circulation (Holmer 1998). Racial and geographical differences have also been found to be a cause of inter-individual variation (Hellstrom 1965). Within participants, variation occurs within the hand as skin thickness can vary over different parts of the hand (Molnar *et al.* 1973).

### 3.2.4 Constitution of Contact

People are exposed to cold surfaces everyday in industry. Contact with these surfaces may be accidental or intentional. These two types of contact will result in different durations of contact. The longer the hand is in contact with the material, the longer time there is for heat transfer to occur. If the contact is intentional, then it may be as a result of picking up a small object e.g. a nail or hammer, or something larger e.g. a box of tools or gripping onto a ladder. The range of materials in such an environment, including their size shape and texture will affect the speed of cooling, and the type of contact (e.g. full hand or finger) that occurs. Effects of pressure have been found to have a significant effect on contact cooling (Chen *et al.* 1994 and Geng *et al.* 2000).

### 3.2.5 Manual Dexterity

Manual Dexterity will be discussed in more depth in Chapter 4, but a brief overview will be discussed here.

Manual dexterity can be affected as a result of effects on several components, including reaction time, sensitivity, nerve conduction, grip strength, time to exhaustion and mobility (Havenith *et al.* 1995). These factors are caused by physiological changes including nervous blocks, decreases in rate of nerve conduction velocity, changes in power, contraction, speed and/or endurance of muscles, and a thickening of the synovial fluid that lubricates the joints. There are critical temperatures at which the cold starts affecting each of these structures. De Jong *et al.* (1966) found a linear decrease in nerve conduction velocity of  $60\text{ms}^{-1}$ . Below  $20 - 24^{\circ}\text{C}$  there is a stronger decrease in nerve velocity and a nervous block occurs at temperatures below  $10^{\circ}\text{C}$ . Reduced skin sensibility is most likely due to physiological changes in the receptors whereas reduced mobility is most likely attributable to changes in muscles, joints and tendons. The mobility of a joint is affected by cooling, as the synovial fluid that lubricates the joint thickens so movement becomes slower. This is often referred to as joint stiffness, and when the fluid becomes more viscous more muscle power is required to make movements. Joints cool more quickly than the muscle core and average skin temperature (Hunter *et al.* 1952).

At present much is known about the effects of air and water cooling on the extremities and subsequent effects on manual dexterity. However, very little is known about the effects of contact cooling and subsequent effects on manual dexterity. The effects of a cold body and warm hands have been investigated in the past (Keiss and Lockhart 1971) however due to the nature of contact cooling the localisation of cold exposure is likely to be more extreme with local 'cold' and 'hot' spots appearing within the hand. It is currently unknown what these effects will have on manual dexterity. For this reason, an experiment was devised that will investigate the effects of gripping materials with different contact coefficients on manual dexterity. This will be compared to the effect of air exposure on dexterity.

For these reasons this study will compare reduction in manual dexterity due to contact cooling while gripping bars of different materials, and cooling by air, and investigate the effect of the contact with the material on dexterity. It is thought that the materials that

induce fast cooling will have a more significant effect on contact cooling than materials inducing a slower rate of cooling, due to the lower skin temperatures that will be reached during the fast cooling conditions.

### 3.3 Methods

#### 3.3.1 Participants

Ten participants (5 men and 5 women) participated in this study. All participants were volunteers; aged between 19 and 36 ( $24.6 \pm 4.9$  years) had no history of any cold related injury, vascular disease or cold acclimatisation. All participants signed a consent form prior to exposure.

*Table 3.1. Shows the participant details*

Age (Years)	Weight (Kg)	Height (cm)	Sex (M/F)	Hand Surface Area (cm <sup>2</sup> )	Hand volume (cm <sup>3</sup> )	Contact area (cm <sup>2</sup> )
36	87.7	166.5	F	156.2	299	83.5
25	67.3	166.5	F	144.8	310	78.7
22	84.7	188	M	155.2	449	77.94
29	75.01	171	F	154.7	337	81.04
27	72.1	171	F	139.3	375	80.96
21	91.05	182.5	M	169.4	347	80.37
22	59.42	169	F	147.9	378	80.89
19	81.7	194.5	M	184.4	466	89.7
24	74.8	179.5	M	167.7	427	72.39
25	77.1	176.5	M	157.7	376.4	80.6

#### 3.3.2 Material Properties

For contact cooling, bars of five different materials were used: wood, nylon, stainless steel, aluminium or stone, all with different thermal properties as defined by the contact coefficient (see chapter 2).

Each participant gripped a bar that was approximately 400mm in length and 40mm or 42mm (stone) in diameter. The bars were weighted from outside the cold-box so that each one weighed 500g. This resulted in the same pressure being applied to each bar in order to lift it and hold it in the air. The five materials and air as a reference (holding the hand in a 'gripping' position in air of the respective temperature) were only tested at temperatures

appropriate to their thermal properties in terms of risk of tissue damage to the participant (Table 3.2). Metals were tested only at the higher temperatures as the risk of tissue damage through supercooling was high. Nylon and wood were tested at much lower temperatures, as at the higher temperature range, they would have insulative effects and any changes in skin temperature observed would have been minimal and eventually leading to the skin re-heating.

Table 3. 2. *Environmental Test Conditions of Materials*

Materials						
	Wood	Nylon	Stainless Steel	Aluminium	Stone	Air
Temperature	-20°C, -30°C	-10°C, -20°C, -30°C	0°C, -5°C	0°C, -5°C	-5°C, -10°C	0°C, -5°C, -10°C, -20°C, -30°C

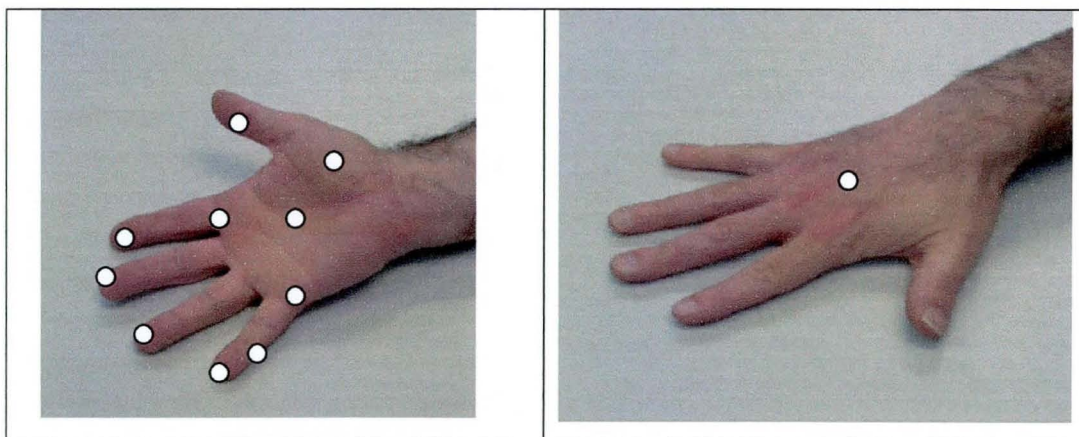
Participants accessed the bar through a hole in the cold-box door. A window was also cut into the door so that the participants could see the correct section of the bar to grip. Participants were asked to lift the bar from its rest and hold it in the air for a total of thirty minutes or until one of the withdrawal criteria (a contact temperature of 0°C as measured by one of the 15 thermocouples on the hand, the sensation of frostnip and/or intolerable pain) were experienced by the participant, or if the participant wished to withdraw at any time for any reason. A pressure pad under the bar ensured that it was possible to tell that the participant was lifting the bar and not merely holding it. The environmental conditions of the room where the cold-box was situated were  $T_a = 21.3^{\circ}\text{C} \pm 0.87^{\circ}\text{C}$ ,  $R_h = 40\%$  (estimated). These conditions (together with selected clothing) ensured that the participants were at a steady thermal state of slightly cool ( $PMV=-1$ ) for fifteen minutes prior to exposure.

### 3.3.3 Manual Dexterity Test

To test dexterity a modified version of the O'Connor test was used. This test was selected, as it was thought that finger dexterity would be likely to be affected as a result of contact cooling. The O'Connor dexterity test required tactile sensitivity of the thumb and index finger pads, co-ordination of the hand/arm and joint mobility in the thumbs and index finger. The modification ensured that the participant's hand was not out of the cold-box for a prolonged period of time. The participant was asked to place three pins in each of the

holes in the top row only. The participant filled the holes from right to left if they were right handed and from left to right if they were left handed. The participant picked up three pins in one attempt. If more or less pins were picked up then the participant could not correct the mistake. The three pins should be placed in one hole. The participant was not allowed to tap the pins on a desk to straighten them, or to use their other hand. If any pins fell when the participant was trying to put them in the hole, they were not allowed to collect them and the participant placed the remaining pins in the hole and continued. The test is scored by a) the time needed to fill the first row of holes b) the total number of pins taken from the container and c) the number of pins placed correctly in the hole. Prior to the experimental sessions, the participants performed the modified O'Connor test until there was no significant improvement in their scores.

Each participant sat in a room at a PMV of  $-1$  for 15 minutes. During this time, thermocouples were placed on the participants hand (see figure 1 for locations). The thermocouples were on the participants hand prior to the initial (control) manual dexterity test, so and interference that the positioning of the thermocouples caused was constant both pre and post experience and as such can be discounted as a factor in the findings.



*Figure 3. 1. Locations of the thermocouples on the participant's hand*

Once instrumented, the participant then performed the modified O'Connor test. The participant then put their hand into the cold-box and picked up the bar for 15 minutes. Then, the hand was taken out and the O'Connor test performed and the hand replaced in the cold-box. The participant then resumed gripping the bar for a further 15 minutes whereupon they completed the O'Connor test for a final time (if the participant withdrew their hand before the 15 or 30 minute exposure had been completed, they performed the

O'Connor test immediately upon withdrawing their hand). Participant measurements of pain, thermal sensation, numbness and tingling were recorded throughout the session. Only the results for the first 15 minutes of the experiment were analysed due to the high rate of early withdrawals in the second period.

Performance Reduction was calculated with the following equation:

$$\text{Performance Reduction} = \frac{(\text{Time for test after} - \text{Time for test before})}{\text{Time for test before}} \times 100$$

### 3.4 Results

The graphs below shows typical cooling curves that were seen during the exposures. Under these conditions, few participants lasted for the duration of thirty minutes.

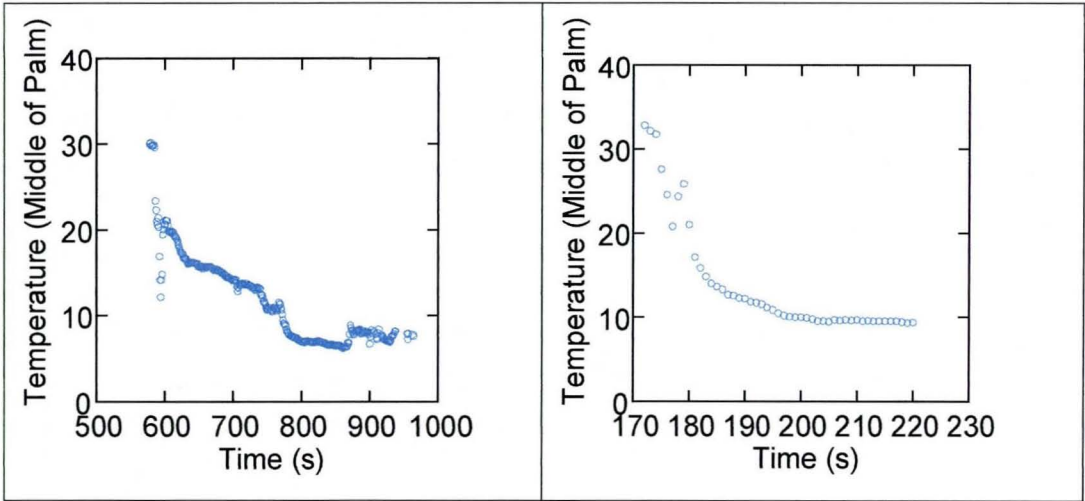


Figure 3.2. Participant 6, Gripping Nylon at 20 °C      Figure 3.3. Gripping Stainless Steel at -5 °C

Figure 2, shows a typical cooling curve for contact with nylon at -30°C, The participant maintained contact with the bar for 350 seconds before withdrawing from the exposure through pain. Figure 3.3, shows a typical cooling curve for contact with stainless steel. Contact this time only lasted for 50 seconds, but skin temperature reached approximately the same temperature as contact with the nylon bar induced after 350s. After 50 seconds of exposure to the stainless steel bar, the participant withdrew through intolerable pain.

The results are presented in figures 4 - 7. In Figure 3.4, the performance reductions at all five air temperatures, where the hand is not in contact with a bar but 'gripping' air, are presented in box - plots. In the box plot, the centre vertical line marks the median of the sample. The length of each box shows the range within which the central 50% of the values fall with the box edges (hinges) at the first and third quartiles. The graph shows that performance reductions increase as the temperature decreases as expected.

For the following three figures, the mean over participants has been taken for each condition. Air has been excluded as the following graphs will deal only with materials involved in the contact cooling. Figure 3.5, shows the relationship between performance reduction and the thermal properties of the bar at each individual environmental condition (i.e. the starting bar temperature). The graph shows that the higher the contact coefficient is, the lower the resultant performance reduction is opposite to expectations.

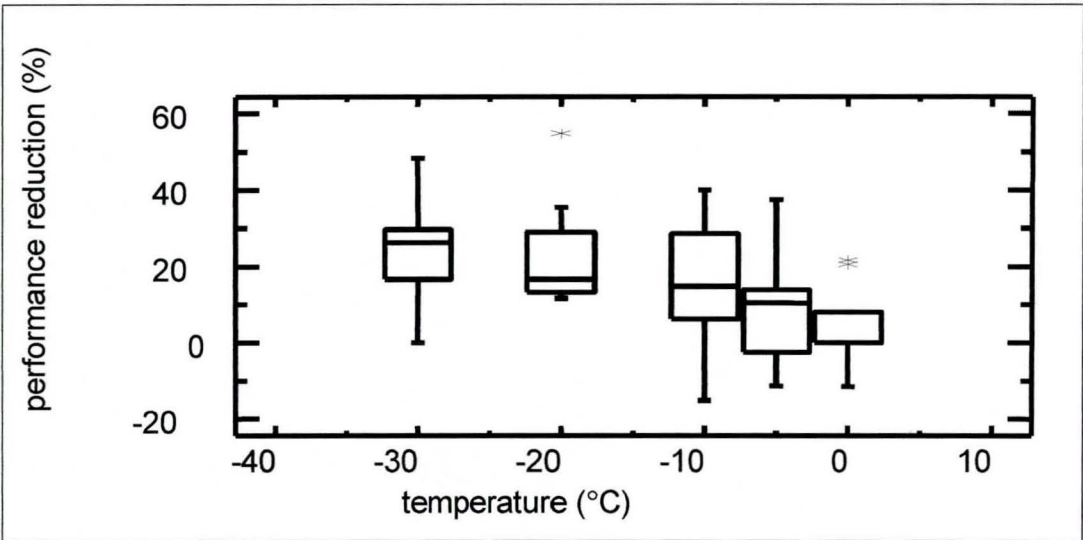


Figure. 3.4. Performance Reduction at Each Temperature for Every Participant whilst 'Gripping' Air. The centre horizontal line marks the median of the sample and the length of the box shows the range within which the central 50 % of the values fall. The ends of the box (hinges) fall at the first and third quartiles. The whiskers show the range of values within the inner fences. Values between the inner and outer fences are denoted with an asterisk, these are likely to be outliers.

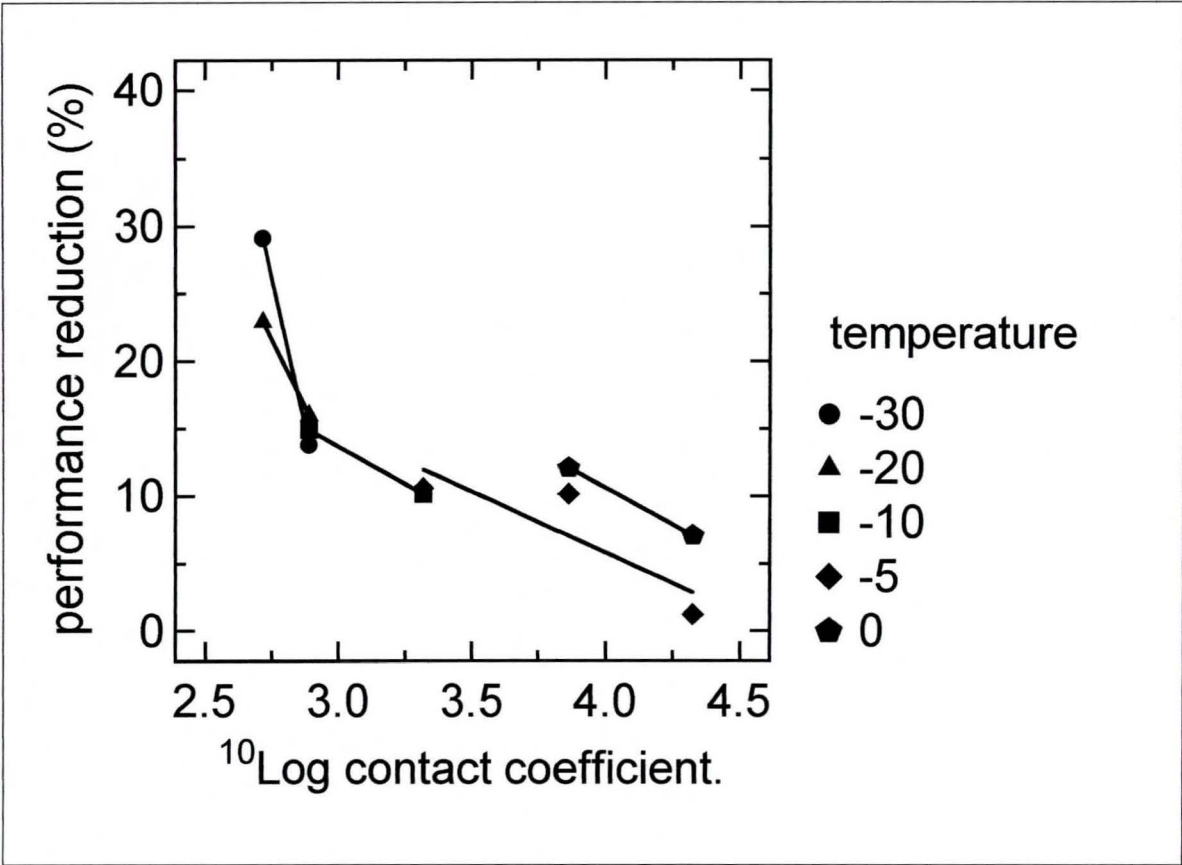


Figure. 3.5. Relationship Between Performance Reduction at or Before 15 Minute Exposure and Contact Coefficient of the Material.

Figure 3.6, shows the relationship between contact material properties and test duration. It can be observed that the lower contact coefficients also had the longer exposures to the bar and environmental conditions. As stated previously only the first 15 minutes of data has been analysed, so the data was capped at 900 seconds.

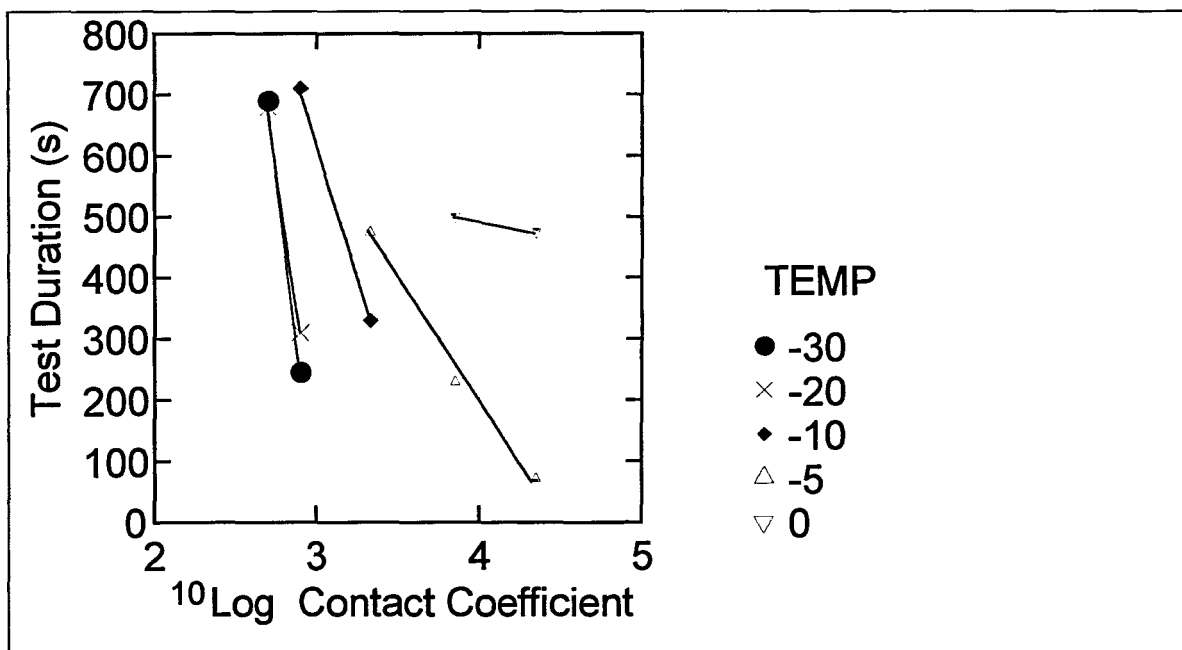


Figure. 3.6. Relationship Between Contact Coefficient of the Material and the Duration of Exposure.

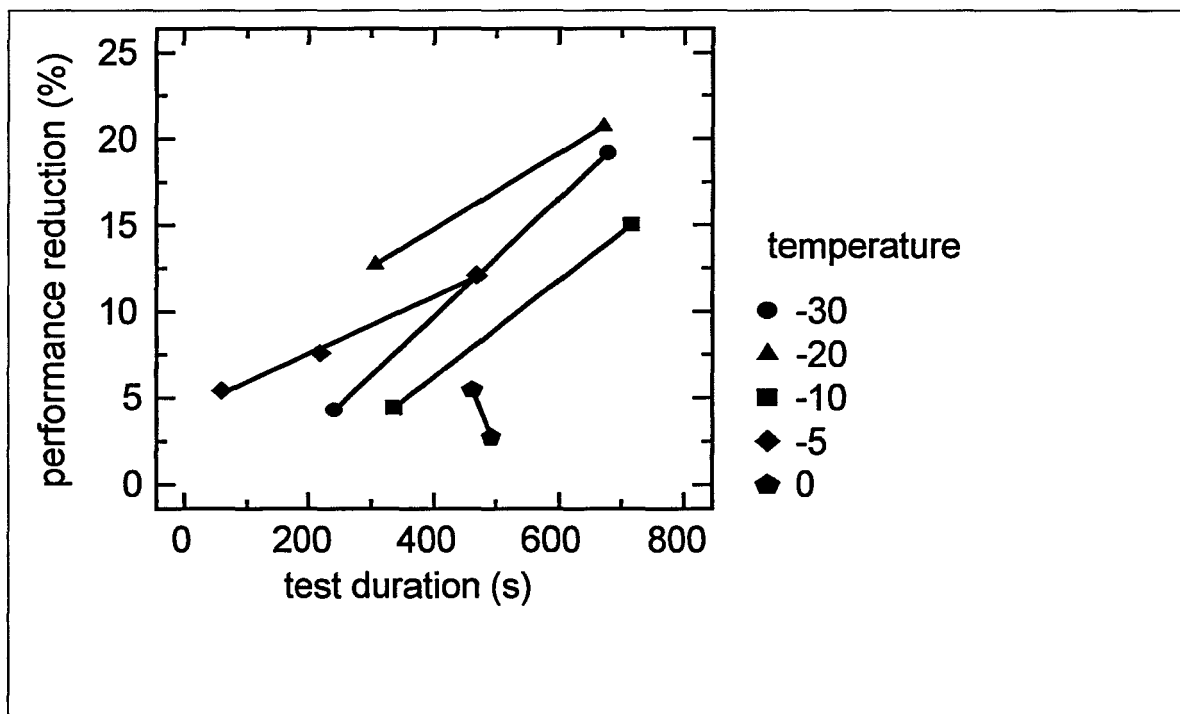


Fig. 3.7. Relationship between test duration and performance reduction.

Figure 3.7, shows the relationship between performance reduction and contact duration. The graph shows that as duration of exposure increases, so does performance reduction.

### 3.5 Discussion

It was expected that as temperature decreased so would performance for the conditions where the participants were exposed to air. This was indeed observed in the results as shown in Figure 3.4 which showed performance reduction after a maximum of 15 minutes exposure to the material. For the gripping tests, it was expected that the contact coefficient rather than temperature would be the main factor in determining the reduction in performance. Obviously a metal is expected to affect dexterity more than wood for example at the same temperature, but it was also expected that, gripping aluminium at 0°C would have a greater effect on manual dexterity than gripping nylon at -20°C. This was not observed however. Though it was expected that the higher the contact coefficient the higher the reduction in performance would be, the actual results showed the opposite: the higher the contact coefficient the lower the decrease in performance (fig. 5). A confounding factor was present however: time. The effect observed was likely due to the effect of the duration that the participant held the bar for. For materials with a relatively high contact coefficient (e.g. aluminium), the hand was only in contact with the material for a very short period of time, as the participants withdrew their hand from the stimulus because of the high pain levels experienced, or because the contact temperatures set for safety had been attained (Figure 3.6). Conversely, materials with a low contact coefficient (e.g. wood) initially cooled the hand quickly but then due to the thermal properties of the material began to warm up relatively quickly, possibly even to the point where the material became insulating from the thermal environment. This would mean that the participants were able to grip the bar for longer periods of time than if the bar had had a higher contact coefficient, despite the lower temperatures.

In the first instance, using the material with the high contact coefficient and the short duration of exposure, it is likely that only contact surface cooling was able to occur. In the second instance, when contact was made with the material with a lower coefficient, the back of the hand was exposed to low temperatures for a longer time. The inside of the hand however, initially exposed to a low temperature became relatively insulated within a short time frame as the heat was transferred from the hand to the bar. It is likely therefore, that with the increased duration compared to contact with the metals, that deeper cooling may have taken place. The deeper cooling would have a more profound effect on manual

dexterity than the more superficial surface cooling as it is likely in the superficial cooling, that only the skin and structures immediately adjacent to the skin would be affected, rather than the deeper underlying structures affected as a result of the deeper cooling. It is therefore likely, that contact cooling, occurring as a result of contact with a material with a low contact coefficient, would have effects on manual dexterity similar to those caused by cooling by air. It should be noted however, that this is only the case, if the dorsal aspect of the hand was exposed to air and the palmar aspect shielded. This time effect on depth of cooling is consistent with observations of Havenith *et al.* (1992) who found a similar effect regarding pain.

It is believed that the following temperatures are critical for various aspects of manual dexterity to be affected (Havenith Heus and Daanen 1995). A muscle temperature of 38°C is optimal for work requiring maximal force.

*Table 3.3. Critical Temperatures for different physiological structures at which manual dexterity is significantly reduced.*

Physiological Structure	Critical Temperature for loss of manual dexterity (°C)
Receptors	10
Nerves	20
Joints	24
Muscles (task dependant)	28-38
Skin	15

Fast cooling, invoked by contact with a material with a high contact coefficient, might affect aspects of manual dexterity, such as tactile sensitivity and pain sensations. This would be as a result of the  $T_{sk}$  falling below 15°C and thus affecting the skin and receptors (see table 3.3). It is unlikely however, that the modified O'Connor test would highlight the effects fully, as although it does investigate tactile sensitivity, it primarily investigates effects on the tactile perception of the first phalanx of the index finger and thumb, co-ordination of these two digits and the speed of the arm (a gross movement unlikely to be affected by contact cooling). These are areas not fully in contact with the bar. It is likely that other aspects of manual dexterity are affected as a result of contact cooling, but were not sufficiently identified due to the limited scope of the O'Connor dexterity test.

The O'Connor dexterity test can be completed with very little flexion or extension of the fingers and requires little strength. It also requires little accuracy in tactile perception of the hand as a whole. The experimenter noted through conversation with the participants, that complaints of numbness, tingling and pain were predominantly reported elsewhere within the hand and subsequently not reflected in the results of the O'Connor test. It is also unlikely, because of the rapid nature of cooling and short duration of exposure occurring as a result of contact with metals, that the structures (joints, muscles, nerves etc.) responsible for some types of manual dexterity losses would be affected by the rapid cooling. This type of cooling is most likely to affect the skin and tissue immediately adjacent to it and is unlikely to have affected the majority of these structures.

It is hypothesised that in cooling of this type (rapid contact cooling resulting from contact with a material with a high contact coefficient) that tissue damage would usually result before manual dexterity was severely affected. The theory behind this, is that as a result of rapid contact cooling, the skin becomes supercooled. This occurs so quickly, that the underlying structures do not cool at the same rate and remain relatively warm. This can effectively result in skin damage, while the underlying structures remain warm enough to perform adequately.

As regions of pain, numbness and tingling were reported in areas other than those tested by the O'Connor dexterity test, it is probable, that manual dexterity losses experienced as a result of slow cooling (contact with non metals at relatively low ambient temperatures), were not detected by the O'Connor test. However, this is not to say that manual dexterity deficits are not present as a result of contact cooling. The deeper tissue cooling that occurs as a result of slow contact cooling (e.g. during contact with wood and nylon at relatively low ambient temperatures), may affect aspects of manual dexterity relying on the functioning of the underlying structures, but may not be represented in the results. These structures include joints, receptors, muscles and nerves and would be more likely to be severely affected than the results of the modified O'Connor dexterity test indicated. These structures would affect aspects of manual dexterity such as strength, joint mobility and speed. These aspects would not have been illustrated by this test, and yet are likely to have been affected by contact cooling of this nature.

As shown in Figure 3.6, the duration of exposure was longer for materials with a lower contact coefficient than for those with a higher contact coefficient. This was due to the level of early withdrawals by participants after contact with the materials with high contact coefficients through intolerable pain. When for each bar temperature the contact duration was compared between materials tested at that temperature, it was found consistently that the materials with the highest contact coefficients had the shortest durations. This is therefore consistent with the above explanation. For this reason the relationship between exposure duration and performance was considered (Figure 3.7). It was expected that longer durations of exposure would result in a higher decrease in performance. This was indeed observed but only in a weak positive correlation.

### **3.6 Conclusion**

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

The modified O'Connor dexterity test may have given an insufficient picture of the scope and scale of manual dexterity deficits experienced as a result of contact cooling. Thus it is suggested to expand the test battery of manual dexterity tests in future research to cover aspects of manual dexterity including strength, tactile sensitivity of the whole hand, and speed of flexion and extension of the fingers.

## **4 Aspects of Manual Dexterity Affected as a Result of Contact Cooling**

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### **4.1 Chapter Summary**

Chapter 3 showed that manual dexterity was affected as a result of contact cooling. The dexterity test used however only reflected loss in one aspect of manual dexterity. It was felt likely other aspects of manual dexterity would be affected. This chapter looks at tests that investigate a number of areas of dexterity likely to be affected and based on literature identifies the most suitable test. It was determined that the areas of manual dexterity most affected as a result of contact cooling were tasks requiring speed and strength.

### **4.2 Background**

Chapter 3 highlighted differences observed in manual dexterity as a result of fast contact cooling (materials of a high contact coefficient) and slow cooling (materials of a low contact coefficient). To measure the effects on manual dexterity, a modified version of the O'Connor dexterity test was used. It was felt through conversation with the participants and observation of the coolest parts of the participant's hand, that this test did not reflect the full range of manual dexterity deficits that occur during contact cooling. For this reason, it was decided to investigate a range of manual dexterity tests that address a number of properties of manual dexterity, and find out exactly which aspects of manual dexterity are effected as a result of contact cooling.

### **4.2.1 Manual Dexterity**

It is generally accepted that there are several factors responsible for decreases in manual dexterity with body cooling. These are considered to be increasing reaction time, reduced skin sensibility, muscle function, mobility and motivation. These factors (with the exception of motivation) are caused by physiological changes including nervous blocks, decreases in rate of nerve conduction velocity, changes in power, contraction, speed and/or endurance in muscles and a thickening of the synovial fluid, which lubricates the joints. (Heus R et al.. 1995). The O'Connor dexterity test used in chapter 3 only investigates a small number of these potential changes over a small section of the hand, primarily reduced skin sensibility and to a lesser extent increasing reaction time.

### **4.2.2 Why there is a Need for Manual Dexterity Tests to Assess Loss as a Result of Contact Cooling**

The previous experiment (Chapter 3) used the O'Connor dexterity test to investigate manual dexterity. It became apparent during the testing however; that this particular manual dexterity test did not require the skills or utilise areas of the hand most affected by contact cooling. Although some changes were noted in terms of time to complete the O'Connor dexterity test, it was felt that the results did not reflect the range or severity of manual dexterity decrements experienced due to contact cooling. The experimenter observed that subjects complained of numbness, pain and tingling elsewhere within the hand, which was not reflected in the test and subsequently the results. The sensations of pain, numbness and tingling were located in areas other than the first phalanx of the index finger and the thumb, which are the main areas of the hand required to complete the O'Connor dexterity test.

The O'Connor dexterity test can be completed with very little flexion or extension of the fingers and requires little strength. It also requires little accuracy in tactile perception of the hand as a whole. It primarily relies on tactile perception of the first phalanx of the index finger and of the thumb, co-ordination of these two digits and the speed of the arm (which is a gross movement). It is possible to pick up and release the pins with very little flexion or extension of the digits.

For these reasons it was decided to investigate other manual dexterity tests and to identify those that would reflect a more realistic and representative view of the effects of contact

cooling on manual dexterity. To do this it was necessary to consider tests used prior to this experiment in terms of: conditions in which the tests were used, the aspect of manual dexterity the test investigates and the areas of the body/hand/arm that are required for each test.

From the experiment detailed in chapter 3 it was observed that strength, tactile sensitivity and speed of flexion and extension of the fingers were affected. This was noted through conversation with the subjects after the experiment and also through the actions of the subjects after the experiment including, trying to grip a pencil or attempting to straighten fingers upon completion of the O'Connor dexterity test.

Therefore it was decided that the manual dexterity tests chosen for future experiments should represent four different components of manual dexterity most likely to be affected by contact cooling; strength, speed, tactile perception and a fine finger (motor) test. It was felt that the first three areas are representative of skills that could conceivably be required in cold conditions. They also represent aspects of manual dexterity that are likely to be affected by contact cooling. A fine finger (motor) test is required, that is less passive than the O'Connor dexterity. This test should require a combination of tactile perception, speed and skill. The combination of these three aspects of manual dexterity will provide a more complex test of manual dexterity than testing for a single aspect alone, and therefore reflect more fully the effects of contact cooling on manual dexterity.

#### **4.2.3 Manual Dexterity Tests Reviewed**

A number of investigations have been conducted to quantify the effects of cooling on manual dexterity. There are many different aspects of manual dexterity e.g. fine or gross manipulation. Giesbrecht *et al.* (1995) investigated several different aspects of manual dexterity including strength, speed, fine finger manipulation and co-ordination. An experiment to assess the independent contributions of local and/or whole body cooling on manual performance and oesophageal and muscle temperatures was undertaken. To look at the manual performance aspect of the experiment six manual dexterity tests were used.

a) Speed of finger flexion and extension (time for five repetitions)

- b) Monitoring the thinnest disk that could be picked up using the thumb and forefinger (finger dexterity)
- c) Measurement of isometric hand grip strength
- d) Screwing nuts along a screw (finger dexterity and tactile perception)
- e) Moving rings from one peg to another and then back again (manual movement)
- f) The depression of two buttons sixty centimetres apart (speed of gross movement)

Six subjects took part in three conditions; a) cold body with cold arm, b) cold body with warm arm and c) warm body with cold arm. Subjects were immersed in a water tank for 75 minutes. A separate tank was used to warm or cool the arm as necessary. The temperature of the water in each tank was independently controlled. The water was either at 8°C for the cold conditions or between 29°C and 38°C for the warm conditions. It was found that cooling of the body and/or the arm caused large reductions in finger and arm performance and that those reductions were primarily due to the effects of local arm and hand tissue cooling.

Tests e) and f) are unsuitable for the following experiment as they utilise areas of the body that would not be cooled during contact cooling of the hand. Test e) relies on movement of the shoulder and therefore is more applicable to experiments involving whole body cooling. Test f) is again more related to whole body cooling, as it measures spatial awareness and gross arm movement controlled at the shoulder.

Horvath and Freedman (1947) tried to define the loss of efficiency due to cold exposures by exposing 22 men to 25°C air for a period of four days. The men were then transferred to an environmental chamber, temperature -29°C for a further eight to fourteen days where the men followed a set regime of eating and exercising. Four tests were used during this investigation, with two being dexterity tests:

- Simple Visual Discrimination Reaction Time (measure of speed and precision (two stimulus's))
- Johnson Code Test (measures responses at a cortical level and finger dexterity as it requires the writing of answers)
- Hand Grip Test (using a hand dynamometer)

- Gear Assembly Test (devised at the laboratory requiring participants to use a hammer and open wrench)

These tests were administered either during long term exposure (up to fourteen days) or short-term exposure (up to three hours). It was found that the reaction time to visual stimuli did not decrease with low ambient conditions. However, hand strength and finger dexterity did decrease with exposure to low ambient conditions even over short durations of up to half an hour. The visual discrimination task and the Johnson code task were not felt to be suitable for this study, as they are more applicable to whole body cooling. The gear assembly task was not used as it was devised at the laboratory and not felt to hold any advantage over other more established tests.

Egerton and Parsons 1985 investigated the effect of different finger combinations of gloves on manual dexterity by using four different manual dexterity tests:

- star maze tracing test (wrist/finger speed)
- Fingertip block rotation test (fine finger dexterity)
- Pegboard test (fine finger dexterity)
- Modified Stromberg test (a board test measuring manipulative skill and measuring speed and accuracy of arm and hand movement)

All of the above manual dexterity tests were scored in time taken to complete the tasks. A subjective view of the tasks was also taken. Nine subjects were exposed to 5°C air for fifty minutes. The subjects wore glove/mitts that resulted in different combinations of digits being held together in order to restrict movement. This was achieved by either taping digits together or by the use of cotton Terylene gloves. Each subject held his or her gloved hand out in front of a fan, which circulated the air. It was found that the manual dexterity tests used provided erratic results, although there was a significant difference in performance of finger dexterity with gloves that did not have a finger combination of the first two digits when compared to designs that did. It was also concluded, that the combination of only the little finger and the ring finger had little effect on manual performance. It was also noted, that the digits were much cooler than the back of the

hand. These results would seem to indicate that the index finger and thumb is important in finger dexterity.

Kiess and Lockhart (1970) tried to determine if the rate of lowering mean weighted skin temperature affected manual performance. To achieve this, 24 male subjects were exposed to air temperatures of 24°C, 10°C, 7°C and 4°C for periods of either 90 or 15 minutes. In this time, in order to create a fast and slow cooling conditions, the subject's mean weighted skin temperatures were lowered to 21°C, 23°C, 26°C, or 29°C. However, the subject's hands were kept warm by the use of a heated box.

Four dexterity tests were used:

- Knot tying test (wrist and finger)
- Purdue Pegboard (finger dexterity and arm movement)
- Block stringing task (wrist and finger dexterity)
- two plate tapping (gross hand and arm movement)

It was determined that the Block Stringing and the Purdue Pegboard tasks were affected by low mean weighted skin temperatures, whilst the Two Plate Tapping task and Knot Tying task were not. This may be due to the fact that the knot-tying test relies solely on wrist and finger dexterity, the temperatures of which were maintained by the use of the hand box, so test scores were not adversely affected. In the case of the two Plate Tapping tests the movements required were not precise enough to be affected by the lower skin temperatures. It was concluded that a slow rate of cooling impairs certain types of manual dexterity more than a fast rate, but that this only occurs at low mean weighted skin temperatures.

Keiss and Lockhart (1971) also looked at the effect of auxiliary heating of the hands during cold exposure and the subsequent effects on manual dexterity. To achieve this, 20 subjects performed five manual dexterity tests in an ambient condition (16°C), a cold condition (-18°C) and three cold ambient conditions where auxiliary heat was applied to the hands (-7°C, -18°C, and -29°C). The tests were completed after 0, 60, 120 and 180 minutes. The tests used were the:

- Purdue Pegboard (finger dexterity)
- Block Stringing (wrist and finger dexterity)
- Minnesota Rate of Manipulation (MRM) (hand and arm dexterity (gross movements))
- Knot Tying (wrist and finger dexterity)
- Screw Tightening (hand and arm strength)

The cold condition (-18°C) without auxiliary heat applied to the hands, resulted in significant dexterity losses in all tests. The three conditions that used auxiliary heating of the hands resulted in either no dexterity losses or less dexterity losses than might have been expected under the ambient conditions, although this depended to some extent on the ambient condition, task and duration of exposure. This study did show that local cooling of the hand and forearm is the determining factor for manual dexterity in the cold. It was concluded that the auxiliary heat packs were effective in decreasing the effect of cold on performance. The Purdue pegboard was eliminated from this study, as it was considered too similar to the O'Connor dexterity test in that both involve primarily the thumb and index finger in a similar range of movement. The MRM was felt to be not sensitive enough to the expected manual dexterity losses as it relies on more gross hand movements than would be expected to be affected as a result of contact cooling.

Giesbrecht and Bristow (1992) investigated the effect of whole body cooling on manual dexterity. Six subjects were immersed up to their neck in water (8°C) and performed three manual dexterity tests:

- speed of flexion and extension of the fingers
- hand grip strength
- peg and ring test

These tests were performed immediately prior to immersion, every 15 minutes after immersion and when the core temperature decreased to 33°C. It was determined that there was no immediate affect on manual dexterity after immersion, although performance on all tests was affected significantly as the core temperature decreased by 0.5°C. This decrease in dexterity continued with decreases in core temperature, although the decrease in dexterity was slower after the first 0.5°C decrease. The flexion and extension of the fingers was affected more than handgrip strength or performance of the peg and ring test.

This may be because the flexion and extension test is more reliant on the quick movement of cold joints than the other two, as the strength test only required static muscle contraction and the peg and ring test required less speed in the movements and a smaller range of movement.

Hammarskjöld *et al.* (1992) investigated the effect of cold on manual performance. To do this, ten carpenters were asked to perform three tasks before and after cold exposure. Subjects were exposed to an ambient air temperature of 15°C and the dominant hand of the subject was cooled using a fan (3m.s<sup>-1</sup>) and a cold water spray for 60 minutes. The three tasks were:

- Nailing
- Sawing
- Screwing

The subject's tools were kept at 0°C to prevent rewarming of the subject's hand and after each task a cryo pack was placed in the subject's hand and a wet towel was wrapped around it for two minutes. The number of movements and time taken to complete each task was recorded. The quality of the subject's work was also assessed. It was determined that the performance of the tasks was significantly slower in the cold condition than prior to cold exposure although the quality of the work was not affected. All of the above mentioned tasks would require strength of the forearm and hand.

#### **4.2.4 Strength**

The following studies will consider the strength aspect of manual dexterity. Clarke *et al.* (1958) investigated whether there is an improvement in muscular performance in water temperatures above 34°C and if so, if improvements in muscular performance were further increased in water below 18°C. Four males placed their forearm in stirred water at 2°C, 10°C, 14°C, 18°C, 26°C, 34°C and 42°C. A handgrip dynamometer was used to assess strength and duration of muscular contraction. It was determined that the optimal water temperature for maintaining sustained muscle contractions is a water temperature of 18°C which corresponds to a muscle temperature of 25 - 29°C. Temperatures below this level decrease the duration of sustained contractions. It was also found that the maximal

tension that could be exerted after an immersion period of 30 minutes decreases sharply with decreasing temperature.

Tochihara *et al.* (1990) investigated the changes in physiological reactions and manual performance in actual working environments in cold stores. Two groups of subjects were used. Group R contained 10 subjects who were exposed to temperatures between -20 and -23.2°C daily. Group C had 8 subjects whom were exposed to temperatures between 12 and 15.2°C. All the subjects were forklift truck drivers by occupation. The following tests were performed before work, at 10am, before lunch, at 3pm and after work.

- Hand tremor
- Handgrip strength
- Pinch strength
- Counting task
- Flicker value
- Blood pressure

It was found that there were no significant differences between the two groups in terms of handgrip strength, pinch strength, counting task, flicker value and peak flow rate.

However changes in hand tremor and diastolic blood pressure were greater for group R than for group C. It was thought that these differences were partly attributable to the heavier workload of group R caused by the extreme cold and large temperature gradient between the inside and outside of the cold stores.

#### **4.2.5 Tactile Sensitivity**

The following papers will deal with tactile sensitivity, another aspect of manual dexterity. Kok *et al.* (1984) investigated the relationship between finger sensitivity and finger skin temperature in cold conditions. A further aim of this study was to determine whether there are any differences in tactile sensitivity as a result of sex or ethnic characteristics.

To complete this study, a modified version of the Macworth V test was used. To perform this test, a subject's hand is placed on a plastic block which is either flat or has a recessed gap with well defined edges either 1, 2, 3 or 4 mm apart. The blocks were not visible to the subject and the subject is asked to say whether or not he/she can detect a gap. Subjects were exposed to air temperatures of 6, 12, 18 or 24°C with an air velocity of 0.1m.s<sup>-1</sup>. All

subjects wore standardised clothing and were trained on the dexterity test during the first hour of testing. It was determined that male factory workers regardless of race are unlikely to show more than an 8% decrease in tactile discrimination when finger skin temperatures are above 15-16°C. However, female worker's tactile discrimination will decrease by at least 10% when their finger skin temperature reaches 18-19°C. It was also found that white subjects had significantly higher finger skin temperatures than black subjects below air temperatures of 24°C, although above finger skin temperatures of 15-16°C the black males maintained performance equal to that of the white groups despite the lower finger temperatures. Above finger skin temperatures of 21°C, the ability of the black group of subjects to detect a gap was equal to or better than that of the white group.

Mackworth (1952) tried to determine an easy to administer method for assessing numbness in the field and to also determine whether a biological index of numbness could assess the effects of two environmental factors that contribute to wind-chill; air temperature and wind speed. To do this, 35 male subjects were exposed to temperatures between -32°C to -34°C and -35°C to -37°C. Subjects sat indoors for about an hour prior to exposure and wore a thick woollen glove with the index finger removed. Subjects stood in a 'wind tunnel' and were exposed to five different air speeds 0 to 2 mph, 2.1 to 4 mphs, 4.1 to 6mph, 6.1 to 8 mphs and 8.1 to 10 mphs. After this exposure, subjects were asked to perform the Mackworth V test where subjects were asked to indicate whether they could detect one or two gaps whilst their finger was pressed against the tester. It was found that all wind speeds produced a numbing effect although faster wind speeds caused greater numbness than the slower wind speed. It was also found that the higher wind speeds caused a more lasting effect than the slower wind speeds. With regards to temperature, it was found that numbness resulted at both air temperatures and that the colder air produced more numbness than the relatively warmer air. It was concluded, that increasing wind speed from still air had an effect equivalent to decreasing the air temperature by 5°C. The three point aesthesiometer is a variation on this method.

In a continuation of Macworth's work, Mills (1956) conducted a similar experiment to the one detailed above but looked at longer durations of exposure. Again, the Macworth V test was used to determine the level of numbness resulting from cold exposure. Twenty-five subjects were exposed to six different air temperatures (4, 8, 12, 14, -18 and -23°C). The subjects all wore standard arctic clothing but prior to the test removed their gloves. It

was discovered that the log of the gap distance that could be detected was inversely proportional to the skin temperature of the subject (between 0 and 33°C). It was also found that after 15 minutes exposure to -18 or -23°C air, the finger spontaneously rewarmed and that tactile sensitivity recovered with the increase in skin temperature. It was also noted, that if this spontaneous rewarming did not occur, then frostbite usually resulted.

Provins and Morton (1959) investigated the amount of numbness experienced at different temperatures and also assessed the tactile sensitivity of the finger after it reached equilibrium with the water temperature. To do this 10 subjects immersed their index finger in water (0.75°C) for forty minutes. Tactile discrimination was then measured using a Mackworth V test (with the rulers made of transparent plastic instead of wood) during cooling and rewarming of the hand. It was determined that there was a significant decrease in tactile discrimination below finger skin temperatures of 8°C. Tactile discrimination was then tested on five subjects who immersed their index temperature in water at six different temperatures (2, 4, 6, 8, 15 and 30°C) for twenty minutes. After the first five minutes, the blood supply to the finger was cut off. It was found that there was little decrease in tactile discrimination after a 15 to 20 minute exposure in water temperatures of 6°C or higher, however at 4°C there was some impairment and at 2°C all subjects experienced complete numbness at the test site.

Provins and Morton (1958) also conducted an experiment to investigate whether the local exposure of hands resulted in results similar to Macworth's when only the hands were exposed to the cold environment rather than the whole body. A further aim was to determine to what extent the relative performance of two tasks varied before and after exposure to cold under different conditions. To do this, 20 subjects exposed their index finger to air at -22°C with a wind speed of  $0.02\text{ms}^{-1}$  until the subject's skin temperature reached -5°C. A pressure discrimination test and the Macworth V test were then administered in separate sessions. The pressure discrimination test involved the subject deflecting a metal piece of apparatus by 25mm. The subject was told whether they had correctly managed this or not, and then had to repeat the test again with the correction given to them in mind. It was determined that the subject's manual dexterity decreased significantly although the subject's body remained warm. It also determined that the reproduction of finger pressure is dependant upon cutaneous information and that once

this is reduced by numbness, the subjects were significantly less accurate even when told the extent of their error than before cold exposure. The experiment also determined that while the Mackworth V test was a good test of reduced tactile performance after cold exposure, the test gave no indication, when performed at normal skin temperatures, of the relative effect that cold exposure would have on the subject's performance.

#### 4.2.6 Speed

The following experiment will detail manual dexterity tests used to assess the speed aspect of manual dexterity. LeBlanc (1955) aimed to determine whether the arm, hand, fingers or a combination of all three had the largest effect on manual dexterity when cooled. To do this, 8 subjects were instructed to place their arm (with the hand excluded), their hand or their finger in ice cold water. Subjects were later asked to place their arm in ice cold water whilst their hand was kept in water of 33°C. Two finger dexterity tests were then carried out at one minute intervals:

- Plate tapping
- Moving the index finger from one point to another around a baffle

When the hand was cooled, it was found that the performance in the second manual dexterity test was comparable to results obtained for the finger only cooling. However when the plate-tapping test was performed, no reduction in performance was observed when the finger only was cooled. It was determined through these experiments, that finger dexterity decreased when the arm was cooled and the hand was not. This would indicate that increased viscosity of synovial fluid is not the only influencing factor on manual dexterity and that the small muscles of the hand may play an important role when considering manual dexterity losses due to cold exposure.

Gaydos and Dusek (1958) considered fine finger dexterity when assessing the effects of localised hand cooling versus total body cooling on manual dexterity. Subject's were either exposed to air (7.2°C air speed 8Km<sup>-1</sup>) with their hands in a warming box kept between 32.2 and 37.8°C. Subjects were asked to complete two manual dexterity test:

- Block stringing
- Knot tying

The subjects completed the tasks a) upon entry to the chamber, b) when fingertip temperature had dropped to between 15 and 18.3°C and c) when the fingertip temperature had dropped between 10 and 12.8°C. It was determined that if the hand was not cooled, then lowering the mean body temperature had no effect on performance of the dexterity tests. However, when the hands were cooled by exposing them to the same ambient conditions as the rest of the body, performance reductions were dependant upon the degree of hand cooling that had taken place. Manual dexterity decreased as finger skin temperature dropped from 23.9° to 15.6°C although these decreases were not significant until the finger skin temperatures were between 10°C and 12.8°C.

#### **4.2.7 Test Selection**

Based on the above information, four tests were chosen to represent four different aspects of manual dexterity likely to be affected by contact cooling. The test chosen were done so on the basis of whether they were likely to test areas of manual dexterity likely to be affected by contact cooling (for this reason test relying on central effects or gross hand and arm movements were discounted). The test chosen also had to be well documented as being used in the past and also have shown an effect of loss of dexterity through cold exposure. The tests selected also had to represent different aspects of manual dexterity, so it was possible to establish exactly which aspects are affected as a result of contact cooling.

The four tests selected were:

- 1) A strength test measured by a grip dynamometer,
- 2) A speed test measured in time taken to open and close the hand
- 3) A nut and bolt test to measure fine finger accuracy
- 4) A three point aesthesiometer to measure tactile sensitivity

All four tests have been validated by previous work and are established in literature. The tests chosen were also considered to be reliable, in that they measured what they were designed to. It was felt that strength would be affected due to the number of small muscles in the hand and arm that are utilised in a test of hand/arm strength. The thickening of synovial fluid surrounding the joints should also affect performance in this task. The screw test should also indicate thickening of synovial fluid and reflect dexterity

losses as a result of the numbness. The three point aesthesiometer will indicate any losses in tactile sensitivity as a result of contact cooling. The speed test will give an indication of detrimental effects to the hand muscles and forearm flexors and extensors and as such is a fine motor test. Thickening of synovial fluid will also be a major contributory factor for this test. The table below taken from Havenith and Heus (1995) shows at what temperature structures are likely to be affected.

*Table 4.1. Critical Temperatures (°C) for Different Physiological Structures at which Manual Dexterity Becomes Substantially Reduced (Havenith and Heus 1995)*

Receptors	10
Nerves	20
Joints	24
Muscles (task dependant)	28-38
Skin	15
Core	?

As can be seen, tactile sensitivity would be expected to be affected at temperatures of around 15°C. As this is a relatively high temperature it could be expected that both cooling conditions would result in skin temperatures at this level. It is expected to be particularly appropriate to the fast cooling condition where other manual dexterity tests may not be as the skin would be affected by the superficial cooling occurring as a result of rapid cooling where deeper structures (muscles may not). The strength test is expected to be especially appropriate to the slow cooling condition, as deeper cooling will occur as a result of the increased duration of exposure to ambient conditions of -20°C, combined with cooling occurring as a result of contact with the nylon bar. A muscle temperature of 28-38°C could reasonably be expected to be achieved at this temperature. Again, joints and receptors are affected at relatively high temperatures 24°C and 10°C respectively. These structures will come into play in the speed test. These temperatures could be expected to be achieved in both conditions, but as the joints are located at a deeper level than the skin it is probable that any effects will be seen more prominently in the slow cooling condition. The nut and bolt test should highlight differences in both conditions, as numbness experienced as a result of low skin temperatures will make the nuts difficult to initially pick up in the fast cooling condition. Whilst skin numbness will also be a factor in the slow cooling condition, it is also thought, that thickening of synovial fluid will

make it more difficult to screw the nuts onto the bolts and that this will again cause a greater effect in the slow cooling condition.

#### **4.2.8 Cooling Patterns**

Clark and Cohen (1960) investigated manual dexterity as a function of rate of change in hand skin temperature. Twenty male subjects were exposed to an ambient condition of 23°C 50% relative humidity. The subject's hands were enclosed in a separate chamber where the rate of cooling was independently controlled. For a fast rate of cooling an air temperature of -17°C was used inside the hand chamber, and for a slower rate of hand cooling a temperature of -7.7°C was used. A modified knot-tying test was used to monitor dexterity (the modification meant that several knots were tied in one piece of string instead of one knot being tied in several pieces of string). The dexterity test was performed a) when the subjects placed their hands into the hand chamber b) when mean hand skin temperature reached 12.8°C, c) when mean hand skin temperature reached 7.2°C, d) upon entrance of the hands into the rewarming chamber e) when the skin had rewarmed to 12.8°C and f) when the hand skin temperature had returned to normal.

It was found that rate of cooling significantly affected manual dexterity performance, and that the rate of rewarming varied according to the cooling speed but this was only significant at the later stages of rewarming. It was also found that manual dexterity performance increased as the subject's hand skin temperature increased. When the subject's hands were cooled slowly and then rewarmed slowly the performance decrease was still apparent even after the hand skin temperature had returned to normal, however when subjects were cooled rapidly and rewarmed rapidly the performance of the subjects increased to a level superior to that prior to cooling. It was therefore concluded that rate of cooling is also important to consider in addition to skin temperature when considering manual performance losses.

Chapter 3 demonstrated that contact cooling was dependent upon time and duration of exposure. It was determined, that there are two types of cooling that result from contact with materials of either high or low contact coefficients. Contact with materials with low contact coefficients, for example nylon, results in a slow deep cooling, whereas contact with a material of a high contact coefficient (e.g. aluminium) results in a faster more superficial cooling. It would be therefore reasonable to assume that different aspects of

manual dexterity may be affected differently by these two types of cooling. To investigate this possibility further, all four selected tests were completed by subjects in both a fast cooling (high contact coefficient) and a slow cooling (low contact coefficient) condition.

### **4.3 Aims**

The aims of this study are to determine which aspects of manual dexterity are most affected by contact cooling by using the four selected tests. A secondary aim is to determine whether the aspects of manual dexterity affected as a result of fast cooling (as a result of contact with a material at a relatively high temperature  $>-3^{\circ}\text{C}$  but with a high contact coefficient) are similar or different to those affected as a result of slow cooling (occurring as a result of contact with a material with a low contact coefficient at a relatively low temperature  $>-20^{\circ}\text{C}$ ).

#### **4.3.1 Pilot Studies**

During pilot studies problems with the tactile test were assessed. For the tactile test participants consistently reported that they perceived the one point (used as a control) to be sharper than the two points that are used in graduating steps. This perception resulted in the subjects being able to determine with ease whether one point or two was being applied to the skin. To compensate for this, only the two points of the aesthesiometer were used, with the second point being moved out of the way when the control was required. The full protocol and picture is described/shown later in this chapter.

The material and duration that the bar was gripped for, were based on several pilot studies and from the results from chapter 3, which indicated that participants could be exposed to the material for the periods of time selected below without withdrawing through intolerable pain. The pilot studies also indicated differences in performance pre and post exposure. It was important to ensure that the conditions were not so extreme as to induce withdrawal through pain, as in order to compare the manual dexterity results effectively, all participants needed to be exposed to the bars for the same period of time before completing the tests. In the experiment discussed in chapter 3 this was not the case and lead to problems with in the interpretation.

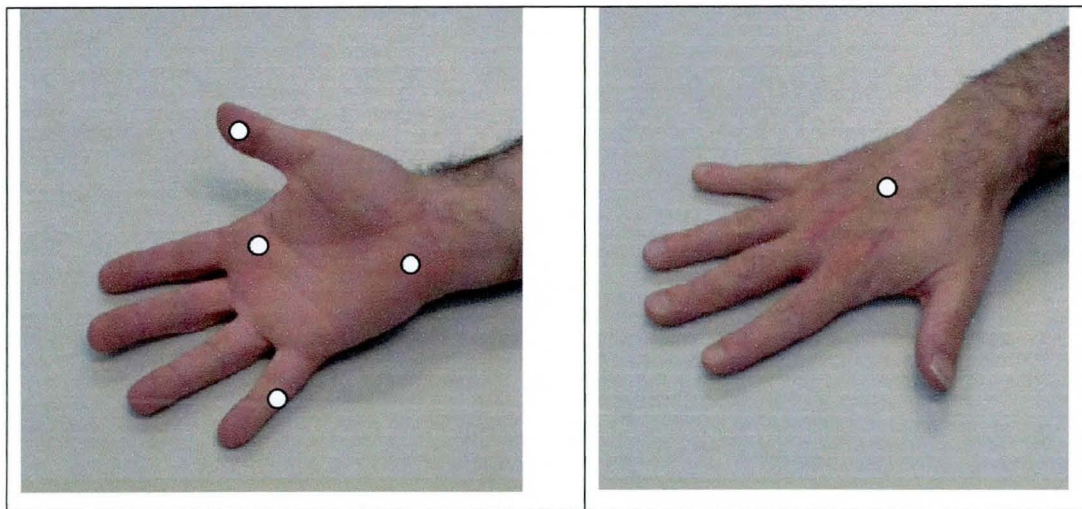
## 4.4 Methods

### 4.4.1 Procedure

Upon arrival at the laboratory, participants completed an informed consent form. Participants were then instrumented and performed one of the four manual dexterity tests. The order of exposure of the dexterity test for participants was randomised using a 10 by 4 incomplete Latin Square design. The participant then placed his or her dominant hand into the freezer and gripped the bar. After the set duration of either five or ten minutes, the participants remove their hand from the freezer and performed the manual dexterity test again.

### 4.4.2 Contact Cooling

Participants were asked to grip a bar 400mm in length and 40 mm in diameter. Each bar was counterweighted from the outside (see chapter 2) so that each bar weighed the equivalent of 500g. Thermocouples were used to measure skin temperature and were placed at several locations on the participant's hand. (See Figure 4.1)



*Figure 4.1. Shows the placement of thermocouples on the participant's hand*

The following conditions were used in order to induce the two types of cooling (see Table 4.2)

Table 4.2 shows the Experimental Conditions

	Material	Temperature	Duration of Grip
Slow Cooling	Nylon	-20°C	10 minutes
Fast Cooling	Aluminium	-3°C	5 minutes

#### 4.4.3 Participants

Five male and five female participants took part in this repeated measures within subject study. Table 4.3 shows the participants characteristics

Table 4.3. Participant Characteristics with mean and standard deviation (SD)

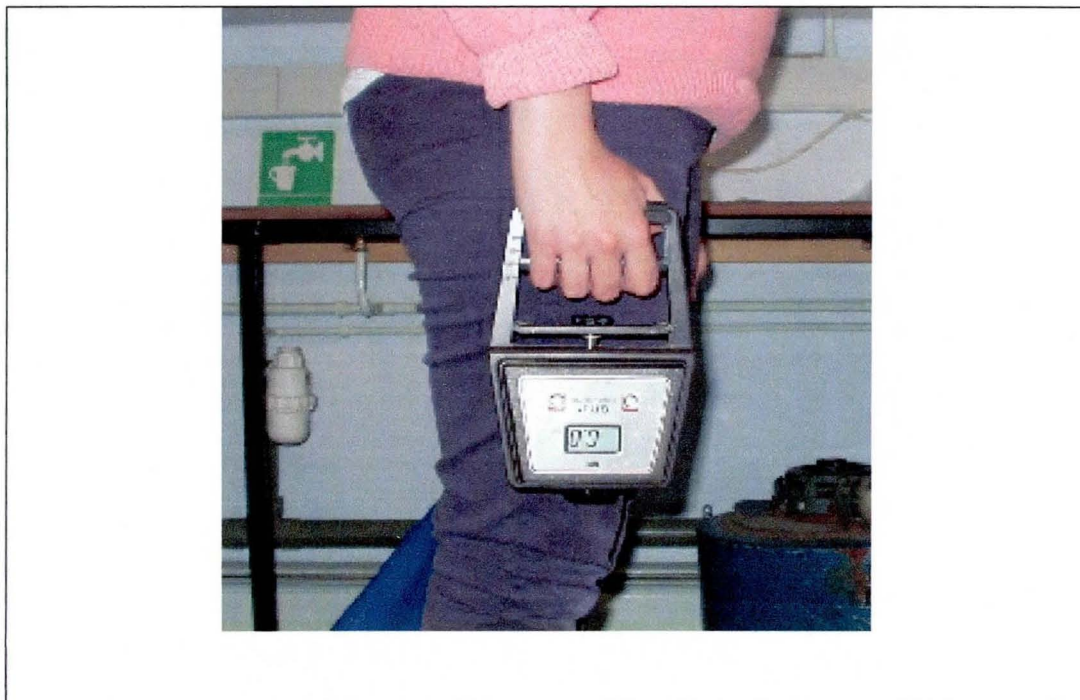
Subject	Sex	Age	Height	Weight	Volume of Hand	Palm Length	Palm Width	Third Phalanx Length	Third Phalanx Width
1	M	27	183	88.7	331	10.1	8.4	7.6	2
2	F	31	171	77.5	312	10.7	8.3	8.2	1.9
3	F	22	170	73	276	10.1	7.9	7.5	1.8
4	F	21	169	65	301	9.7	7.6	7.6	1.8
5	F	21	162	60.5	290	9.2	8	6.7	1.7
6	M	25	185	80.4	394	11	8.7	8.7	2
7	F	23	169	58.3	297	11	8	7.9	1.8
8	M	22	188	84.7	392	11	8.7	8.8	1.9
9	M	25	179.5	74.8	315	10.8	8.2	8.3	1.8
10	M	23	180	80.3	389	10.9	8.8	8.5	2
Mean	-	24	175.7	74.3	329.7	10.5	8.26	7.98	1.87
SD	-	3.1	8.5	10.2	45.2	0.64	0.39	0.65	0.11

#### 4.4.4 Manual Dexterity Tests - Training

Prior to the experiment, all participants visited the lab and completed all manual dexterity tests until a plateau of performance had been established. This was to avoid any learning effects in the actual data.

#### 4.4.5 Grip Strength

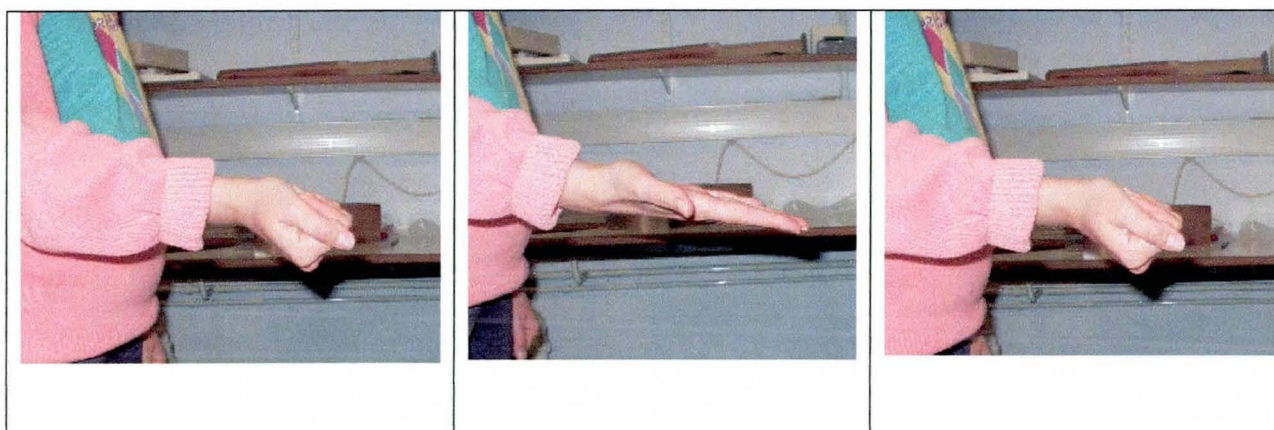
Participants were asked to hold the dynamometer as shown in the picture below (Figure 4.2). The participants then squeezed the handle of the dynamometer as hard as they could. The reading was taken in kilogramforce, and the test was repeated a total of three times.



*Figure 4.2 shows the correct position for gripping the dynamometer*

#### 4.4.6 Speed Test

Participants were asked to assume the starting position, which palms closed, then as quickly as possible open their hand and close it again as shown in Figure 4.3. This was done three times. The time taken to do this was recorded and the test scores in seconds.



*Starting Position*

*First Position*

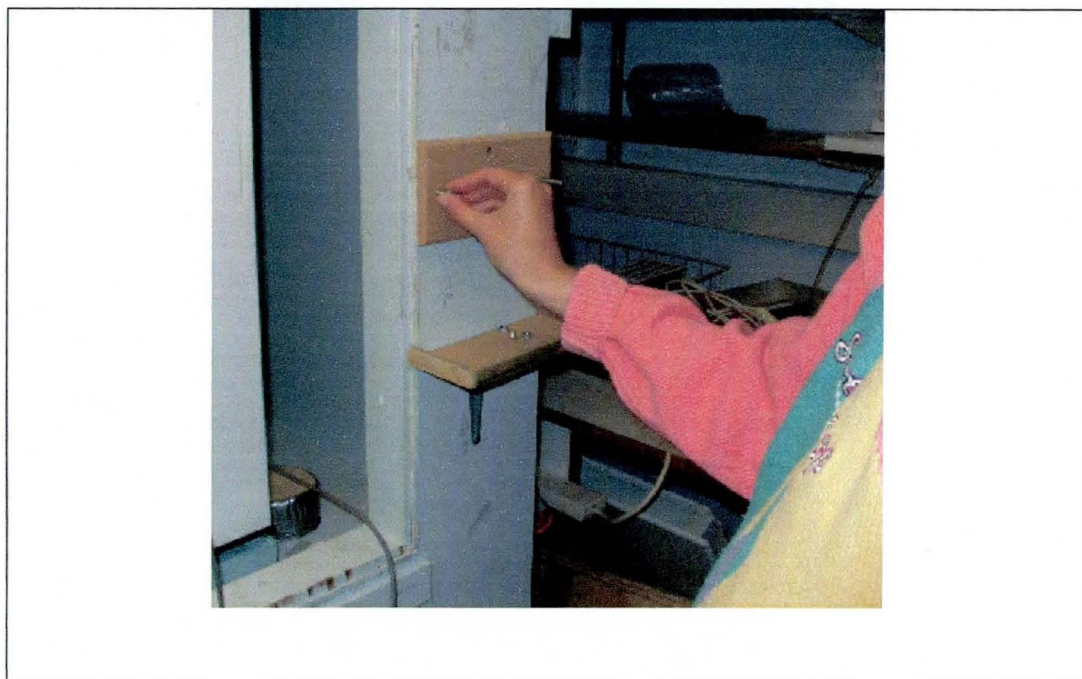
*End position*



*Figure 4.3. Shows the range of movement the participants were asked to complete in order to complete 3 repetition of the exercise*

#### 4.4.7 Nut and Bolt test

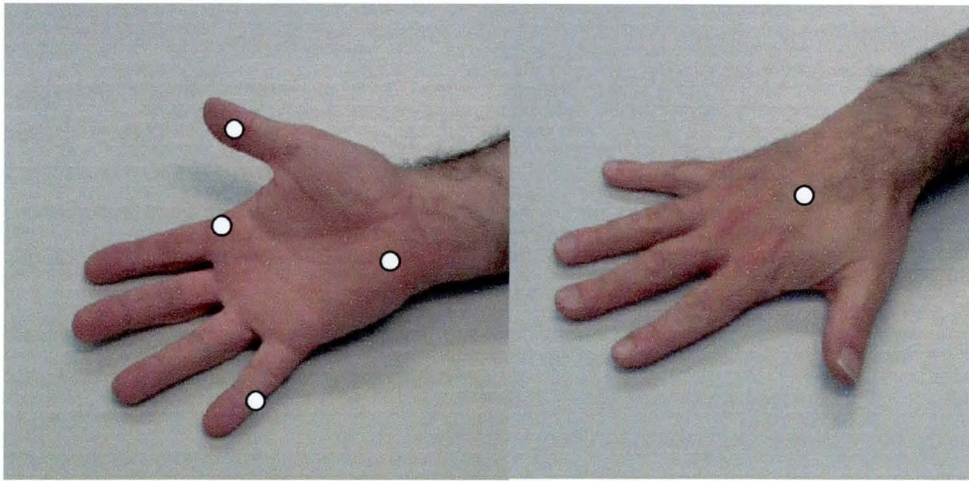
Participants were asked to screw four nuts, which were gathered from a tray underneath the test, onto four bolts until the nut wouldn't turn any further, (see Figure 4.4). The time taken to do this was recorded. The number of nuts dropped was also noted. The test is scored in seconds to complete the test.



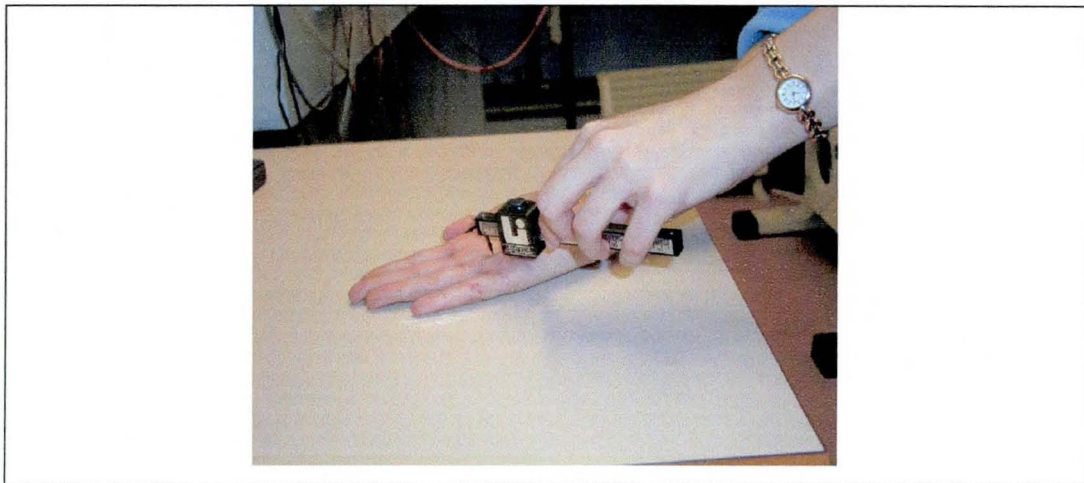
*Figure 4.4. Shows a participant completing the nut and bolt test*

#### 4.4.8 Tactile Discrimination Test

The two points of the aesthesiometer were placed together and touched to one of the four selected sites on the subject's hand. The distance between the two points was then increased by 1 mm at a time, each time the distance was increased, the subjects were asked whether they could detect one point or two. The two-point pressure was interspersed at suitable intervals with a single point pressure. When the participant could distinguish 2 points of pressure, one point was then used again as a control. If the participant correctly determined one point, the distance between the two points was decreased until the participant was unable to distinguish two points again. The smallest distance between the two points where the participant could detect the presence of two points was the final measurement. Participants were asked to report verbally to the experimenter whether they could detect 'one point or two' making contact with their hand. This test was administered at four sites on the hand (see Figure 4.5). The test is scored in mm. Figure 4.6. Shows the tactile discrimination test.



*Figure 4.5. Sites where the tactile discrimination task was administered.*



*Figure 4.6. Tactile Discrimination Test*

#### **4.4.9 Withdrawal Criteria**

Participants were asked to withdraw their hand from the freezer immediately, if any of the five thermocouples registered a temperature of  $0.5^{\circ}\text{C}$ , if the participant experienced the sensation of frost nip which was described to them in a pre visit, or if the participant experienced intolerable pain.

Statistical analysis was done in SYSTAT 9.

## 4.5 Results

### 4.5.1 Analysis

For all tests (except the nut and bolt test which was only completed once due to the amount of time required to complete it and the subsequent effects on rewarming of the hand) three measurements were recorded for each participant both before and after exposure. The results from the manual dexterity test prior to exposure to the bar were then compared to the results of the manual dexterity tests after exposure to the bar. A t-test was carried out on the mean from the three trials.

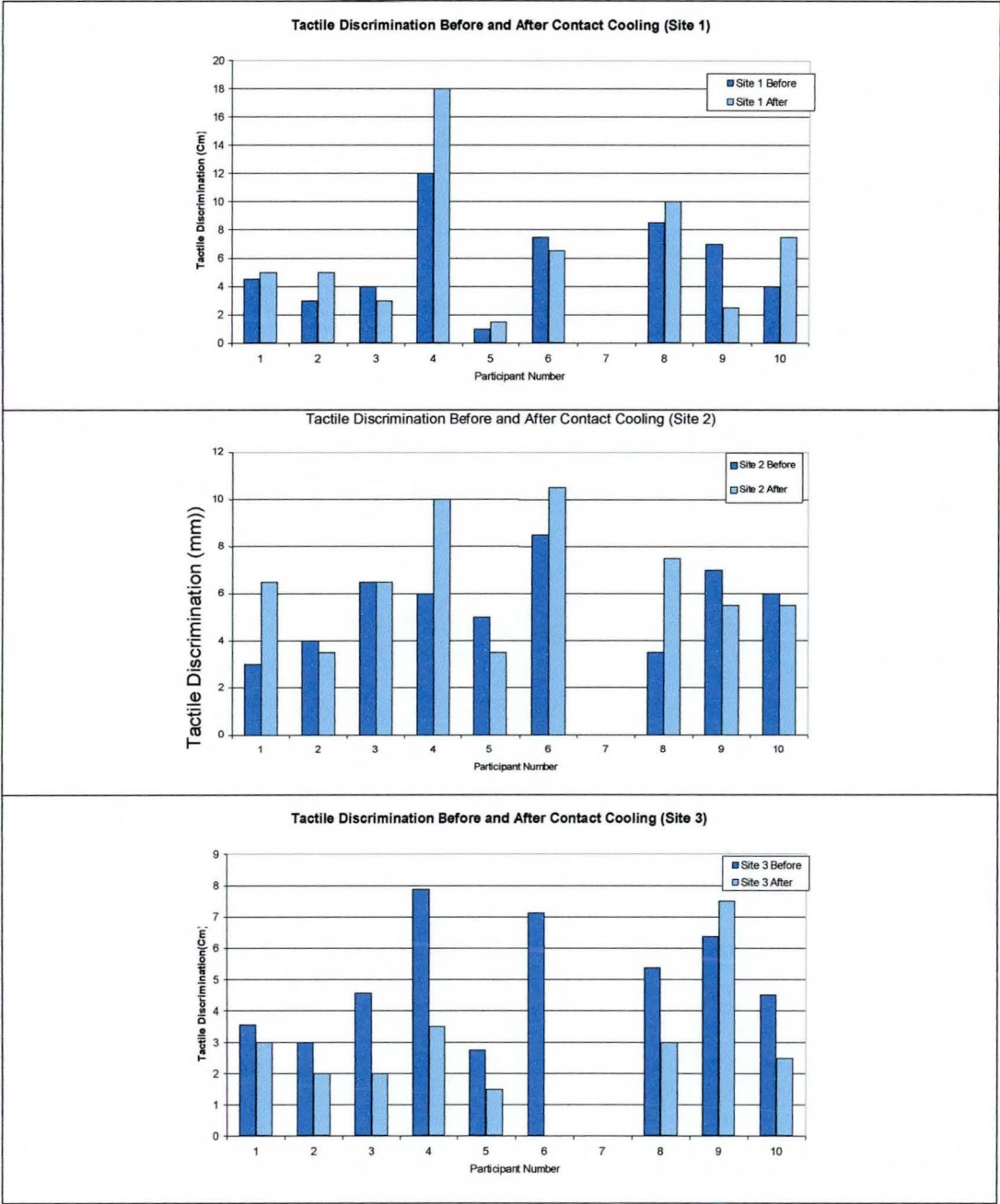
### 4.5.2 Slow Contact Cooling

Table 4.4 below, shows the mean score before and after exposure to the bar, and the significance values of all the participants.

*Table 4.4. Shows mean scores and significance values for the mean of all subjects for the long term cooling experiment.*

Manual Dexterity Test	Average of All Scores Prior to Exposure	Average of All Scores After Exposure	Mean Percentage Change (%)	P value for t-test
Speed (s)	1.3±0.06	1.6±0.1	23	0.000
Strength (Kg)	37.3±1.3	33.9±1.1	9.1	0.003
Nut and Bolt test (s)	84.5±11.2	103.5±20.2	22.5	0.016
Tactile (site 1) (mm)	5.7±2.8	6.6±1.4	15.8	0.342
Tactile (site 2) (mm)	5.5±1.5	6.6±1	20	0.174
Tactile (site 3) (mm)	3.2±0.4	3±1.2	6.3	0.318
Tactile (site 4) (mm)	8.4±3	9.6±3.7	14.3	0.247

The time to complete the speed test became significantly longer ( $p \leq 0.01$ ) after exposure to the bar and strength decreased significantly after exposure to the bar ( $p \leq 0.01$ ). The nut and bolt test was performed significantly slower post exposure than pre exposure ( $p \leq 0.05$ ). There was no significant difference pre or post exposure for the tactile discrimination test at any site



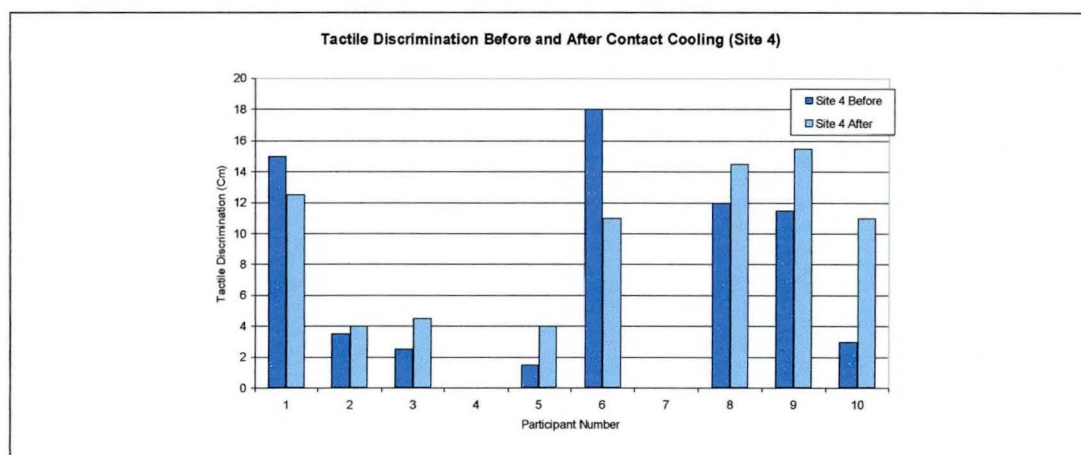


Figure 4.6 shows the individual performance of subjects at each site for the tactile discrimination test.

As can be seen from Figure 4.6 subject seven did not complete this test (subject withdrawal) and subject 4 didn't complete the tactile discrimination test at site 4. Subject 4 was unable to determine either pre or post exposure the correct number of contact points at site 4. At site 1, the distance of the two points before the subject was able to distinguish the correct number was larger for five of the subjects, but decreased for three of the participants. At site two the distance increased for 4 participants decreased for four participants and remained equal for one. At site three, seven subjects decreased the distance required to distinguish two points after exposure, one increased, and one was unable to successfully determine the number of points after exposure. At site 4, the distance decreased for two subjects post exposure but increased for six. As two subjects were missing from this experiment, the degrees of freedom were decreased proportionally, possibly indicating that significance may have been found if the full contingent of subjects had completed the test at this site. Over all the tactile discrimination test was ruled unsuccessful at quantifying manual dexterity deficits as a result of contact with materials with low contact coefficients.

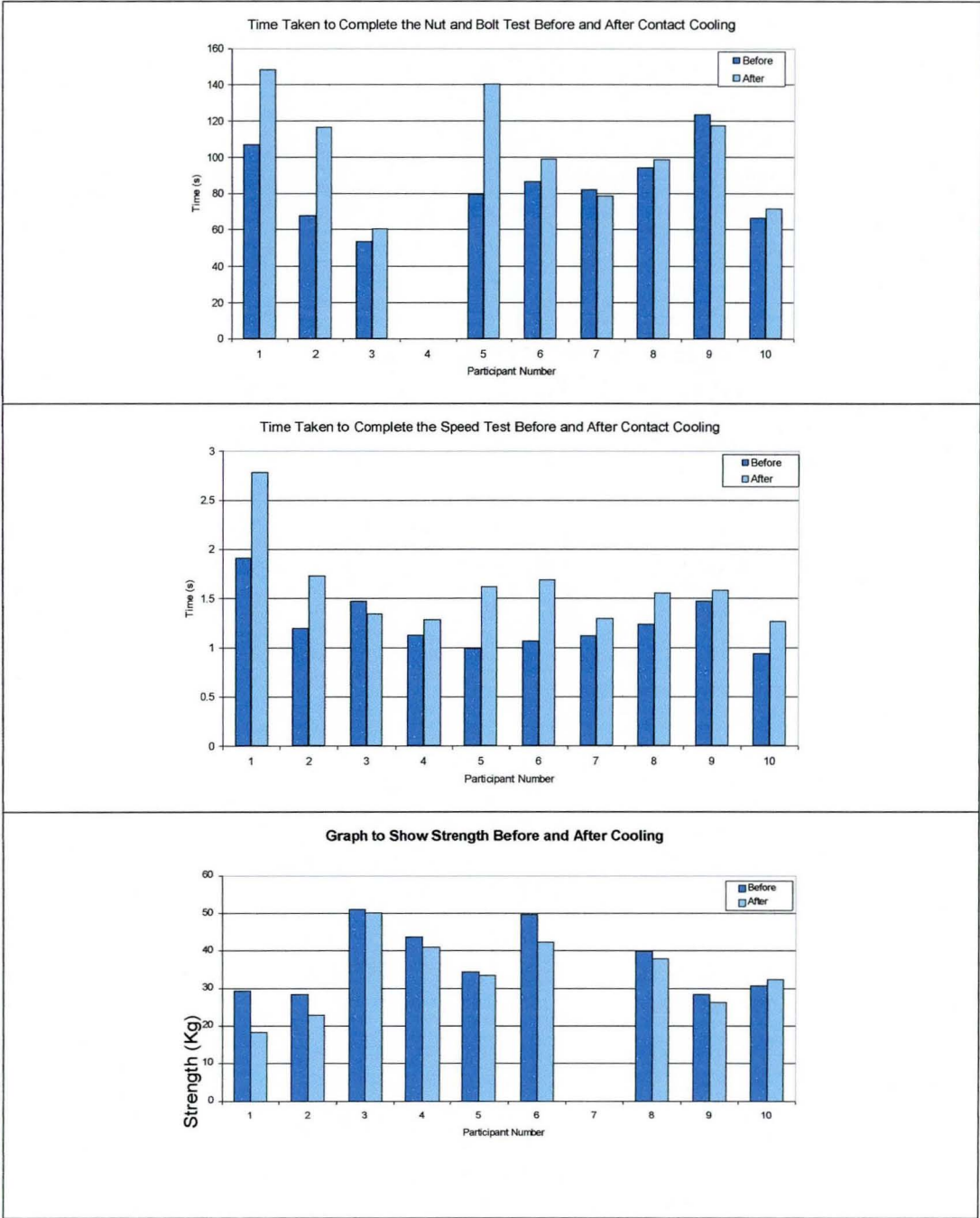


Figure 4.7. Shows the mean performance for subject's pre and post exposure for the Strength and Speed test and the actual scores (both hands combined) for the Nut and Bolt test.

As can be seen from Figure 4.7 one subject was missing from this condition (subject withdrawal). Seven of the participant's time to complete the nut and bolt test increased after exposure to the bar and two of the subjects decreased slightly.

Figure. 7 also shows that the time taken to complete the speed test significantly increased for nine of the subjects but decreased for one. The overall result was highly significant.

Strength decreased significantly in eight of the nine subjects that completed this test, with the increase in strength of subject ten being very slight. These results were found to be significant at a very high level.

### 4.5.3 Fast Contact Cooling

Table 4.5. below, shows the mean score before and after exposure to the bar, and the significance values of all the participants.

*Table 4.5. show the mean before and after scores with significance values across all subjects for fast cooling*

Manual Dexterity Test	Average of All Scores Prior to Exposure	Average of All Scores After Exposure	Mean Percentage Change (%)	P value for t-test
Speed (s)	1±0.1	1.1±0.1	10	0.000
Strength (Kg)	42±1.3	41.2±1.8	1.9	0.044
Nut and Bolt test (s)	84.9±12.9	88.5±8.9	5.3	0.735
Tactile (site 1) (mm)	6.3±2.3	8.4±1.5	33	0.045
Tactile (site 2) (mm)	7.2±0.9	7±2.02	0	0.888
Tactile (site 3) (mm)	4.5±2.2	5.1±0.9	13.3	0.376
Tactile (site 4) (mm)	13.2±4.5	14.6±5.0	10.6	0.569

As can be seen from Table 4.4 there was no significant difference in performance of the nut and bolt test pre and post exposure ( $p = 0.745$ ). Performance of the speed test decreased significantly after exposure to the bar ( $p \leq 0.01$ ). Strength decreased significantly after exposure to the bar ( $p \leq 0.05$ ). There was no significant difference in tactile discrimination at sites two, three or four, however the distance required to successfully detect two points in contact with the hands was significantly increased at site 1 ( $p \leq 0.05$ ).

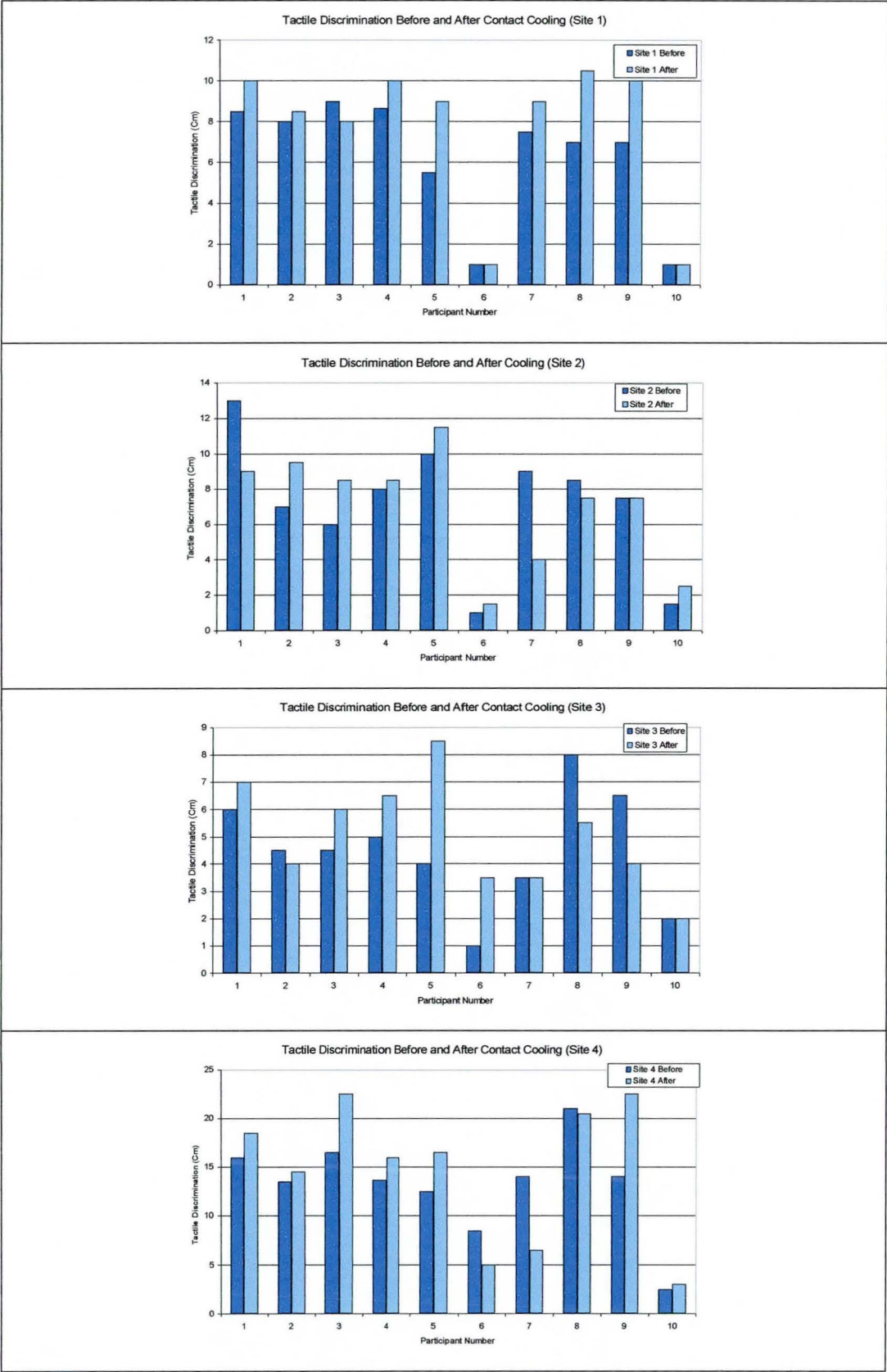


Figure 4.8. Shows the individual performance of subjects at each site for the tactile discrimination test.

Figure 4.8 shows that the distance taken for seven of the subjects to detect the presence of two points was larger post contact than pre contact. Two subjects could detect the two points post contact at the same distance as pre contact, and one subject decreased post contact. At site two the distance required increased for six of the subjects, decreased for three of the subjects and remained constant for one. At site 3, five subjects increased in distance before perception of the two points, three decreased and two remained constant. At site 4, seven subjects increased whilst three decreased.

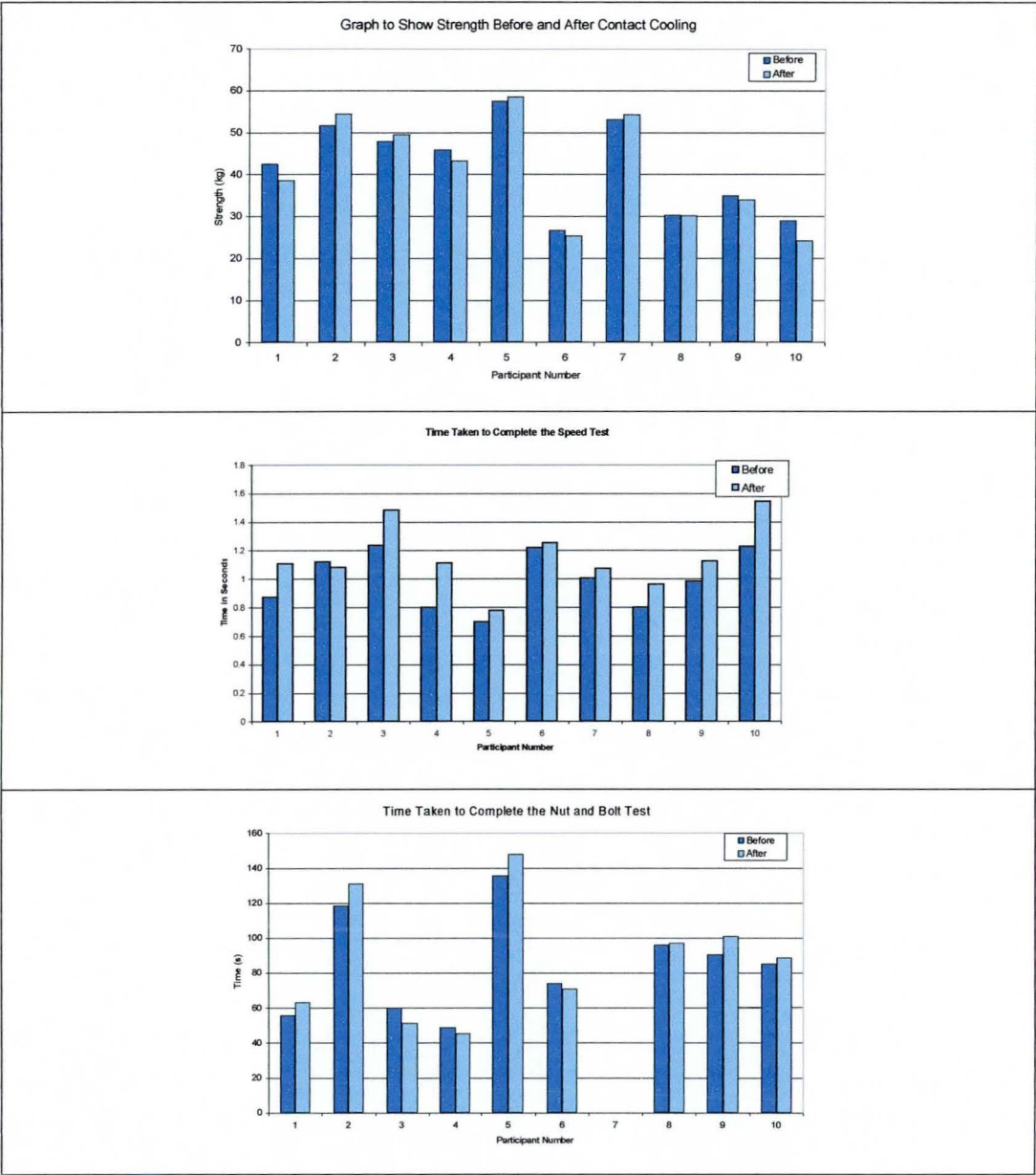


Figure 4.9. Shows the mean performance for subject's pre and post exposure for the Strength and Speed test and the actual scores (both hands combined) for the nut and bolt test.

For the nut and bolt test, six subjects took longer to complete the test post exposure and 3 subjects completed the test more quickly. Due to the lack of significance found for this test it was determined to be unsuitable for demonstrating manual dexterity deficits as a result of cooling cause by contact with a material of high contact coefficient.

Nine of the ten subject's performance became significantly worse post exposure on the speed test.

Strength also significantly decreased post exposure, with six subjects finding their strength decreased after contact with the bar and four subjects finding their strength increased.

## **4.6 Discussion**

### **4.6.1 Speed of Cooling**

Kiess and Lockhart (1970) found that a slow rate of cooling impairs certain types of manual dexterity more than a fast rate, but that this phenomenon only occurred at low mean weighted skin temperatures. Clark and Cohen (1960) also found that the rate of cooling significantly affected manual dexterity performance (slow cooling resulted in a greater loss of dexterity) and that the rate of rewarming varied according to the cooling speed but this was only significant at the later stages of rewarming. They also determined that manual dexterity performance increased as the subject's hand skin temperature increased. It was therefore concluded that rate of cooling is also important to consider in addition to skin temperature when considering manual performance losses. For single digit contact cooling Jay and Havenith (2000) observed a higher pain sensation at the same skin temperature for slow versus fast cooling, suggesting a deeper cooling at equal skin temperatures in slow cooling. These results would suggest that in the full hand contact used in the present experiment similar observations should be made. In this experiment however, no real differences were found between conditions in the strength and speed tests as both were significantly impaired in both conditions. However, there was a difference in performance decrements as in both cases manual dexterity was affected more severely in the slow cooling than fast cooling condition (see tables 3 and 4). The nut and bolt test however was only significantly affected with performance being significantly worse after contact cooling in the slow cooling condition ( $p > 0.05$ ). The main

difference between cooling types for tactile performance was that performance in the fast contact cooling condition was significantly decreased ( $p \leq 0.05$ ) at site 1 but was not in the long term experiment. All other sites were unaffected as a result of contact cooling. Both Kiess and Lockhart and Clark and Cohen investigated manual dexterity after uniform cooling. This was either done in air or water. Contact cooling results in a different cooling pattern, with cooling being localised and not uniform. In the present experiment contact cooling in both conditions results in a quick rate of cooling relative to cooling by air or water in either of the other two experiments, either as a result of a high contact coefficient of the two materials or as a result of the initial starting temperature of the low coefficient material. So what is termed a quick and slow rate of cooling for the experiments involving water and air may not be comparable to quick and slow rates of cooling as experienced as a result of contact cooling.

As all participants were gripping bars to induce contact cooling, the contact cooling occurred on the palmar aspect of the hand only. The palmar aspect of the hand has more pulp than the back of the hand so many of the structures that affect manual dexterity will be located closer to the surface of the dorsal aspect of the hand than the palmar aspect. This will again have some bearing on the results when compared to the results from previous experiments which induced cooling by air or water, as these experiments would have cooled both aspects of the hand simultaneously.

#### **4.6.2 Speed Test**

Speed was the most affected of all the manual dexterity components in the tests. The use of the speed test would be most in both fast and slow contact cooling conditions, as in each condition all but one subject showed a decrease in performance after exposure. In both conditions, the general trend was for a decrease in performance. The speed test would be primarily influenced by quick movement of cold joints. This would be affected by the thickening of synovial fluid, which occurs at a relatively high temperature. Hunter *et al.* (1952) demonstrated that in the cold, joint temperature decreases more than muscle, core and average skin temperature does. Although the tests were conducted over very small time periods (1s), the same experimenter was used in all conditions so any errors were constant between participants and conditions. The speed test was a good test for highlighting manual dexterity deficits as a result of both slow and fast contact cooling,

### 4.6.3 Strength Test

The strength test, whilst showing statistically significant deficits in both the long term and short term contact cooling conditions showed greater consistency across subjects in the expected direction (i.e. strength decreasing after performance as a relative percentage change) in the long term exposure condition when compared to short term exposure. This was expected, as the strength test is primarily influenced by the small muscles of the hand and the muscles in the forearm. The forearm muscles are exposed to the ambient conditions inside the freezer, so a greater effect would be expected in the long term condition, as the temperature was lower and the duration that the forearm was exposed to the ambient conditions was greater than for the short term condition. Clarke *et al.* (1958) found that there was a minimal decrease in maximal contraction force at temperatures of 28° - 39°C but below 28°C there was a strong linear decrease in performance. The Strength test is primarily dependent upon the muscle force and the contraction velocity of the muscle. For maximal force to be exerted by a muscle as is required by this test, muscle temperature needs to be high (optimally about 38 °C) (Havenith *et al.* 1995). This strength test proved to be a good indicator of manual dexterity deficits occurring as a result of contact cooling and can be used in both fast and slow cooling conditions. Although this test also relied on the cooling of some of the forearm, participants reported feelings of weakness in their fingers as they tried to grip the handle of the dynamometer, so this test was considered acceptable as a measure of manual dexterity affected by contact cooling.

### 4.6.4 Nut and Bolt Test

The nut and bolt test did not show any significant differences in the short term exposure condition but did illustrate significant differences in the long term exposure condition. The nut and bolt test would highlight any deficits in terms of skin sensibility and joint stiffness. When observing participants complete this test, it was apparent that the most difficult part of the test was the picking up of the nuts. Actually screwing the nut onto the bolt did not present a problem for subjects. This would seem to indicate that this test was in fact primarily affected by numbness of the skin rather than joint mobility. It's also likely that receptor sensitivity was affected. There are two main types of receptors. Receptors in the motion apparatus provide information relating to the position of the hand in relation to the body and environment. Receptors in the skin provide information on the structure and texture of handled objects (Havenith *et al.* (1995)) so it is possible that

these receptors affected performance on the nut and bolt test. The most likely explanation for this is that the very tip of the thumb and index finger are required to pick up the nuts. These are areas of the hand likely to cool the quickest due to being extremities and also because of the blood supply to these areas. It is likely that these areas were exposed more to the ambient condition than the bar so the decrease in performance in the long term cooling condition could again be attributed to the longer duration of exposure in this condition and the lower ambient temperature. Due to the fact that it is likely this test then measures the effects of ambient air exposure rather than contact cooling, it is concluded with hindsight that this test may be inappropriate to measure effects of contact cooling.

#### **4.6.5 Tactile sensitivity**

This test appeared to be the least effective test at measuring manual dexterity deficits as a result of contact cooling. It is likely this was the case as the skin temperature required to affect tactile sensitivity are quite low. Mackworth (1953) found a minor impairment in tactile sensitivity at skin temperatures below 25°C. Morton & Provins (1960) and Mills (1956) found that a nervous block occurred at skin temperatures of approximately 6°C and that skin temperatures of between 6-8°C result in sensitivity being decreased rapidly. Based on previous experiments, it is unlikely that in either condition skin temperature reached this level.

Several problems were identified with the three point aesthesiometer that may have contributed to the lack of difference found pre and post exposure. It was difficult to administer the test after each increase or decrease in distance between the two points with the same pressure. Sometimes the participant moved their hand or their hand shook. This problem was partly alleviated by placing the participants hand onto a firm surface, but if the experimenter's hand shook at all it was possible that the point made contact more than once with the participants hand. It was also difficult for the experimenter to judge exactly how much pressure was being exerted by the points onto the subject's hand. If this test were to be replicated a machine to administer the test would eliminate any doubts as to the administration of the test. Finally, due to the individual contours of each participants hand, it occasionally was difficult to touch the hand with the two points of the aesthesiometer at exactly the same time resulting in the participant feeling two distinct contact points.

Although a significant difference was found at site one in the short term cooling condition this was only significant at the  $p \leq 0.05$  level and due to the lack of significance found at any other site, it is likely that this significance was due to factors other than the condition.

#### **4.7 Conclusions**

It would appear that the aspects of manual dexterity affected by fast contact cooling (contact with materials of high coefficients) and slow contact cooling (contact with materials with low coefficients) are similar, but the severity of deficit varies.

The Speed and Strength tests are the most sensitive to the effects of contact cooling as a result of contact cooling for both long term exposure to a material with a low contact coefficient and short term exposure to a material with a high contact coefficient.

Aspects of manual dexterity most affected by contact cooling are fine motor tasks and strength tasks. This is consistent with changes in synovial fluid, muscles and nerve conduction.

## **5 A Comparison of Effects on Manual Dexterity Between the Dominant and non Dominant Hand as a Result of Contact Cooling**

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### **5.1 Chapter Summary**

In the previous chapter four tests were identified that assessed different aspects of manual dexterity. Two of those tests were identified as being particularly sensitive to losses in manual dexterity as a result of contact cooling of the dominant hand. In this chapter those tests shall be used to determine whether any differences exist between the dominant and non dominant hand in terms of manual dexterity as a result of contact cooling. It was determined that there is a difference in the strength aspect of manual dexterity with the non dominant hand being significantly more affected than the non dominant hand, although this difference may be attributable to chance.

### **5.2 Background**

The European Standard investigating the effects of contact cooling on the human hand was based on data from the dominant hand. Subsequent guidelines established were to protect both hands. The aim of this study was to determine if there are any differences in effects on manual dexterity as a result of contact cooling between the dominant and non dominant hand and if there are, to determine how it would affect the standard.

### **5.2.1 Differences and Similarities between the dominant and non dominant hand**

Embryological differences occur in the origin of the right and left arms and hands. The left arm and hand originate in the neck of the embryo from the same tissue whereas the right do not (Guyton 1964). This is lent further credence by the fact that when a person suffers from angina, the pain is experienced first in many cases down the left arm. This may indicate the persistence of a neural connection that is absent in the right arm. It is therefore possible that there may be a difference in the perception of pain between the left and right arm at the neural level associated with the receptors and nerve fibres, which is unaffected by patterns of dominance in the brain (Murray and Safferstone 1970).

### **5.2.2 Pain**

Murray and Safferstone (1970) investigated the pain responses of 41 females aged 18 -21 years (these included 36 dextral, 3 sinistral and 2 ambidextral). Participants were asked to place their hands up to the wrist in a water bath containing water of either 32°C or 2°C. Participants were asked to rate the temperature of the bath from cold to neutral. After two minutes, the participants were then asked to remove their hand from the 32°C water bath and place it in the 2°C water bath. Participants were then asked to indicate the sensation of pain and leave their hand in the water bath until the pain became intolerable. It was determined, that the threshold and tolerance values for the right hand were consistently higher than those for the left, for both dextral and sinistral participants. However, the fact that only 3 sinistral participants were used was noted as a confounding factor.

Wolff and Jarvik (1964) used ice water with chronic arthritic participants who had a median age of 52 years. It was determined that the dominant side was more sensitive to pain than the non dominant side.

In a replication of Murray and Safferstone's experiment, where the majority of participants had been right handed, Murray and Hagan (1973) repeated this study using 10 sinistral and 10 dextral participants. The procedure was the same as the experiment described previously, with the exception that the feet of the participants were also immersed separately to the hands. It was determined; that the left hand and foot had a significantly lower threshold and tolerance to pain than the right hand and foot, regardless of whether the participants were sinistral or dextral. This difference was attributed to the brain being

bilaterally asymmetrical regarding certain functions. The left hand side of the brain is predominantly concerned with speech productions and perceptions, whereas the right hand side of the brain is concerned primarily with perception of language and other non-language sounds (Murray and Safferstone 1970). Based on these observations, it is thought that the difference in pain tolerance and onset of pain would also be evident after contact cooling of the hand and reflected in the subjective sensations. It is also possible that there may be differences in tactile sensitivity between the dominant and non dominant hand related to the functional asymmetry of the brain. The studies described above, use homogenous cooling, rather than asymmetric cooling which occurs as a result of contact cooling, so it is not clear whether the findings could be applied to pain sensations experienced as a result of contact cooling.

Wolff, Krasnegor and Farr (1965) found that the left or non preferred hand was more sensitive to pain when using electrically induced pain rather than cold induced pain. They thought that the difference in pain sensation experienced between the two limbs might lead to a decrease in motivation affecting the results of the manual dexterity tests they performed. Electrically induced pain occurs in very short exposures, whereas the type of pain experienced as a result of contact cooling is over a longer time period, again meaning these finding may not be applicable to contact cooling.

### **5.2.3 Pressure**

Weinstein and Sersen (1991) in an experiment using 66 sinistral participants found greater left-hand sensitivity to pressure. It is possible that the left hand, being the dominant hand in the participants used, was more accustomed to detecting pressure through frequency of use, although dependant upon day to day use, it could be expected that the dominant hand would be less sensitive to pressure as a result of callus build up on the hand used most frequently. Callus is a thickened keratin layer of the epidermis, which builds up due to more frequent use (Lederman 1976). However, Fennell, Satz and Wise (1967) and Carmon, Bilstrom and Benton (1969) found that there was no asymmetry between hands for perception of either pressure or sharpness.

Hellstrom *et al.* (1970) investigated human peripheral rewarming during exercise in the cold. It was determined that on several occasions throughout the experiment, the third

finger on both the dominant and non dominant hand rewarmed simultaneously regardless of the fact that the right hand was covered using a 6mm thick, wind tight insulative nylon mitten. Imamura *et al.* (1998) investigated the rewarming of the dominant and non dominant hand after exposure to a steel bar at  $-10^{\circ}\text{C}$ . It was determined, that rewarming occurred more quickly in the dominant than in the non dominant. No conclusions can be drawn from this study however, as only one condition was tested.

#### 5.2.4 Manual Dexterity

Manual dexterity is discussed in greater detail in chapter 4. A brief recap shall be given here. Manual dexterity is affected by several components, including reaction time, sensitivity, nerve conduction, grip strength, time to exhaustion and mobility (Havenith *et al.* 1995). Increasing reaction time is possibly caused by physiological changes in receptors, nerves and effectors. De Jong *et al.* (1966) found a linear decrease in nerve conduction velocity of  $1.8\text{ms}^{-1}\text{C}^{-1}$  at a normal mean conduction velocity of  $60\text{ms}^{-1}$ . Below  $20 - 24^{\circ}\text{C}$  there is a stronger decrease in nerve velocity and a nervous block occurs at temperature below  $10^{\circ}\text{C}$ . Changes in dexterity can also occur through changes in the muscle in terms of power, contraction, speed or muscle endurance. The muscle force and contraction velocity determines muscle power. The cold can affect muscle power due to changes in maximal power, which can be decreased due to a change in the maximum contraction velocity and maximum force. A decrease in time to exhaustion is also apparent.

Reduced skin sensibility is most likely due to physiological changes in the receptors whereas reduced mobility is most likely attributable to changes in muscles, joints and tendons. The mobility of the joint is affected by cooling, as the synovial fluid that lubricates the joints thickens so movements become slower. This is often referred to as joint stiffness, and when the fluid becomes viscous it requires more muscle power to make movements. Joints can cool more quickly than the muscle core and average skin temperature (Hunter *et al.* 1952).

In addition to these physiological changes responsible for decreases in manual dexterity, reduced motivation as a result of central effects is also a consideration. When manual

dexterity decreases and work production is also reduced it has been shown to lead to an increase in accidents (Osbourne and Vernon 1922).

### **5.2.5 Contact Cooling**

Chapter 3. Identified two types of cooling that occur as a result of contact with materials with either high or low contact coefficients. The type of cooling that results from contact with a material with a low contact coefficient is a slow deep cooling, the other type of cooling occurs as a result of contact with a material with a high contact coefficient. This type of contact cooling results in a faster more superficial cooling. The two types of cooling patterns lead to different aspects of manual dexterity being affected (chapter 4). To investigate all aspects of manual dexterity (from gross hand tasks to fine finger tests) that might be affected in both the dominant and non dominant hand, the four dexterity tests selected and discussed in chapter 4 were used for this experiment. These were a dynamometer, a timed speed test, a nut and bolt test and a tactile discrimination test

## **5.3 Aims**

The type of cooling that occurs, as a result of contact cooling is different from cooling that may occur in air or water. As tests carried out previously used either a water bath or electrically induced pain, it was an aim of this study to see if a difference in onset and tolerance of pain between the dominant and non dominant hand are present as a result of contact cooling rather than cooling by water or electrically induced pain. To do this, two conditions were designed in order to affect a slow contact cooling condition and a fast contact cooling condition. These two conditions were used in case a difference was apparent between the dominant and non dominant hand in one condition, but not the other. One of the aims of the E.U sponsored cold surface project, discussed earlier in this thesis, was to assess safety issues in terms of loss of dexterity for gripping manual tools in cold environments. All the work in this area has been conducted on the dominant hand of participants. The aim of this study was to determine whether there are any differences in responses between the dominant and non dominant hand in terms of manual dexterity deficits and subjective responses. The rationale behind this is that if responses were different for the two hands, then depending upon the differences found, it is possible that the standard would need to incorporate these differences in order to effectively protect both hands from the effects of contact with cold materials. At present, the standard is designed to protect 75 % of the population (i.e. based on 75 percentile data). The standard

is based on results for the dominant hand, so are the findings applicable to the non dominant hand?

## **5.4 Methods**

### **5.4.1 Procedure**

Upon arrival at the laboratory, participants completed an informed consent form. Participants were then instrumented and performed one of the four manual dexterity tests to obtain baseline data. The order of exposure of the dexterity test for participants was randomised using a 10 by 4 incomplete Latin Square design. The participant then placed his or her hand into the freezer and gripped the bar. The order of exposure of the hand was determined by a pseudo Latin square. After the set duration of either five or ten minutes, the participants removed their hand from the freezer and performed the manual dexterity test again. When all sensations of the hand had returned to normal, the participants then repeated the experiment using their other hand. Subjective responses of pain, numbness, tingling and thermal sensation were monitored throughout the sessions, with the initial sensations of the participant being recorded, the sensations at first contact with the bar, and then participants were asked to verbally report any changes in their condition as and when they occurred.

### **5.4.2 Contact Cooling**

Participants were asked to grip a bar 400mm in length and 40 mm in diameter while their hands were in the freezer. Each bar was weighted from the outside (see chapter 2) so that each bar weighed the equivalent of 500g. Thermocouples were used to measure skin temperature and were placed at several locations on the participant's hand. (See table 5.1)

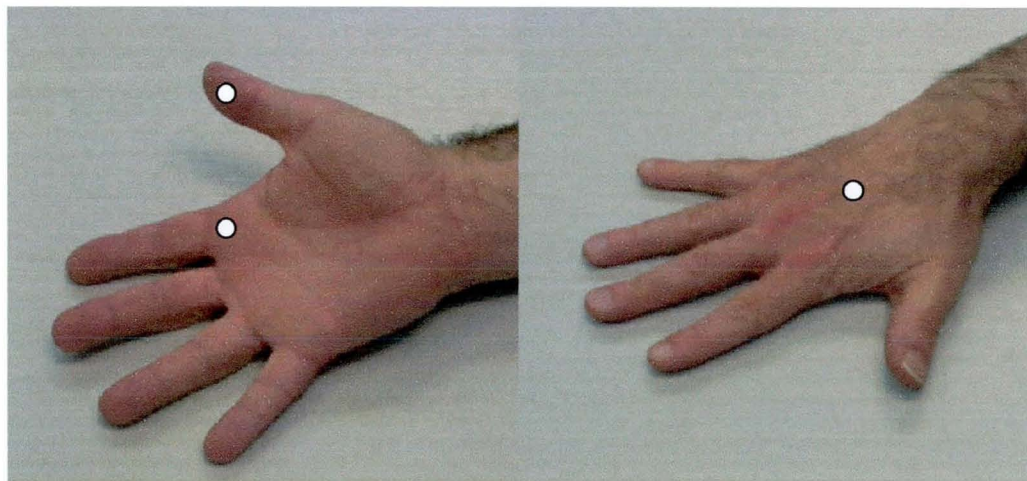


Figure 5.1. Shows the placement of thermocouples on the participant's hand  
Palmar Aspect Dorsal Aspect

### 5.4.3 Participants

Five male and five female participants took part in this repeated measures within subject study. All participants were right handed. Table 5.2 shows the participants characteristics

Table 5.2. Participant Characteristics

Subject	Sex	Age	Height	Weight	Volume of Hand		Palm Length		Palm Width		Third Phalanx Length		Third Phalanx Width	
					R	L	R	L	R	L	R	L	R	L
1	M	27	183	88.7	331	329	10.1	10.1	8.4	8.1	7.6	7.8	2	1.9
2	F	31	171	77.5	312	319	10.7	10.5	8.3	7.8	8.2	7.9	1.9	1.9
3	F	22	170	73	276	269	10.1	10.1	7.9	7.6	7.5	7.8	1.8	1.7
4	F	21	169	65	301	291	9.7	9.6	7.6	7.4	7.6	7.5	1.8	1.7
5	F	21	162	60.5	290	277	9.2	9	8	8	6.7	7.1	1.7	1.7
6	M	25	185	80.4	394	388	11	10.6	8.7	8.7	8.7	8.6	2	2
7	F	23	169	58.3	297	293	11	10.7	8	7.9	7.9	8	1.8	1.7
8	M	22	188	84.7	392	389	11	10.9	8.7	8.7	8.8	8.7	1.9	1.9
9	M	25	179.5	74.8	315	319	10.8	10.9	8.2	8.1	8.3	8.5	1.8	1.7
10	M	23	180	80.3	389	384	10.9	10.7	8.8	8.7	8.5	8.4	2	1.9
Mean		24	175.7	74.3	329	325.	10.5	10.3	8.2	8.1	7.9	8.0	1.8	1.8
SD		3.13	8.54	10.2	45.	46.2	0.64	0.62	0.3	0.4	0.6	0.5	0.1	0.1
					2	8		1	6		8	3	7	1
									9	7	5	2	1	2

(R = Right Hand, L = Left Hand)

### 5.4.4 Conditions

The following conditions were used in order to induce the two types of cooling (see table 5.3)

Table 5.3 shows the Experimental Conditions

	Material	Temperature	Duration of Grip
Fast Cooling	Aluminium	-3°C	5 minutes
Slow Cooling	Nylon	-20°C	10 minutes

The material and duration that the material was gripped for were based on the results from chapter 3, which indicated that participants could be exposed to the material for these periods of time without withdrawing through intolerable pain for the non dominant hand. This was important as in order to compare the manual dexterity results effectively, all

participants needed to be exposed to the bars for the same period of time before completing the tests.

#### **5.4.5 Manual Dexterity Tests**

Prior to the experiment, all participants visited the lab and completed all manual dexterity tests until a plateau of performance had been accomplished. This was to avoid any learning effects. The full protocol for each manual dexterity test is discussed in chapter 4.

The four tests used were a strength test, a tactile discrimination test, a speed test and a nut and bolt test. For all four tests, the reasons for selection and methodology were discussed in chapter 4.

#### **5.4.6 Withdrawal Criteria**

Participants were asked to withdraw their hand from the freezer immediately, if any of the five thermocouples registered a temperature of 0.5°C, if the participant experienced the sensation of frost nip which was described to them in a pre visit, or if the participant experienced intolerable pain.

### **5.5 Results**

#### **5.5.1 Analysis**

For all tests (except the nut and bolt test which was only completed once due to the amount of time required to complete it and the subsequent effects on rewarming of the hand) three repeated measurements were recorded for each participant. The results from the manual dexterity test prior to exposure to the bar were then compared to the results of the manual dexterity tests after exposure to the bar. The results after exposure were looked at as a percentage increase or decrease of the results prior to exposure. The average percentage was then taken for each participant for each hand. This percentage value was then tested for significant difference between the dominant and non dominant hand using a t-test across all participants.

#### **5.5.2 Long Term Cooling - Manual Dexterity Test**

Table 5.4 below shows the mean percentage increase or decrease in performance between the dominant and non dominant hand, and the significance values over all participants.

*Table 5.4. Means, standard deviations and average changes in % as recorded for the manual dexterity test for long term (slow) cooling.*

Manual Dexterity Test	Average Score of All Subjects Before Exposure		Average Score of All Subjects After Exposure		Percentage (%) in- or decrease in average score after exposure		p-value for t-test
	Dominant	Non Dominant	Dominant	Non Dominant	Dominant	Non dominant	
Speed (s) (time required)	1.2 ±0.2	1.5 ±0.2	1.3 ±0.2	1.8 ±0.2	8	20	0.75
Strength (Kg)	37.3 ±8.0	37.9 ± 7.9	34.0 ± 7.2	34.2 ±10.6	-9	-10	0.046
Nut and Bolt (s)	81.0 ±25.2	87.4 ±26.7	93.3 ±19.8	106.9 ±40.7	15	22	0.72
Tactile (site 1) (cm)	5.3 ±2.5	6.3 ±4.5	6.4 ±5.2	6.3 ±6.1	21	0	0.28
Tactile (site2) (cm)	6.2 ±1	6.7 ± 3.4	5.1 ±2.6	5.3 ±2.5	-18	-21	1.000
Tactile (site 3) (cm)	3.2 ± 6.9	3.4 ±1.6	2.9 ±1.6	3.6 ±2.5	-10	9	.353
Tactile (site 4) (cm)	7.0 ± 6.9	9.1 ±5.0	8.9 ± 7.2	9.7 ±7.8	27	7	0.999

There were no significant differences between the hands in terms of manual dexterity ( $p > 0.05$ ), except for strength which was significantly, but marginally more reduced in the non-dominant hand. As can be seen from table 5.4, though tactile responses were sometimes very different between hands, these findings however were not significant. Individual response variation to the test was great as evidenced by a high standard deviation.

### 5.5.3 Long Term Cooling - Subjective Responses

Wilcoxin sign rank tests were used to investigate the subjective responses. There were no significant differences between the pre-contact sensations of the participants across all four sensations. There were no significant differences overall in time to the onset of pain between the dominant and non dominant hand ( $p = 0.4$ ). No significant differences were found in the pain tolerance of the participants, as all ten participants lasted for the full ten minute duration. There were also no significant differences in the highest or end values of each sensation vote (pain, numbness thermal and tingling).

### 5.5.4 Short Term Cooling - Manual Dexterity Responses

Table 5.5. Below shows the mean percentage increase or decrease in performance between the dominant and non dominant hand, for the short term cooling and the significance values of all participants.

*Table 5.5. Means, standard deviations and average changes in % as recorded for the manual dexterity test for short term (fast) cooling.*

Manual Dexterity Test	Average Score of All Subjects Before Exposure		Average Score of All Subjects After Exposure		Percentage (%) in- or decrease in average score after exposure		p-value for t-test
	Dominant	Non Dominant	Dominant	Non Dominant	Dominant	Non dominant	
Speed (s)	0.98±0.2	1.01±0.2	1.10±0.2	1.23±0.2	12	22	0.955
Strength (Kg)	41.7±9.8	37.9±11.7	41.1±11.0	36.3±13.1	-2	-4	0.845
Nut and Bolt (s)	73.9 ±28.5	96.7 ±33.4	85.3 ±32.5	89.2 ±41.6	15	-8	0.999
Tactile (site 1) (cm)	6.9 ±3.7	5.7 ±3.2	8.2 ±3.8	7.9 ±4.1	18.8	38.6	0.866
Tactile (site2) (cm)	7.4 ±2.3	6.8 ± 4.4	6.8 ±3.9	6.2 ±3.2	-8	-9	0.421
Tactile (site 3) (cm)	4.5 ± 8.1	4.4 ±2.5	4.9 ±3.3	5.2 ±1.9	9	18	0.740
Tactile (site 4) (cm)	14.3 ± 8.1	12.5 ±9.5	14.9 ±5.8	14.2 ±9.6	4.2	13.6	0.674

The results from the manual dexterity tests for short term cooling were analysed in the same way as the results from the long term cooling data. For short term cooling, occurring as a result of contact with the aluminium bar, none of the tests showed a significant difference.

### 5.5.5 Short Term Cooling - Subjective Responses

Wilcoxon tests were used to investigate the subjective responses. There were no significant differences between the pre-contact sensations of the participants across all four sensations. There were also no significant differences in sensation at the end of the test between both hands or between the highest sensations reached for pain, numbness, thermal or tingling sensations. No significant difference in the onset of pain was found between the dominant and non dominant hand ( $p = 0.18$ ) and no significant difference in pain tolerance was found as all the participants completed the five minute duration of contact.

## 5.6 Discussion

### 5.6.1 Manual Dexterity Tests

The population group studied, were primarily people unaccustomed to manual labour. This means that they would be unlikely to have any callus build up on their hands. The measured quantity of heat transferred through the skin to the material depends upon the heat conductivity through the skin, the sensitivity of the thermal sensor and the thermal

contact of the material being gripped (Chen 1994). The condition of the skin i.e. actual surface roughness and skin thickness (Chen 1997) would influence contact resistance (Holman 1989). It is possible, that had a population been studied where calluses were present, that there would have been an increase in statistical significance between manual dexterity performance using the dominant and non dominant hand whilst gripping cold materials due to the extra 'protection' calluses offer.

The only significant difference found in performance for the manual dexterity tests between the dominant and non dominant hand was for the strength test, where strength was found to decrease significantly more for the non dominant hand when compared to the dominant hand in the slow cooling condition only. Chapter 4 showed that fast cooling did have a significant effect on manual dexterity but at a lower level (1.9% mean decrease in performance when compared to 9.1% decrease in the slow cooling condition). It was expected, that if a difference would occur it would indeed be in the slow cooling condition, as the structures that affected strength were shown not to have been cooled adequately by the fast cooling condition in chapter 4. Despite the significant difference, the magnitude of the difference is very small, and its relevance may be questioned. If these finding were repeated however, then possible implications for the standard would have to be considered.

Armstrong and Oldham (1999) compared the hand strength in both the dominant and non dominant hand of both dextral and sinistral participants. No differences in grip strength or pinch strength were found between the dominant and non dominant hand in the sinistral participants. A small but not significant difference was found in both grip strength and pinch strength of the dextral participants, with the dominant hand being stronger. An average of three readings were taken for analysis, with the arm becoming weaker with each trial as a result of exhaustion. This is in line with the findings of this study.

### **5.6.2 Subjective Responses**

The majority of studies to date (Murray and Safferstone 1970, Murray and Hagan 1973) have found the right hand to be less sensitive and to have a greater tolerance of pain than the left, regardless of hand dominance. Due to the unique physiological conditions induced by contact cooling, it may not be possible for the participants to determine any differences

in pain sensation. The experiment was specifically designed so that participants would not withdraw through intolerable pain, based on results from the original study discussed in chapter 3. This was done to ensure that all participants had the same exposure times to the bar in the dominant and non dominant hand condition before completion of the manual dexterity tests. The rationale for this was that the primary aim of this study was to determine if there were any differences in manual dexterity after cold contact exposure between the two hands. Subjective sensations were a secondary investigative point to this. However, it was considered as a result of previous studies, and from experimental experience, that participants would withdraw their non dominant hand from the cold chamber prior to the limit set for exposure, as the durations selected were at the edge of tolerance for the dominant hand. Therefore, any deficit in tolerance of pain of the non dominant hand when compared to the dominant hand should have been apparent. It is possible though, that a difference in pain tolerance exists and that it would have become apparent if the experiment had been continued until the subject withdrew their hand through pain. However, as there was no significant difference in the highest pain sensation achieved, or the end sensation achieved, it is likely that this difference, even if significant, would have little application in the 'real world' as the majority of people are unlikely to work to the tolerance of pain limit.

Although 'quality' of pain was not officially recorded, anecdotally, nearly all of the participants reported a difference in the quality of pain being experienced, with the short term cooling resulting in a burning stinging sensation, and the long term cooling resulting in an achy pain sensation. The burning and stinging pain experienced after contact with the high contact coefficient bars resulted in subjects complaining more even though the level of pain experienced was the same. This pain was also reported to last longer than the pain induced by slow cooling. The pain experienced as a result of short term cooling resulted in reduced motivation when completing the manual dexterity tests, as it actually caused the participant more pain to have contact between the manual dexterity tests and the skin on the hand.

## **5.7 Conclusions**

For the participant group studied, there are no significant differences in subjective responses reported as a result of fast and slow contact cooling between the dominant and non dominant hands.

For the participant group studied there are no significant differences in manual dexterity deficits between the dominant and non dominant hand as a result of fast or slow contact cooling except for strength in the slow cooling condition.

The European Standard is sufficient to protect the population at the level it was intended to (75%).

## **6 The Effect of High and no Blood Flow on Slow Contact Cooling**

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### **6.1 Chapter Summary**

Blood flow is the main source of heat input to the hand. There are many factors that may affect blood flow to the hand, including the wearing of tight fitting cuffs, or disorders or diseases that affect the circulation. This study investigates whether there is a difference between high and no blood flow states on contact cooling. It was found that there was a significant difference in end skin temperature, with temperatures being significantly lower in the no blood flow condition when compared to the high blood flow condition, when participants underwent contact cooling.

### **6.2 Background**

As described previously, the intentional sustained gripping of cold surfaces within the work place is common, and can affect the human in terms of pain, decreased manual dexterity and eventually possible skin damage. Contact cooling, occurs when contact with a material that is colder than the skin is made. Heat flows away from the warmer skin to the cooler material (1<sup>st</sup> law of thermodynamics). The rate of heat flow is determined by factors including the properties of the material and thermal gradient. The amount of heat flow is affected by factors such as contact time, surface area of skin exposed and how 'perfect' the contact with the block is. The latter factor is related to pressure, which is known to have an effect on contact cooling (Chen 1997).

There are two main reasons why pressure can affect cooling of the hand; a) the greater the pressure, the more perfect the fit of the hand to the object and b) when sufficient pressure is applied by the hand to an object the increased tissue pressure will cause the blood supply to skin capillaries to be affected. When sufficient pressure is applied, the blood supply will be cut off. Blood perfusion and the rate of blood flow will greatly influence heat transfer (Parsons, 1993). Previous research (SMT4-CT97-2149) has identified safe contact temperatures and durations for contact with cold materials. This research is based on data from the general population and has not discriminated between different contact pressures or reactions of different populations. Whole body cooling will cause physiological amputation as discussed in chapter 1. This leads to an increase in blood flow to the skin and extremities in particular. As blood flow is expected to have an effect on cooling rate, this raises the question as to how big this effect would be for the present application. More specifically, whether special worst case scenarios of contact cooling in the work place, where employees are affected with disorders which may affect blood flow, such as vibration white finger, Raynaud's disease, or even something as simple as tight fitting clothing, which may impede normal blood flow, should receive special treatment in standards. Therefore this experiment will look at the effect of blood flow on hand cooling whilst touching cold objects.

### **6.2.1 Blood Flow and Cooling**

The thermal situation of the body influences that of the hand. Humans are homeotherms, this means that the human body tries to maintain an internal temperature of 37°C. If the human body is exposed to conditions where it is unable to maintain a positive or neutral heat balance, then the body starts to cool down. The majority of the heat lost will be through the skin, a dynamic system able to alter depending upon the body's thermal condition. Vasodilation of the skin's blood vessels increases heat loss and vasoconstriction reduces heat loss due to a concomitant rise and respective fall in skin temperature. Constriction of superficial veins allows countercurrent heat exchange to occur, so that cool blood from the skin returns along the venae comitans close to the artery, thereby gaining heat while returning to the core. The extreme superficial vasoconstriction and this heat loss reduction mechanism is often referred to as physiological amputation. The hands are particularly sensitive to heat loss both anatomically and physiologically. It is therefore common to experience the combination of a warm body and cold hands. Whilst it is

possible to wear protective clothing for the hands (i.e. gloves) these have been shown to reduce manual dexterity and can have safety implications (Enander *et al.*, 1979). As described in Chapter 1 and 8 blood flow is the main source of heat input to the hand, as the hand itself is only able to produce a minimal amount of heat due to the small muscle mass (Lotens 1992). Blood flow to the hand is described in greater detail in chapters 1 and 8.

Spealman (1945) showed that at any given temperature, blood flow to the hand was increased as the temperature of the body increased. Havenith (1992, 1995) also showed that an increased initial core temperature (induced by previous exercise) resulted in a higher starting hand temperature, which was sustained throughout the contact cooling. Enander (1982) found that a higher initial hand skin temperature was associated with a slower rate of cooling.

### **6.2.2 Representative Hand Skin Site**

Individual Variation in initial hand skin temperatures is well documented. Chen *et al.* (1996) found that there are individual differences between subjects, from finger to hand temperature and also between fingers. The differences between finger skin temperatures ranged between 2 - 3°C but could be up to as much as 7.7°C. Enander (1982) found that inter individual - variation of initial hand temperatures varied from between 26 - 34°C. Variation within a finger was also discovered, with the proximal and distal phalanx varying by as much as 5.3°C (Chen *et al.* 1996). Research to date has identified the back of the hand to have, on average, a lower mean temperature than the contact side, except when the palm of the hand is in contact with cold materials with a high contact coefficient. Thumb temperature has been reported as the lowest temperature (Havenith *et al.* 1992) while gripping, with the digits being more susceptible to cooling fluctuations (Enander, 1982). For these reasons it was determined that the hand skin temperature could not be represented with a single location measurement, so several measuring sites were used for this experiment.

### **6.2.3 Safety Considerations**

As discussed earlier, the intention of this experiment is to study the effect of blood flow on skin contact cooling. To start with, it needs to be established whether any effect is present at all. Hence, a comparison between a high blood flow state (vasodilated) and a very low

one (vasoconstricted) would be relevant. In previous work on finger skin contact (Jay 2002) and from the pilot studies, methodological problems in such a comparison became apparent. The vasoconstricted state is not easy to define, and starting hand temperatures are much lower in the vasoconstricted state than in the vasodilated state, which makes analysis very difficult. Havenith (1995) showed that arterial occlusion resulted in the same cooling effect when the hand is exposed to cold as vasoconstriction. Hence, it was decided to compare a high blood flow condition with an occluded blood flow condition, both starting from the same baseline situation. In order to induce occlusion of the hand it was decided that an inflatable cuff should be used. Originally, the intention was to occlude the hand for up to thirty minutes, so literature relating to safe occlusion times was reviewed. Despite numerous publications on the topic of 'safe' times for absolute limits of tourniquet application, a conclusive time has never been established and times range from 45 minutes to four hours with two hours being the most widely accepted figure. The basis for the two-hour limit comes from research by Wilgis (as cited in Operative hand surgery) who showed progressive acidosis in venous blood distal to the pressure cuff in direct proportion to ischemia time. However, other factors such as damage to underlying tissues as a result of application of the tourniquet are also a consideration when determining tourniquet application time. The two tissues at greatest risk from resultant damage are nerve and muscle, the nerve being more susceptible to direct pressure and the muscle being more intolerant of ischemia. However Sapega *et al.* (cited in operative hand surgery) and Solonen and Hjelt reported that the abnormalities in muscle were not apparent until after at least two hours of ischemia. Personal correspondence with Mr. John M. Jones (Consultant Orthopaedic Hand surgeon ref.: JMJ.clp.) stated that during surgery it was common practice for him to keep tourniquets inflated to 250mmHg, on the upper limb for up to one and a half hours. He also stated that, under Dr. Robert Schenck at the Rush Presbyterian St Luke's Medical Centre in Chicago, he had often observed tourniquets applied during digital replantation for up to three hours without any adverse effects. For these reasons it was deemed safe to apply a tourniquet inflated to 200mmHg for thirty minutes.

Based on these considerations, the present experiment will compare the effects of high versus no hand blood flow on the cooling response of the hand whilst in contact with both nylon and wood bars at -20°C. The choice of material and experimental condition was

based on experimentation described in chapter 3. The conditions in chapter three and results from the pilot study indicated that at  $-20^{\circ}\text{C}$  participants should be able to maintain contact with the nylon and wood bars for the required duration, without withdrawing through pain (unequal withdrawal times leads to difficulties in the analysis). The results also indicated that the minimum contact temperatures should not fall below the minimum temperature criteria for withdrawal (see chapter 1).

## **6.3 Methods**

### **6.3.1 Pilot Studies**

Although literature has suggested it is safe to occlude the hand for up to two hours, this wasn't whilst undergoing contact cooling. Several studies (Swanson *et al.* 1991) have demonstrated that inducing local hypothermia of the tourniquet area prior to tourniquet application can decrease the adverse effects of tourniquet ischemia and allow continuous tourniquet inflation time to be safely extended past the two-hour barrier. However, no studies have specifically investigated the effects of occlusion on contact cooling. For this reason four pilot studies were conducted to establish safe times for the hand to be in contact with cold materials whilst occluded and to establish conditions that highlight any difference present as a result of the occlusion condition. A final aim of the pilot study was to determine a suitable method for heating the subjects to induce a high skin blood flow without inducing significant differences between the starting temperatures of the hand with and without occlusion prior to introduction to the freezer within subjects.

To induce contact cooling over long periods of time ( $> 5$  minutes) a female subject was exposed to a low contact coefficient bar (nylon) at  $-10^{\circ}\text{C}$  and  $-20^{\circ}\text{C}$ . Wood was not piloted due to the results in chapter 3 which illustrated that objective and subjective responses were unlikely to be significantly worse than those experienced by subjects when gripping nylon. The temperatures chosen for the pilot study were deemed to be temperatures at which the subjects would be most likely to sustain gripping for up to twenty minutes without withdrawing their hand through pain or too low contact temperatures. This was based on the results from the project work and prior experimentation in chapter 3.

### 6.3.2 Heating Procedure

In order to raise the level of vasodilation, subjects were heated. They exercised in a warm room (approximately 35°C and 30% Rh) dressed in shorts and T-shirt on a bicycle ergometer at 70-80 rpm with a 0.5, 1 or 2kg weight (see table 6.1 below), depending upon fitness level, in a warm dry environment. This exercise was continued until the subject's core temperature was raised by 1.5°C.

*Table 6.1 Shows the work rate of participants in  $Wm^{-2}$  at a cycling rate of 70 - 80 rpm*

Cycle ergometer weights			
	0.5 Kg	1 Kg	2 Kg
$Wm^{-2}$	22-30	38-44	78-88

It was determined that this was a suitable method for inducing a high blood flow state thereby raising the subject's hand skin temperature. By immediately clothing the subject in a track suit and removing them into a warm room it was apparent, that there would be no significant differences between the starting temperatures of the hand prior to each exposure within subjects.

From the pilot studies, it appeared that there was a difference in cooling between the occluded and free blood flow conditions, although as this wasn't a primary aim of the pilot study and as only one subject was used this data wasn't analysed. It was also determined that the effect was less apparent at -10°C than at -20°C. For this reason -20°C was chosen as the experimental temperature for the bar. It was anticipated that the subject should grip the bar for a period of twenty minutes to fully illustrate any effects of occlusion on contact cooling, however, after ten minutes of occlusion, the subject started to feel faint and reported a lot of pain in the occluded hand. The experiment was stopped after 12 minutes, due to subject withdrawal. The subject then went on to develop a cold within a couple of days, so it was felt that the results from this study and resulting faintness, could not be attributed solely to the experimental conditions as the faintness may have been a result of the impending cold. The experiment was repeated again with the same condition and subject a week after the cold had passed however the subject again withdrew after 12 minutes because of dizziness. Upon examination on the results, it was determined that a visible difference in skin cooling both throughout the curve and end temperature was

present after a duration of eight minutes, and at this time, subjective results indicated that the subject was not in substantial pain. However, as a result of the subject feeling dizzy both times after gripping the nylon bar whilst occluded, it was decided that for the subject's safety, all subjects should be sat whilst gripping the bar. A final pilot study was conducted using nylon at  $-20^{\circ}\text{C}$  for a duration of eight minutes. These conditions provided no adverse effects to the subject and demonstrated a difference between the two conditions. The final conditions decided upon based on the above experiments were nylon at  $-20^{\circ}\text{C}$  and wood also at  $-20^{\circ}\text{C}$ .

### **6.3.3 Participants**

All participants were volunteers with no history of frostbite, cold acclimatisation, hand or cold related injury, vascular disease or circulatory problems. All participants were given an instruction form detailing the experiment and asked to fill out an extensive health questionnaire and consent form. For this study, four male and four female subjects were used (females were controlled for the menstrual cycle phase and were on the contraceptive pill). Participants were aged  $22.3 \pm 1.7\text{yrs}$ , (21-26yrs). A balanced  $8 \times 4$  Latin square design was used with female participants being assigned to the rows with paired materials to ensure the two conditions for one material were tested over a short period of time avoiding any effects of the menstrual cycle.

### **6.3.4 Anthropometric measurements**

Upon arrival to the laboratory, participant's height (m), weight (kg), hand volume ( $\text{cm}^3$ ), total surface and contact area ( $\text{mm}^2$ ), palm width, finger lengths and hand length (mm) measurements of the dominant hand were taken. The results of which are shown in the table below. All equipment was calibrated prior to measurements being taken.

Table 6.2. Anthropometric Measurements

Dimension	Mean + SD
Height (m)	175.4 ± 10.1
Weight (Kg)	70.0 ± 10.1
Hand Volume (cm <sup>3</sup> )	0.3 ± 0.1
Hand Length (mm)	170.6 ± 15.8
Palm Length (mm)	92.9 ± 14.2
Palm Width (mm)	91.6 ± 24.0
Digit 1 (mm)	63.6 ± 5.0
Digit 2 (mm)	71.1 ± 4.0
Digit 3 (mm)	77.8 ± 5.0
Digit4 (mm)	72.3 ± 3.2
Digit 5 (mm)	60.4 ± 3.2
Total Surface Area (mm <sup>2</sup> )	152.1 ± 13.4
Gripping Surface Area (mm <sup>2</sup> )	78.5 ± 6.3

### 6.3.5 Physiological Measurements

An 8-bit squirrel (Grant) with a 2mm tip aural thermistor was used to measure aural temperature. Data was recorded at 30 second intervals. The thermistor was inserted into the participant's outer ear canal and taped into position using micropore tape. Cotton wool was then placed over the sensor and ear defenders were worn to further insulate the thermistor from the external environment ensuring an accurate approximation of brain temperature. The aural thermistor was placed into the outer ear canal and insulated at least twenty minutes before the experiment began to allow the air in the canal to reach equilibrium with the air inside the inner ear canal. Heart rate was measured using a heart rate monitor (Polar Electro) at 15-second intervals throughout the experiment. Blood pressure was measured using an automatic pressure cuff (Speidel & Keller). Under the free blood flow condition, blood flow was measured using a strain gauge plethysmograph (Hokanson), the methodology of which is detailed in chapter 2.

### 6.3.6 Pre Contact

In order for the experiment to begin, subjects had to display a minimum aural temperature of 36°C. To ensure a state of high blood flow prior to contact with the bar, participants exercised on the ergomedik bike in a thermal chamber as described in the pilot study. The thermal chamber was set at 35°C and 33% humidity. Exercise was stopped when the subject's aural temperature increased by 1.5°C, if the participants heart rate exceeded the maximum rate set for safety ((220 -20)- age), or if the subject's aural temperature reached 38.4°C or if the subject wished to withdraw. The mean exercise time was 22 minutes. The amount of time that it took for the subjects to increase their aural temperature by 1.5°C

was also noted. Room temperature and humidity were noted at the start of the experiment and at five minute intervals after that time. Upon increasing aural temperature by 1.5°C the participant was asked to cycle with all weights removed at a rate of 50 rpm for two minutes, this ensured there was no sudden cessation of exercise which would increase risk of fainting and subsequent muscle soreness. The participant then put on their tracksuit and moved from the thermal chamber to the room with the cold chamber - keeping their hands in their pockets. Blood pressure and blood flow (in the free blood flow condition) were measured at this point.

### **6.3.7 Occlusion Procedure**

Blood flow to the hand was occluded using a wrist cuff that was situated proximal to the condoloids on the dominant arm. This position was chosen to reduce the risk of nerve or muscle damage resulting from compression between the cuff and the condoloids. The cuff was inflated rapidly to a pressure of approximately 200mgHg. After the occlusion period the pressure was released over a five second period and the subject's hand was checked for discolouration.

### **6.3.8 Contact Cooling**

Once the blood flow to the arm was occluded, or directly in the non occluded condition, the participant entered their hand into the freezer and gripped either a nylon or wooden bar at -20°C. All participants completed all four conditions. Prior to inserting their dominant hand into the freezer, participants were asked to rate their pain, thermal numbness and tingling sensation using 5pt, 7pt, 4pt and 4pt scales (Table 6.1). Participants were then asked to rate their sensations every time they changed from that point. The location of pain was also noted.

Thermal sensation scale			Pain sensation scale		
Vote		Description	Vote		Description
+1		Slightly warm	0		No pain
0		Neutral	1		Slightly painful
-1		Slightly cool	2		Painful
-2		Cold	3		Very painful
-3		Very cold	4		Intolerable pain
-4		Very, very cold			

Tingling sensation scale			Numbness sensation scale		
Vote		Description	Vote		Description
0		No tingling	0		No numbness
1		Slight tingling	1		Slight Numbness
2		Tingling	2		Numbness
3		Severe tingling	3		Severe numbness

*Table 6.1 Sensation scales used by the subjects to rate sensations of pain, numbness, tingling and thermal sensation.*

Participants were asked to grip the appropriate bar for a period of eight minutes unless they experienced sensations of frostbite or intolerable pain, or the safety contact temperature for this experiment was reached at any measurement site. This was set at 3°C. Thermocouples were placed at the following sites on the subject's hand.

Table 6.3. Sites of thermocouple placement

Thermocouple Number	Thermocouple Placement
T2	Beneath proximal phalanx (2 <sup>nd</sup> digit)
T3	Centre of abductor digiti minimi muscle
T4	On distal Phalanx (thumb)
T5	Above interphalangeal joint (5 <sup>th</sup> digit) *
T6	Between tendons of extensor digitorum muscle (dorsal side)
T7	Beneath Proximal Phalanx (5 <sup>th</sup> digit)
T8	Middle Phalanx (2 <sup>nd</sup> digit)
T9	Middle Phalanx (3 <sup>rd</sup> digit)
T10	Middle Phalanx (4 <sup>th</sup> digit)

\*Denotes a non contact site (i.e. exposed to air)

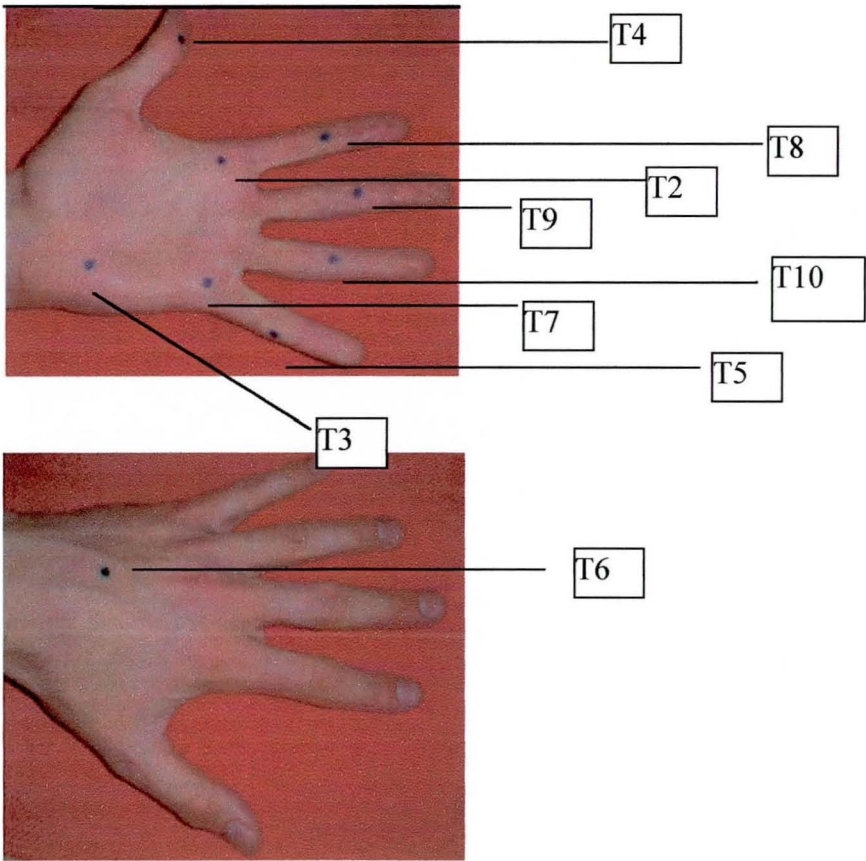


Table 6.2 shows thermocouple placement on the palmar and dorsal aspect of the hand.

## **6.4 Results**

### **6.4.1 Blood Flow**

Blood flow was measured pre and post exercise. The mean pre exercise blood flow was found to be 2.9ml blood / 100 ml tissue / minute ( $\pm 1.9$  ml). The mean post exercise blood flow was found to be 3.4ml blood / 100 ml tissue / minute ( $\pm 2.7$ ml). The overall mean increase in blood flow as a result of the exercise condition was found to be 1.5ml / 100 ml tissue / minute. A T-test was used to compare the two conditions, and it was found that the post exercise blood flow was significantly greater than in the pre exercise condition ( $p < 0.01$ ).

### **6.4.2 Subjective Sensations**

#### **6.4.3 Pre contact**

Subjective sensations were taken prior to insertion of the hand into the freezer.

It was determined that after inflation of the cuff, but before insertion of the hand into the freezer, 9.4% of the subjects described the thermal sensation of the hand as neutral, 46.9 % as slightly warm and 43.8% as warm. At this time, no pain was experienced by any of the participants, however the sensations of numbness and tingling were experienced by 3.1 % and 6.3 % respectively. This was reported to be as a result of inflation of the occlusion cuff, and could not be avoided. There were no differences in reported pain sensations pre contact and when comparing the other sensations, only minimal differences between the occluded and free blood flow conditions for the same materials, varying by a maximum of one point on the respective scales.

#### **6.4.4 Contact**

Upon comparison of the occlusion condition with the free blood flow condition, it was determined that after the occlusion condition there was a significantly higher incidence of pain reported ( $p < 0.05$ ) than in the free blood flow condition. 9.4% of participants reported a sensation of slightly painful in the occlusion condition, compared to 3.1% in the free blood flow condition. For tingling, or slight tingling, 32.3% of subjects reported tingling after the occlusion condition compared to 6.3% after the free blood flow condition, and 15.6% of participants reported numbness after both the free blood flow and the occlusion condition.

### 6.4.5 Post Contact

Occluded nylon resulted in the most pain being experienced at the end of the experiment and the free blood flow conditions resulted in the lowest thermal sensations. There was an increase in numbness after the experiment compared to before the experiment. No significant differences in subjective sensations were found between either conditions or materials.

The most commonly reported areas of pain were the tips of the digits, specifically the fifth digit and the area of the palm between the first and second digit (see diagram below).



**Table 6.3.** Shows most commonly reported areas of pain (blue)

### 6.4.6 Contact Cooling

The initial starting temperature of the bar was  $-18.9 \pm 1.6$  °C. The mean initial temperature of the hand including all thermocouples, conditions and subjects was  $35.7^{\circ}\text{C} \pm 0.36^{\circ}\text{C}$ . Table 6.4 shows the mean initial and end hand skin temperatures for all subjects.

**Table 6.4.** Mean and SD of hand skin temperature prior to insertion of the hand into the freezer and end skin temperatures over all conditions.

Thermocouple Placement	Mean Initial Skin Temperature		Mean End Skin Temperature	
	Occluded	Non Occluded	Occluded	Non Occluded
Beneath proximal phalanx (2 <sup>nd</sup> digit)	36.1 ± 1	35.4 ± 0.8	24.2 ± 8.5	26.46 ± 4.1
Centre of abductor digiti minimi muscle	35.6 ± 2.6	35.4 ± 2.1	19.5 ± 9.9	28.9 ± 7.5
On distal Phalanx (thumb)	36.2 ± 0.9	35.5 ± 1.3	16.4 ± 7.2	24.2 ± 5.0
Above interphalangeal joint (5 <sup>th</sup> digit) *	36.1 ± 0.9	35.9 ± 1.2	15.7 ± 7.5	27.8 ± 5.6
Between tendons of extensor digitorum muscle (dorsal side)	36.8 ± 1.0	35.0 ± 1.1	23.7 ± 5.1	26.7 ± 6.1
Beneath Proximal Phalanx (5 <sup>th</sup> digit)	35.7 ± 1.8	35.1 ± 1.6	19.6 ± 7.2	29.0 ± 3.9
Middle Phalanx (2 <sup>nd</sup> digit)	35.4 ± 1.8	35.3 ± 1.2	21.8 ± 4.0	27.1 ± 4.2
Middle Phalanx (3 <sup>rd</sup> digit)	36.0 ± 0.9	35.5 ± 1.2	22.6 ± 4.0	27.2 ± 4.2
Middle Phalanx (4 <sup>th</sup> digit)	35.6 ± 0.9	35.0 ± 2.4	22.3 ± 3.9	27.8 ± 3.9

In order to ascertain equal starting conditions for the occluded and free blood flow states, the initial skin temperatures *prior* to contact were compared using a three-factor ANOVA. The mean of the five seconds prior to insertion into the freezer was compared for both the occluded and free blood flow conditions across both materials. This was applied to each thermocouple location from T<sub>2</sub> to T<sub>10</sub>. The results of this ANOVA are shown in table 6.5 below. The following model was used and applied to each thermocouple location.

$$\text{Initial Hand Temperature} = \text{Participant} + \text{Condition} + \text{Material}$$

The initial starting temperature of the bar was also compared for the two conditions, and it was determined that there was no significant difference in starting temperatures for the occluded and free blood flow condition (P=0.768). This data for end hand skin temperatures is analysed later using a GLM.

Table 6.5 Results of the ANOVA for initial hand temperature between conditions .

Thermocouple Placement	Variable	F ratio (F)	Sig. (p)
Beneath proximal phalanx (2 <sup>nd</sup> digit)	Participant	1.003	0.458
	Condition	2.454	0.133
	Material	0.615	0.442
Centre of abductor digiti minimi muscle	Participant	1.235	0.326
	Condition	1.864	0.186
	Material	0.204	0.656
On distal Phalanx (thumb)	Participant	3.012	0.024 *
	Condition	4.012	0.058
	Material	0.048	0.828
Above interphalangeal joint (5 <sup>th</sup> digit) *	Participant	2.763	0.032 *
	Condition	0.299	0.590
	Material	0.107	0.746
Between tendons of extensor digitorum muscle (dorsal side)	Participant	2.508	0.047 *
	Condition	5.946	0.023 *
	Material	0.247	0.624
Beneath Proximal Phalanx (5 <sup>th</sup> digit)	Participant	1.192	0.348
	Condition	0.123	0.729
	Material	0.931	0.345
Middle Phalanx (2 <sup>nd</sup> digit)	Participant	0.851	0.559
	Condition	0.458	0.506
	Material	0.107	0.747
Middle Phalanx (3 <sup>rd</sup> digit)	Participant	1.906	0.119
	Condition	1.151	0.296
	Material	1.428	0.245
Middle Phalanx (4 <sup>th</sup> digit)	Participant	1.151	0.375
	Condition	1.079	0.312
	Material	0.018	0.895

\* denotes significance  $p < 0.05$

The results of the ANOVA show that there are no significant differences ( $p < 0.05$ ) across all participants for the initial starting temperature of the hand for all conditions except for the back of the hand ( $T_6$ ) ( $p = 0.023$ ). Three of the thermocouple locations indicated a significant difference between subjects ( $P \leq 0.05$ ).

The end skin temperatures taken at 480s were compared using a three-factor ANOVA to determine whether there was a significant difference between the two conditions. The data for the end skin temperature was compared for both the occluded and free blood flow condition across both materials. This was applied to each thermocouple location from T<sub>2</sub> to T<sub>10</sub>. The results of this ANOVA are shown in table 6.6 below. Interactions were also tested for.

**Table 6.6** shows the *p* values from the ANOVA for end (480 second) hand skin temperature between conditions. Significant Values (*p*≤0.05) are shaded. All *p* values are corrected using Bonferonni. (T<sub>2</sub> = beneath proximal phalanx (2<sup>nd</sup> digit), T<sub>3</sub> = centre of abductor digiti minimi muscle, T<sub>4</sub> = on distal Phalanx (thumb), above interphalangeal joint (5<sup>th</sup> digit) \*, T<sub>5</sub> = between tendons of extensor digitorum muscle (dorsal side), T<sub>6=0</sub> beneath Proximal Phalanx (5<sup>th</sup> digit), T<sub>7</sub> = middle Phalanx (2<sup>nd</sup> digit), T<sub>8</sub> =middle Phalanx (3<sup>rd</sup> digit), T<sub>9</sub> =middle Phalanx (4<sup>th</sup> digit)

Variable and Interaction	T <sub>2</sub> (P value)	T <sub>3</sub> (p value)	T <sub>4</sub> (p value)	T <sub>5</sub> (p value)	T <sub>6</sub> (p value)	T <sub>7</sub> (p value)	T <sub>8</sub> (p value)	T <sub>9</sub> (p value)	T <sub>10</sub> (p value)
Subject	0.170	0.670	0.024	0.792	0.454	0.793	0.004	0.499	0.013
Material	0.002	0.210	0.011	0.676	0.865	0.018	0.001	0.000	0.000
Condition	0.313	0.580	0.001	0.004	0.174	0.001	0.000	0.002	0.000
Subject * Material	0.757	0.460	0.039	0.719	0.795	0.939	0.344	0.803	0.260
Condition * Subject	0.743	0.200	0.143	0.098	0.382	0.529	0.019	0.111	0.017
Condition * Material	0.662	0.035	0.590	0.480	0.628	0.356	0.911	0.721	0.830

A subject effect was found to be significant at sites T<sub>4, 8 and 10</sub>. Material was found to have a significant effect on thermocouple sites T<sub>2, 4, 7, 8, 9 and 10</sub>. Condition was found to be significant at sites T<sub>4, 5, 7, 8, 9 and 10</sub>. Significant interaction between subject and material was found at site 4. Subject and condition interaction was found to be significant at sites 8 and 10, and condition material interaction was found to be significant at site T<sub>3</sub>.

In order to study the development over time, skin temperatures at the moment of first contact (so different from pre-contact in table 6.4), 240s and 480s were analysed and compared between the occluded and free blood flow condition using a t-test, the results are displayed in table 7 below. All the data for material was pooled for this test. The results at 480 s are in essence the same as those in table 6.5). Bonferroni was used as a correction for multiple comparison, and the following sites (highlighted in yellow) were

found to show a significant difference between the two conditions (occluded and free blood flow).

**Table 6.7** shows the significance (*p* values) of any differences in skin temperatures between the occluded and free blood flow condition at first contact 240s and 480 seconds. The shaded areas denote significance. Significance is accepted at 95% level. These values are corrected using Bonferoni. (*T*<sub>2</sub> = beneath proximal phalanx (2<sup>nd</sup> digit), *T*<sub>3</sub> = centre of abductor digiti minimi muscle, *T*<sub>4</sub> = on distal Phalanx (thumb), above interphalangeal joint (5<sup>th</sup> digit) \*, *T*<sub>5</sub> = between tendons of extensor digitorum muscle (dorsal side), *T*<sub>6=0</sub> beneath Proximal Phalanx (5<sup>th</sup> digit), *T*<sub>7</sub> = middle Phalanx (2<sup>nd</sup> digit), *T*<sub>8</sub> =middle Phalanx (3<sup>rd</sup> digit), *T*<sub>9</sub> =middle Phalanx (4<sup>th</sup> digit)

Time	T <sub>2</sub>	T <sub>3</sub>	T <sub>4</sub>	T <sub>5</sub>	T <sub>6</sub>	T <sub>7</sub>	T <sub>8</sub>	T <sub>9</sub>	T <sub>10</sub>
First Contact	0.116	0.169	0.551	0.811	0.075	0.677	0.862	0.126	0.193
240	0.286	0.626	0.561	0.040	0.139	0.012	0.033	0.801	0.002
480	0.231	0.464	0.001	0.000	0.083	0.000	0.001	0.002	0.000

Significant differences between the conditions of occluded blood flow and free blood flow were found after 240s at thermocouple sites 7 and 10. These differences were still there at 480s with the addition of four more sites thermocouple 4, 5, 8 and 9.

### 6.5 Discussion

All participants completed the duration time of eight minutes. The increase in blood flow as a result of the exercise was significant and an increased blood flow state was induced as evidenced by the participant's initial starting hand temperatures. As there were no significant differences between initial hand contact temperatures, any differences observed between the conditions can be attributed to the two conditions, material and blood flow.

It was expected that in the occluded blood flow condition, end skin temperature would be lower than in the free blood flow condition. This was not always the case. In 16 out of 81 cases, when considering end hand skin temperature either the opposite effect or no effect was observed. It was also expected that when participants were gripping the nylon bar, their skin temperatures, as measured by the thermocouples, would be significantly lower than when the participants were gripping the wooden bar. Again however, out of 81 cases, 28 cases showed contact temperatures either significantly lower for wood than nylon, or no difference at all in skin temperatures between the two conditions.

The expected effect of the blood flow condition (where skin temperatures were lower in the occluded rather than free blood flow condition) could be seen in all cases after 120 seconds with the exception of  $T_2$  where it could be seen after 300 seconds and  $T_9$  where it could be seen after 240 seconds.

It was not expected that the effect of blood flow would be apparent immediately, as whilst the blood flow was stopped, the hand wasn't esanguinated prior to exposure, as this was felt to be unrepresentative of situations most likely to occur in the workplace. So the heat in the hand from the blood in the hand prior to occlusion remained and didn't immediately cool to ambient conditions. This may explain why significance was only found at two sites after 240 seconds (table 7) and showed on increasing number of sites to be significant after this time. This would indicate that if the experiment continued after the cut off time of 480s the effect of no blood flow on skin temperatures would have become increasingly apparent.

The effect of material on skin temperature (where lower skin temperatures were experienced whilst gripping the nylon bar than when gripping the wooden bar) was apparent at all sites except  $T_6$  and  $T_5$  after 60 seconds. Prior to this time there was either no difference in skin temperatures when gripping the nylon bar when compared to gripping the wooden bar, or gripping the wooden bar resulted in lower skin temperatures than when gripping the nylon bar (see table 6.7). Material was found to have a significant effect on skin temperature (with the exceptions of  $T_{5,6}$  and  $T_3$  as expected with nylon resulting in the lowest skin temperatures. Thermocouple  $T_6$  was the thermocouple measuring the skin temperature on the back of the hand, so it is logical that material did not have any effect of

skin cooling, as the skin cooling at this site would predominantly be caused by ambient air cooling, rather than cooling resulting from contact with a material. Thermocouples <sub>5</sub> and <sub>3</sub> were the thermocouples measuring the site above the interphalangeal joint (5<sup>th</sup> digit) and the centre of the abductor digiti minimi muscle respectively. Again, thermocouple <sub>5</sub> was a non-contact site so the lack of significance of effect of material found at this site was expected. The lack of significant effect of material on skin temperature at thermocouple <sub>3</sub> can also be explained by its location, as it is probable that this site did not make perfect contact with the bar and was at some time during the experiment exposed to air rather than the bar.

Digit five consistently showed the greatest effects of restricted blood flow on cooling. This was apparent in the earliest onset of an effect and with the greatest significance levels. This was also the area where the subjects reported the most amount of pain. It is hypothesised that the effects of no blood flow on cooling times of the hand were most apparent in the fifth digit for several reasons. It was expected that the digits would show any effects of restricted blood flow on cooling first, as there is minimal blood flow to the digits as capillaries rather than the main deep palmar arch supplies them. Blood upon entering the hand is initially distributed to the digits first (Netter FH 1989), so when blood flow is stopped these are the areas where differences would become apparent. The digits also have very little muscle mass and a relatively large surface area to tissue volume ratio, resulting in heat being lost quickly to the surrounding environment.

Further, the fifth digit generally has a lower heat content than the other digits due to its size, and the highest surface to mass ratio. After occlusion, the remaining blood in the fingers cools more rapidly in this digit than the others, so the effects of no circulation of blood flow are observed more quickly at this site than others.

Finally, the fifth digit has a smaller phalanx length, which enables a more 'perfect' fit around the bar. Chen (1997) described how this was related to pressure and how pressure affected cooling speeds. The more perfect fit of the fifth phalanx results in a greater proportion of surface area being exposed to the bar, facilitating faster cooling than at the other measured sites. It was also considered, that the fifth digit acted as an 'anchor' for the

hand on the bar, resulting in more pressure being applied to the bar through this digit ensuring a more 'perfect' fit when compared to the other digits.

Eventually, it would be expected that the same effect e.g. lower temperatures at all sites for the condition with no blood flow would be observed when compared to the condition with free blood flow. This could be deduced from the results with more and more sites showing significant differences the longer the hand was exposed.

## **6.6 Conclusion**

In comparison of high versus no hand blood flow, a clear difference in cooling rate of the skin was observed for the conditions used.

The difference started in digit 5 and then spread to the to other contact areas.

These results imply that in populations where the blood flow to the hand is likely to be reduced, or for conditions where 'healthy' people may be expected to experience vasoconstriction, special considerations should be made in situations where contact cooling is likely to occur, as cooling times are significantly reduced, leading to an increased risk of tissue damage.

The differences observed were for high versus no blood flow. Differences may be less for vascular patients compared to normal blood flows. This would be an area for future research.

## **7 The Effect of High and no Blood Flow on Fast Contact Cooling**

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### **7.1 Chapter Summary**

As discussed in chapter two, one can differentiate between two typical types of cooling that occur as a result of contact cooling. The first is a fast superficial cooling induced by contact with materials with a high contact coefficient (e.g. metals); the second is a slow deeper cooling typically induced by contact with a material with a low contact coefficient (plastics and wood, down to  $-20^{\circ}\text{C}$  to  $-30^{\circ}\text{C}$ ). The effects of high and no blood flow to the hand on fast contact cooling was investigated in this chapter. It was determined, that under fast cooling conditions described here, for up to five minute, there was no significant difference in either subjective sensations or end hand skin temperatures.

### **7.2 Background**

The literature relevant to the effects of high and low blood flow on contact cooling was reviewed and discussed in depth in chapter 6. The following points summarise the most salient aspects of this:

- Blood flow is the main source of heat input to the hand (Lotens 1992)
- Vasodilation of the skin blood vessels increases heat loss, Vasoconstriction decreases heat loss

- Havenith *et al.* (1995) argued that arterial occlusion has the same cooling effect as vasoconstriction of the hand as a result of exposure to the cold
- There are inter individual differences in hand skin temperatures and differences within the hand, and from finger to hand and from finger to finger (Enander *et al.* 1982, Chen *et al.* 1996, Havenith *et al.* 1992, 1995)
- An increase in body temperature results in an increase of blood flow to the hands. This in turn results in a higher hand skin temperature (Spealman 1945, Havenith 1995)

Chapter six looked at the effects of high and no blood flow (occlusion) to the hand on slow contact cooling (x to y minutes). The following effects were found:

- In the occlusion condition, end  $T_{sk}$  was significantly lower at the following sites

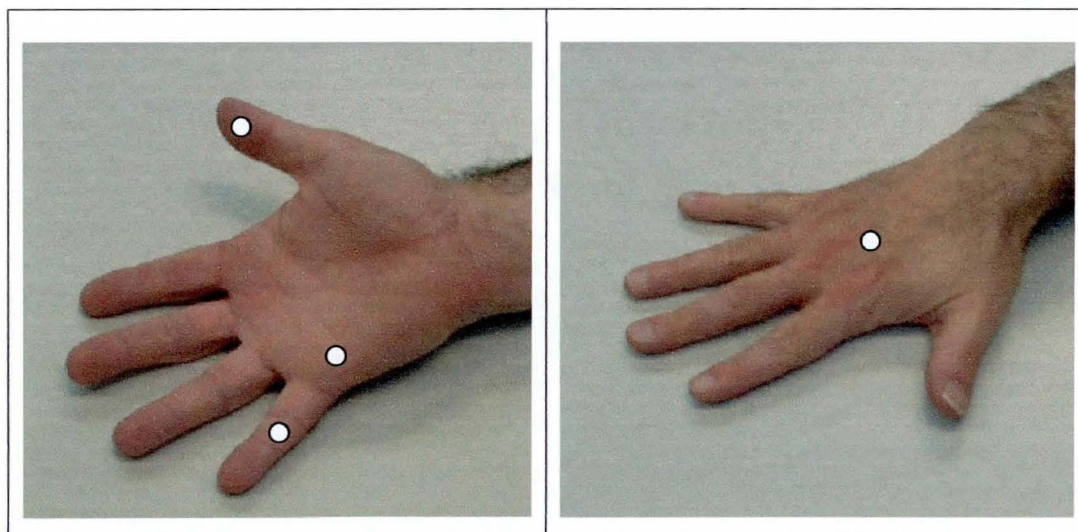
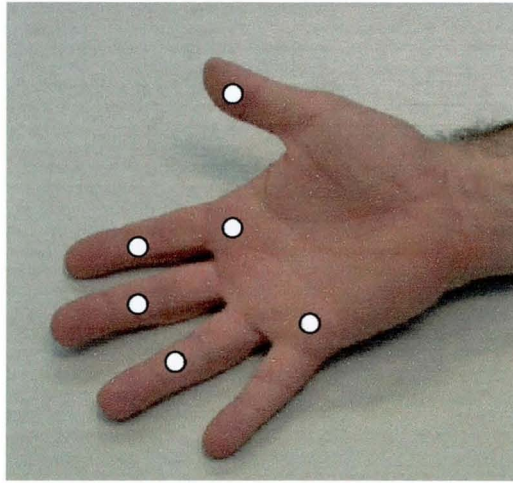


Figure 7.1. Sites at which end skin temperature was significantly lower in the occluded blood flow condition than in the free blood flow condition in the slow cooling experiment

- For both conditions, material (wood or nylon) had a significant effect on end  $T_{sk}$  at the following sites



*Figure 7.2. Sites at which material had a significant effect on end skin temperature*

- There was an increase in the number of measuring sites that had significantly lower  $T_{sk}$  in the occluded blood flow condition when compared to the free blood flow condition as duration increased.
- The most commonly reported regions of pain were at the tips of the digits, the fifth digit and the 'V' between the thumb and second digit
- There was a significantly greater incidence of pain reported in the occlusion condition when compared to the free blood flow condition and the occlusion conditions resulted in the lowest thermal sensations

Given these results for slow cooling, it is hypothesised that blood flow will also have an effect on fast contact cooling, but that the effect will be different from that experienced as a result of slow contact cooling. The reason for the difference anticipated is that during fast cooling, the cooling found is hypothesised to be at a more superficial level affecting the skin and structures immediately adjacent to it. For this reason, it is uncertain how much influence of blood flow on temperature will be seen, especially over such a relatively short duration. For this reason, this chapter shall investigate the effects of no and high blood flow on fast contact cooling and compare and contrast the findings of this study with the results of the slow cooling condition. This study shall also investigate the effect of temperature of the material on contact cooling.

**7.3 Method**

**7.3.1 Pilot Studies**

Four pilot studies were conducted. The aims of the pilot studies were to a) determine a suitable time for any differences in the two conditions occluded and not occluded to become apparent b) to determine a suitable temperatures to induce fast cooling and c) to ensure that the participants could grip the material for the desired duration without risk of tissue damage or withdrawal through intolerable pain. The methodology for the pilots was the same as that detailed in the methodology section below. Blood flow was occluded in pilots 1, 2 and 3 to induce the 'worst case scenario' in terms of duration that the participants were able to grip the bar. Pilot 4 was a free blood flow condition to observe any differences between the two conditions.

**7.3.2 Conditions for Pilot Study**

Aluminium was determined as a suitable material to induce fast cooling and a duration of five minutes was chosen as the total contact duration. These parameters were selected based on previous experimental work discussed in chapter 3. Table 7.1 shows the conditions used for the pilot studies

*Table 7.1 Pilot Conditions*

Pilot Study	Temperature	Condition
1	5 °C	Occluded
2	0°C	Occluded
3	-3°C	Occluded
4	-3°C	Free Blood Flow

**7.4 Results**

**7.4.1 Pilot Studies**

Insufficient hand skin cooling occurred in pilot study one, so it was determined that a lower Surface material temperature ( $T_{sm}$ ) would be required. Pilot study two and pilot study 3 identified skin cooling of an appropriate speed during the five minute duration. So these were the temperatures chosen for the experiment. Pilot study 4 when compared to

the results of pilot study 3 indicated a difference in hand skin temperature between the two occlusion conditions.

#### **7.4.2 Participants**

Eight male Caucasian participants were used for this study (age  $21.88 \pm 0.35$  years, height  $181.75 \pm 7.87$  cm, weight  $87.60 \pm 17.59$  Kg). All participants were asked to fill in a detailed health questionnaire and consent form. All participants had no history of peripheral vascular disease, cold injury, cold acclimatisation or fractures to their dominant arm. Participants were free to withdraw at any time for any reason.

#### **7.4.3 Procedure**

Chapter 2 discusses the following procedure in detail. Participants were asked to insert their dominant arm into the freezer and grip an aluminium bar for a duration of five minutes. The aluminium bar was counterbalanced from the outside of the freezer so it weighed 500g. The starting temperature of the bar was the same as the ambient air temperature within the freezer.

Two physical factors were controlled:  $T_{sm}$  ( $0^{\circ}\text{C}$  or  $-3^{\circ}\text{C}$ ) and blood flow (occlusion (no blood flow) or free blood flow). The factors were combined as a factorial design and the experimental conditions were counterbalanced using a Latin square to eliminate any order effects.

Prior to undertaking the experiment, each participant was exposed to a nylon bar cooled to  $-18^{\circ}\text{C}$  for five minutes to ascertain normal cooling. Each participant then completed one session per day, at the same time of day. Participants exercised as normal, but were asked to abstain from any products containing with alcohol or caffeine. Anthropometric measurements were taken at this time.

#### **7.4.4 Pre Exercise**

Participants wore shorts beneath tracksuit bottoms and a T-shirt beneath a jumper. Participants were then instrumented with a polar heart rate monitor and watch. Resting blood pressure was also measured at this time.

#### 7.4.5 Exercise

In order to ensure a good blood perfusion of the hand in the non occluded condition, body temperature was raised by exercise in both conditions. Upon attaining an aural temperature of at least  $36^{\circ}\text{C}$  participants removed their tracksuit bottoms and jumper and immediately initiated heat-exercise. Participants were asked to cycle using a cycle ergometer with a minimum load of 1Kg whilst maintaining 70rpm ( $38.8\text{Wm}^{-2}$ ). The exercise room was maintained at  $37.5^{\circ}\text{C} \pm 3.65^{\circ}\text{C}$ ,  $20\% \text{ Rh} \pm 5.34$ .  $T_a$  and  $F_c$  were monitored every 30 s and 15 seconds respectively. When the aural temperature reached  $38^{\circ}\text{C}$  or if heart rate exceeded  $220 \text{ bpm} - 20 - \text{the participant's age}$ , or if the participant no longer wished to participate participants ceased exercise and replaced the tracksuit bottoms and jumper.

#### 7.4.6 Post Exercise

Participants rested in a warm room ( $T_a = 37.5^{\circ}\text{C} \pm 3.65^{\circ}\text{C}$ ,  $\text{Rh} = 20\% \pm 5.34$ ) in front of the cold chamber, whilst blood pressure was measured and thermocouples were placed on the dominant hand. Subjective sensations were taken and then the participant entered their hand into the cold chamber and gripped the aluminium bar for five minutes. Participants verbally rated their thermal, tingling, numbness and pain sensations as they changed throughout the experiment.

$T_{sk}$  was measured using copper-constantan T-type thermocouples at five locations (see figure 7.3) on the dominant hand. Data was recorded using a data logger. Table 7.2 describes thermocouple location.

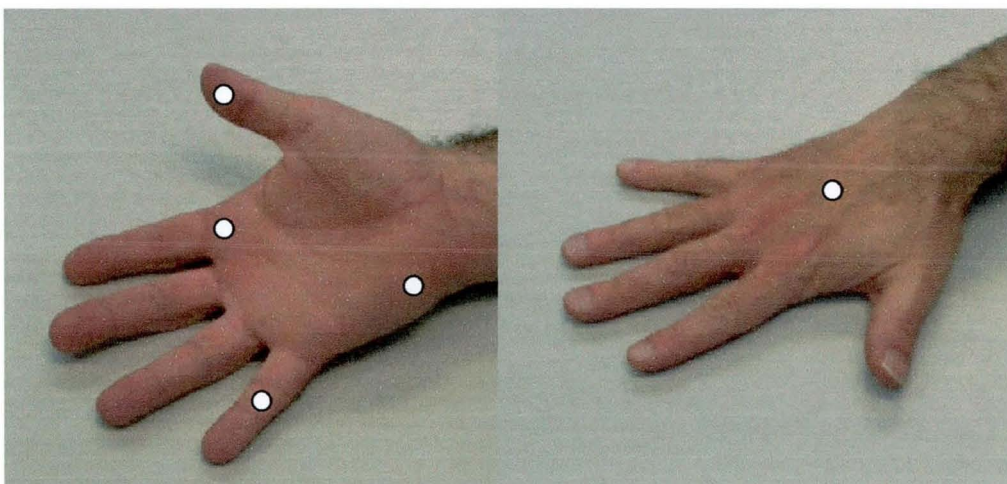


Figure 7.3. Location of thermocouples

Table 7.2. Location of the five thermocouples

Thermocouple Placement
Beneath proximal phalanx
Centre of abductor digiti minimi muscle
On distal Phalanx (thumb)
Between tendons of extensor digitorum muscle (dorsal side)
Beneath Proximal Phalanx (5 <sup>th</sup> digit)

The thermocouple wire was taped to the skin using '3M Blenderm' surgical tape.

To occlude the hand, a wrist cuff situated proximal to the condoloids on the dominant arm was inflated to 200mgHg. The participant was then asked to insert his or her hand into the freezer and grip the aluminium bar in the occluded condition. In the free blood flow condition, forearm blood flow was measured non-invasively by venous occlusion plethysmography (see chapter 2 for full methodology) on three separate occasions: pre exercise post exercise and post contact cooling.

Upon withdrawal of the hand from the cold chamber, participants remained seated for a minimum of five minutes and re-warming of the hand was monitored. Upon reaching  $T_{sk}$  of 26°C participants were de-instrumented and cooling curves analysed.

#### 7.4.7 Withdrawal Criteria

- Unwillingness of the participant to continue due to pain or other reasons
- $T_{sk} \leq 3^{\circ}\text{C}$
- Contact time exceeding five minutes

### 7.4.8 Participant Data

Table 7.3 Mean hand morphology of all the participants.

Dimension	Mean $\pm$ SD	Dimension	Mean $\pm$ SD
Surface area (mm <sup>2</sup> )	168.81 $\pm$ 15.6	4 <sup>th</sup> Digit length (mm)	74.9 $\pm$ 4.3
Contact Area (mm <sup>2</sup> )	92.56 $\pm$ 6.93	5 <sup>th</sup> Digit Length	59.3 $\pm$ 3.7
Volume (cm <sup>3</sup> )	0.46 $\pm$ 0.09	1 <sup>st</sup> Digit Length (mm)	20.5 $\pm$ 1.1
Palm Length (mm)	109 $\pm$ 5.66	2 <sup>nd</sup> Digit Width (mm)	17.4 $\pm$ 1.2
Hand Breadth (mm)	91.1 $\pm$ 6	3 <sup>rd</sup> Digit Width (mm)	17.6 $\pm$ 0.9
Thumb length (mm)	57.1 $\pm$ 15.2	4 <sup>th</sup> Digit Width (mm)	15.9 $\pm$ 0.8
Index Length (mm)	74.5 $\pm$ 5	5 <sup>th</sup> Digit Width (mm)	14.6 $\pm$ 1.1
Middle Finger Length (mm)	81.5 $\pm$ 4.5		

### 7.4.9 Blood Flow

As described in chapter 2 three of the five curves obtained from the plethysmograph were analysed and the mean for each participant in the two free blood flow conditions ( 0°C and -3°C) was obtained. A t-test was then carried out on the means pre and post exercise. Table 7.4 shows the mean blood flow for each participant in the free blood flow condition. The t-test did not reveal a significant difference between pre and post exercise periods.

Table 7.4 Mean blood flow for each participant in the free blood flow condition

Participant	Pre-exercise		Post-exercise	
	Mean	SD	Mean	SD
1	3.940	1.334	-	-
1	3.317	0.683	4.150	0.339
2	4.973	0.583	3.433	0.156
2	3.367	0.696	4.077	0.490
3	4.860	1.883	4.487	1.045
3	2.297	0.522	-	-
4	2.193	0.509	-	-
4	-	-	-	-
5	-	-	-	-
5	1.532	0.431	1.683	0.067
6	2.783	0.999	4.470	0.777
6	3.530	0.944	3.223	0.597
7	2.853	1.567	4.310	2.750
7	4.957	0.427	-	-
8	1.430	0.252	2.570	0.062
8	1.250	0.252	2.647	0.366
Mean	3.1	0.8	3.5	0.7

#### Contact Cooling

In order to determine whether starting conditions were equal for both treatments, the mean temperatures measured at all of the five measuring sites were analysed between 10 and 15 seconds prior to insertion of the hand into the freezer. A repeated measures ANOVA determined no significant differences between the initial pre- contact hand  $T_{sk}$  within subjects. It can therefore be assumed that differences apparent in skin temperature are due to the influence of material temperature and occlusion state. Table 7.5 shows the mean and SD of the initial pre-contact temperatures and end  $T_{sk}$  for all subjects across all conditions.

Table 7.5 Mean and SD of initial hand  $T_{sk}$  over all conditions pre contact and end  $T_{sk}$

Thermocouple Placement	Mean Pre-contact Hand Skin Temperature and SD	Mean End Hand Skin Temperature and SD
Beneath Proximal Phalanx (Digit 2)	$37.2 \pm 1.6$	$9.6 \pm 2.7$
Beneath Proximal Phalanx (Digit 5)	$37.0 \pm 1.4$	$24.8 \pm 9.4$
On Distal Phalanx (Thumb)	$38.2 \pm 1.6$	$14.1 \pm 5.3$
Above interphalangeal joint (Digit 5) *	$36.4 \pm 1.0$	$27.3 \pm 6.9$
Between tendons of extensor digitorum muscle (dorsal side)	$36.3 \pm 1.8$	$29.5 \pm 4.4$

\* Denotes a non contact site

Two types of cooling were observed for different parts of the hand within the fast cooling condition dependent upon whether it was a contact site or not. Figures 1 and 2 show typical cooling curves at a contact site, figures 3 and 4 show typical cooling curves at non contact sites.

Figures 4 and 5 below show the contact  $T_{sk}$  from participant 8. Condition 1 is the free blood flow condition and condition 2 shows the occluded blood flow condition. Both figures demonstrate the typical cooling patterns observed as a result of rapid contact cooling at a contact site, in this case, between the proximal phalanx and the metacarpal bone of digit 2. This type of cooling is characterised by a rapid fall in temperature followed by a slower decrease in temperature as the effects of  $T_{sm}$  and blood flow affect cooling speed.

Figure 7.4. Shows the contact  $T_{sk}$  between the proximal phalanx and metacarpal bone of digit 2. When exposed to an aluminium bar with a  $T_{sm}$  of  $0^{\circ}\text{C}$ . Figure 7.5 shows the contact  $T_{sk}$  between the proximal phalanx and metacarpal bone of digit 2 when exposed to an aluminium bar with a  $T_{sm}$  of  $-3^{\circ}\text{C}$ .

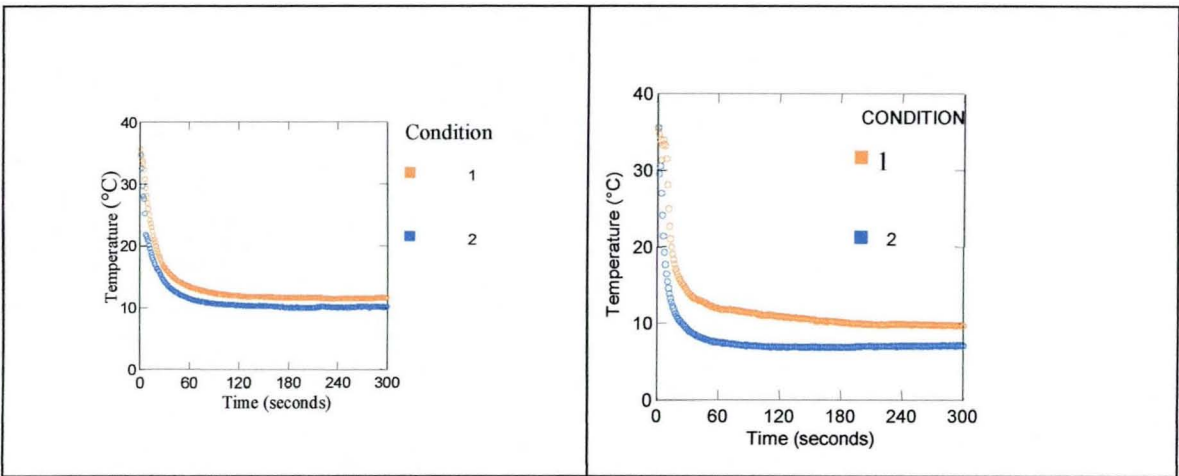


Figure 7.4. Shows the contact  $T_{sk}$  between the phalanx and metacarpal bone exposed to an aluminium bar with a  $T_{sm}$  of  $0^{\circ}\text{C}$

Figure 7.5 shows the contact  $T_{sk}$  between the proximal the proximal phalanx and metacarpal bone when exposed to an aluminium bar with a  $T_{sm}$  of  $-3^{\circ}\text{C}$

Condition 1 = free blood flow  
Condition 2 = occluded blood flow

Condition 1 = free blood flow  
Condition 2 = occluded blood flow

Large differences between individual cooling curves were observed. No incidents of CIVD were observed however, and all cooling curves followed the same pattern.

Figures 6 and 7 are examples of the type of cooling pattern that was typically observed at the non contact sites of the hand. The results are taken from participant 6 and the site is the outside of the middle phalanx of digit 5 (thermocouple 5). As can be seen, the type of cooling occurring at the non contact site, is a slower more uniform cooling without the initial rapid fall in temperature observed at the contact sites. This type of cooling occurred across all participants except when there was little or no decrease in  $T_{sk}$  as a result of exposure to the bar and ambient conditions. For both figure 7.6 and Figure 7.7, condition one is the free blood flow condition and condition two is the occlusion condition.

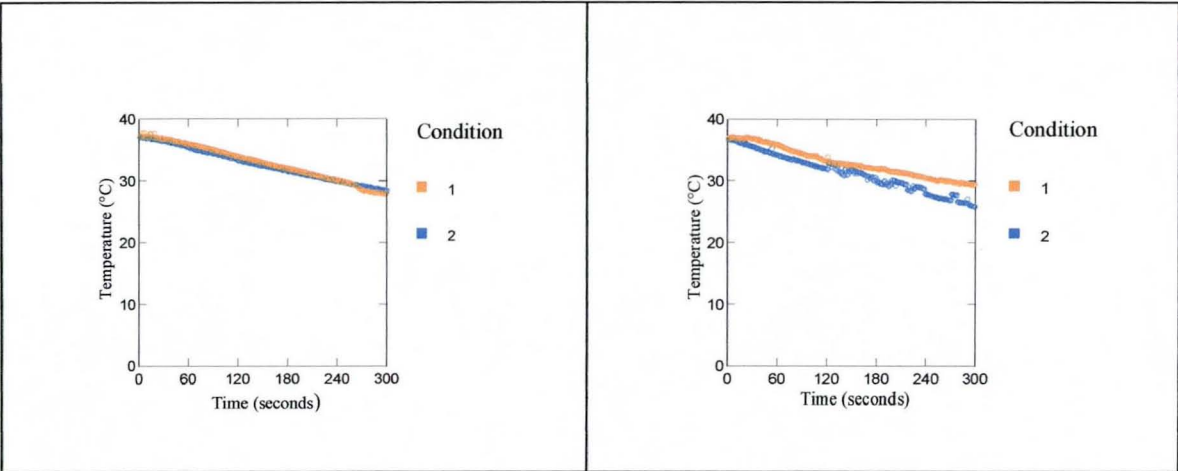


Figure 7.6. Shows the contact  $T_{sk}$  between the proximal phalanx and metacarpal bone of digit 2 when exposed to an aluminium bar with a  $T_{sm}$  of  $0^{\circ}\text{C}$

Condition 1 = free blood flow  
Condition 2 = occluded blood flow

Figure 7.7 shows the contact  $T_{sk}$  between the proximal phalanx and metacarpal bone of digit 2 when exposed to an aluminium bar with a  $T_{sm}$  of  $-3^{\circ}\text{C}$

Condition 1 = free blood flow  
Condition 2 = occluded blood flow

The two individual  $T_{sm}$  conditions were pooled for analysis as it was not anticipated that  $T_{sm}$  would significantly effect the direction of results with regards to the occluded and free blood flow conditions. The temperature at each thermocouple was identified and compared at 0, 180 and 300 seconds using a paired t-test. A Bonferroni correction was then carried out for multiple comparisons ( $0.05/3 = 0.017$ ). Table 7.6 shows the results of the t-test a value of  $p \leq 0.02$  will be accepted as significant.

Table 7.6. Significance Values for differences between the two blood flow conditions.

$T_{sk}$ Location	Significance (p-value) at first Contact	Significance (p-value) at 180 seconds	Significance (p-value) at 300 seconds
(2) Between proximal phalanx and metacarpal bone of digit 2	0.32	0.26	0.51
(3) Base of palm of hand (below digit 5)	0.002	0.003	0.002
(4) Distal Phalanx on thumb	0.27	0.32	0.94
(5) Middle Phalanx (outside digit 5)	0.52	0.65	0.65
(6) Back of hand	0.15	0.05	0.87

#### 7.4.10 Subjective Sensations

Pre contact, initial and end contact subjective sensations were analysed to determine whether there were any significant differences between the two blood flow conditions (high and no). This was done within participants and within  $T_{sm}$ . A Wilcoxon Signed

Ranks test determined that there were no significant differences between conditions for pain, numbness, tingling or thermal sensation ( $p>0.05$ ).

*Table 7.7. Shows significance values for subjective sensations from the Wilcoxon Signed Ranks Test (p values)*

Subjective Sensation	Temperature (°C)	Participant							
		1	2	3	4	5	6	7	8
Pain	0	0.32	1.00	1.00	1.00	0.32	0.32	0.32	1.00
Thermal Sensation	0	1.00	0.32	0.18	0.32	0.16	0.32	0.56	0.41
Numbness	0	1.00	1.00	1.00	0.32	1.00	0.18	0.32	1.00
Tingling	0	0.32	0.32	1.00	0.32	0.32	0.16	0.32	1.00
Pain	-3	1.00	0.32	0.32	1.00	1.00	0.32	0.32	1.00
Thermal Sensation	-3	0.66	0.32	1.00	0.32	1.00	0.66	0.16	1.00
Numbness	-3	1.00	0.32	0.32	0.32	1.00	0.66	0.32	0.32
Tingling	-3	0.32	0.32	1.00	0.32	0.32	0.66	0.32	0.32

## 7.5 Discussion

The only significant effect of blood flow was found for the contact temperature below the fifth digit on the palmar aspect off the hand table 7.6. There was no significant difference between the two conditions (occluded and not occluded) at this site prior to insertion of the hand into the freezer. However, at the initial contact with the aluminium a significant difference between the two conditions was apparent and this difference remained significant throughout the duration of the exposure. This was not expected.

In the slow cooling condition, there were no significant differences between the two conditions at first contact, but more and more sites became significant as the duration of exposure increased. It is unlikely that the effect of blood flow would be present this early in the exposure, as the hand was not esaguinated prior to exposure. This means that the blood left in the hand prior to occlusion would have had to have cooled instantaneously upon contact for the difference present between the two conditions to be due to blood flow. As it is deemed extremely unlikely that the occlusion could show an effect immediately upon contact (none was observed at that time in any of the other experiments described in the previous chapter) this finding is likely to be by chance. The question then

is whether the significant effects later in time for the same site are also due to chance, technical error or are actually real. This cannot be answered directly. A significant difference at the observed location (below digits) would fit with the expectations, as this part of the hand acts as an anchor to keep the bar suspended in the air. Therefore the pressure applied to this section of the hand would be the greatest and the fit more perfect. There would be no air pockets, so contact cooling rather than cooling by air definitely occurs. This part of the hand is indisputably in contact with the bar. Any differences observed, as a result of blood flow would therefore be more apparent here. However, as none of the other sites showed any significant effect of occlusion within the studied time period and this observed effect has some question marks to it, it must be concluded that an effect of occlusion in this fast cooling condition was not indisputably proven. On the other hand, despite showing only one significant result, the majority of  $T_{sk}$  were lower during the occluded condition than the free blood flow condition.

It is possible that a factor other than the effect of blood flow had an effect on the cooling of the hand and subsequent differences between blood flow conditions. Although most factors were controlled for it is possible for example that the introduction of the cuff at the wrist resulted in the participant introducing their hand into the freezer in a slightly different way than in the free blood flow condition where the pressure cuff was not present. This could have resulted in the participant gripping the bar using a different position than for the non occluded position resulting in significantly different temperatures as a result of different contact areas being exposed. However, if this would be the problem, the same would have been expected in the previous study.

As described in the result section, two types of cooling were observed. Sites in contact with the material experienced a rapid initial decrease in temperature followed by slower decline in temperature. This was as a result of the high thermal conductivity of the bar and subsequent rapid heat loss. The large surface area to mass ratio, in particular of the digits resulted in the highest rates of heat loss. This will obviously eventually affect manual dexterity. The sites not in contact with the material demonstrated a much slower, more uniform, cooling and  $T_{sk}$  remained relatively high compared to the  $T_{sk}$  of the contact sites. Thermocouple 2 (between the proximal phalanx and metacarpal bone of digit 2) and thermocouple 4 (distal phalanx of the thumb) registered the lowest contact temperatures. This was in agreement with the finding of Havenith *et al.* (1992) but in disagreement with

the findings of Chen (1996) who determined that the thumb  $T_{sk}$  remained high during contact with cold materials. This however is partly explained by the fact that the thumb and area of the palm leading to digit five are the areas primarily used to lift and suspend the bar, and the only area that can be said to be definitely in contact with the bar. The non contact skin temperatures rarely fell below  $30^{\circ}\text{C}$  regardless of blood flow condition. Over all, the biggest differences were observed between the contact and non-contact sites.

After the initial rapid cooling as a result of contact with the bar, cooling did not always continue.  $T_{sk}$  sometimes remained stable or even increased in temperature. This was expected however, because of the high starting temperatures of the hands. Chen (1997) determined that the extent of heat loss was dependent upon the temperature gradient. Initially the rapid drop in  $T_{sk}$  was due to the large temperature gradient between the hand and the bar, but this temperature gradient decreased and even reversed as the hand warmed the material (more noticeable in the free blood flow condition) resulting in a slower rate of heat transfer. This was also the case with the non contact sites which remained warmer; the temperature gradient and the thermal properties of air (insulating) resulted in heat being lost much more slowly than at contact sites.

It was expected that occlusion would result in lower  $T_{sk}$  in all cooling. This occasionally wasn't the case however. It is possible, that as the hand was not esaguinated prior to occlusion, that this was due to participants altering their grip on the bar, as it became too painful for them. This would subsequently result in a change in location of blood as it re-entered the areas it had previously been 'squeezed' out if under the contact area. This would subsequently increase the heat input to the hand due to re-entry of blood thereby reducing the effect of cooling. The way and amount of applying pressure between the fingers and material has been shown to have a strong effect on contact cooling (Chen F 1992). As it was not possible to measure changes in pressure they may have been subject to great variability.

All participants remained in contact with the material for the full duration of five minutes. Keating and Cannon (1960) showed a  $T_{sk}$  of approximately  $-0.6^{\circ}\text{C}$  was required for skin damage as a result of frost nip or bite. No  $T_{sk}$  went below  $3^{\circ}\text{C}$  during the course of this study, and in the main  $T_{sk}$  remained significantly higher, even in the occluded condition. It could therefore be concluded that these temperatures and durations do not pose a risk in

terms of tissue damage. However, it must be remembered that temperatures fell below critical levels in terms of effects on manual dexterity. The contact  $T_{sk}$  often fell within the range of 13-18°C, which is within the range determined to have detrimental effects on manual dexterity (Enander A 1984). Participants also experienced a significant amount of pain. Therefore the reduced  $T_{sk}$ , especially the lower  $T_{sk}$  resulting from occlusion should be considered in terms of increased pain and loss of sensation rather than frost nip /bite risks.

### **7.5.1 Subjective Sensations**

No significant differences were determined in subjective sensations between the two blood flow conditions. However, it was apparent that the occlusion condition resulted in greater pain, numbness tingling and cold sensation than in the free blood flow condition. It is possible that these subjective results are not as reliable as one may have hoped due to the pre existing level of pain, numbness and tingling experienced by the participants as a result of inflation of the occlusion cuff. Free nerve endings are the principal receptors for pain. They are activated by an inadequate supply of blood to an organ. The onset of pain was initially rapid then reached a plateau and frequently diminished. This could be explained by the strong initial stimulation of the free nerve endings, which upon adapting to the thermal environment and occlusion decreases stimulation resulting in a decrease in pain sensation.

The bulbs of Kraus are located close to the skin's surface and are the receptors for cold sensation (Van de Graaff and Fox 1995, Parsons 1993). Numbness and tingling are an indication of irritation to the nerves as a result of the nerve experiencing distress, for example, as a result of a lack of blood supply. For these reasons it is felt that subjective sensations may not have been the best indication of exactly how the participant was feeling as a result of the thermal conditions.

Once again, the most commonly reported area of pain was below the 2<sup>nd</sup> digit, and the fingertips. This was also the case in the slow cooling experiment.

### **7.5.2 Blood Flow**

It was determined to investigate the effects of blood flow after exercise in order to induce a high blood flow state. The reason that this was done was to observed the maximal effects of high blood flow compared to no blood flow. If there were any differences, they should

be observed in this condition. It would then later be possible to investigate effects of lower blood flow if deemed appropriate.

Prior to exposure to the bar in the cold chamber, all participants were asked to exercise for both conditions. This protocol was used to provoke vasodilation of the peripheral tissues. However, there was no measurable increase in blood flow between pre and post exercise. As stated earlier this was not expected but the assumption of peripheral vasodilation can be maintained due to the elevated  $T_{sk}$  and  $T_{core}$ . It is possible that there was no increase observed in peripheral blood flow post exercise for several reasons. But it is important to remember that if the assumption of high peripheral blood flow can be maintained and the fact that there were no starting differences between  $T_{sk}$  in the two conditions this means that all experimental requirements have been met regardless of whether the blood flow was raised through exercise or passive heating as this would be the same across all participants and for both conditions.

Possible reasons for lack of significant increase in peripheral blood flow when compared pre and post exercise include:

- Participants were asked to sit at rest in a warm room prior to introduction to the exercise room to stabilise their core the temperature. It is probable that participants already experienced vasodilation here as a result of the mean skin and core temperature increasing as a result of exposure to the warm environment.
- SDR Clinical technology 2001 and Hokanson (2001) state that blood flow to the hand is quite variable and for this reason the hand is usually occluded prior to measuring the blood flow in the upper limb. This was not done in this study however, as it was the blood flow to the hand that was of primary interest but could explain erroneous results.
- The venous occlusion cuff was inflated to 50mmHg for all participants despite the varying circumferences of the upper arm. It is possible that this inflation should have been customised to each participant and related to this dimension.
- Due to equipment malfunction there was a lot of missing data in this section, which reduced the available sample size. Possibly statistical significance may have been there had the correct sample size been obtained.

### 7.5.3 Fast and slow Cooling Compared

In the fast cooling condition of the present experiment, there was a trend to lower  $T_{sk}$  in the occluded condition when compared to the free blood flow condition. The logical question is would this difference have become significant if left over a greater period of time? Eventually, it is likely, given enough time that a difference would be observed between the occluded and free blood flow condition, as without heat input to the hand the hand would eventually cool to the ambient conditions of the cold chamber and bar. However, the present results, where no significant difference was determined between the two conditions, would indicate that for the duration of this test the cooling of the contact side of the hand was so superficial and quick, that it was the skin that acted as a barrier to the cold and that blood had little effect. The fact that so many of the sites in the slow cooling condition (chapter 6) showed significant differences and that the number of sites showing significant difference increased with duration would indicate that in the slower cooling condition, cooling is more deep and so relies on blood flow for warmth rather than just the insulative effect of the skin. This is partly explained by the thermal properties of the material. Aluminium conducts heat very quickly from the skin, too quickly for the hand to replenish this heat from the blood to the skin. This would result in very cold skin but the underlying tissues remaining relatively warm. Nylon and wood take the heat much more slowly from the hand. This leaves time for the outside of the skin to come to equilibrium with the underlying tissue and blood. This results in a more uniform cooling than that which occurs as a result of taking all the heat from the skin very quickly (fast cooling).

For the long term exposure condition, differences became apparent after 300s, with more sites becoming significant after this time. It is possible, that had the fast cooling condition exceeded 300s, that differences would have become apparent in this condition also. However, in this condition, people would have released the material after this duration because of pain levels experienced. The level of pain experienced at this level would have induced a high rate of withdrawals from participants after 300s, so was not practical to analyse.

As stated previously, in the fast cooling condition, the warmest sites were the non contact sites. These sites were significantly warmer than the contact sites. However, in the slow cooling condition, whilst the contact sites were warmer than the non contact sites, the non

contact temperature was much closer to the contact temperatures than in the fast cooling condition (due to lower ambient air temperature and a longer duration of exposure). The back of the hand (main non contact site) was one of the few sites not to show a significant difference between the occluded and non occluded condition in the slow cooling condition. Whilst it would be reasonable to assume that the contact sites will reach lower temperatures than the sites exposed to air as a result of the thermal properties of the materials, a second contributory explanation is possible, which would also explain the lack of significance between the two conditions (occluded and free blood flow) in the fast cooling condition.

It is possible that there is a local effect on vasodilation and vasoconstriction. The palmar aspect of the hand exposed to the bar is cooling very quickly. As a result of this vasoconstriction occurs in an attempt to conserve heat. However, on the dorsal aspect of the hand, which is exposed to the ambient air temperature, vasodilation is still occurring as this aspect of the hand tries to rid itself of excess heat.

The following equation taken from Havenith (1997) shows how this may be possible:

$$\text{Vasoconstriction} = \underbrace{\{A (36.5 - T_{\text{core}}) + B (33.7 - \bar{T}_{\text{sk}})\}}_{\text{Part 1}} * 2.0 \underbrace{(33.7 - T_{\text{sk local}})}_{\text{Part 2}}$$

Part 1 shows the central effects of the body on vasoconstriction. Part 2 shows the local effects on Vasoconstriction.

What appears to be happening in the contact cooling is that the body core and mean skin (part 1) are warm, so the central signal indicates vasodilation. Part 2 of the equation, the local skin effect, then has the strongest effect on vasoconstriction. This effectively results in the dorsal aspect of the hand remaining vasodilated whilst exposed to ambient conditions as a result of both the high T<sub>core</sub> and elevated peripheral blood flow, whilst the palmar aspect of the hand becomes vasoconstricted in response to the contact with the material.

Figure 7.9 shows graphically what happens at each aspect of the hand under each cooling condition. Eventually, if there is no intervention the hand will equilibrate and become a stable temperature throughout. Certainly in the occlusion condition this will occur and eventually the hand will reach the same temperature as the bar and material.

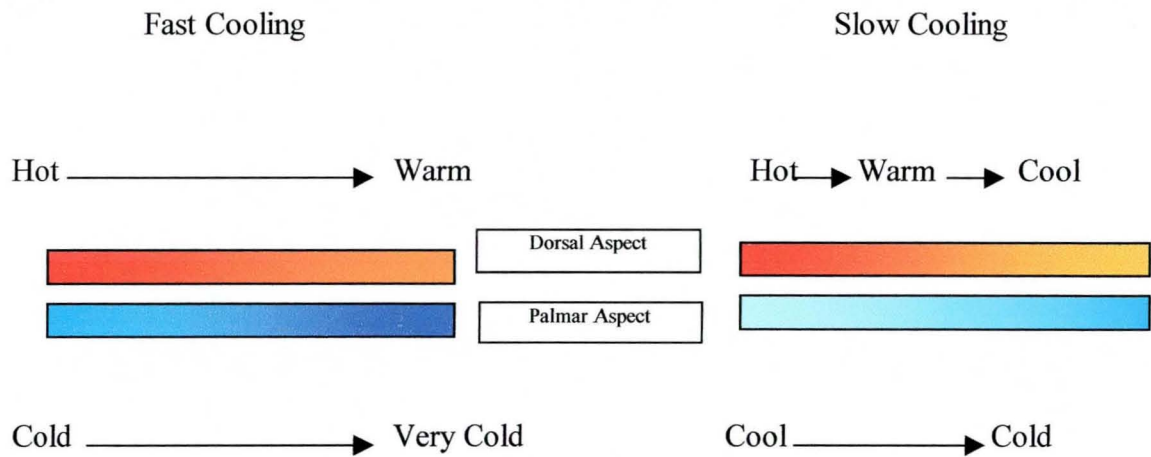


Figure 7.9. Cooling on the contact and non contact side as a result fast and slow contact cooling

Figure 7.9 show what is thought to be happening in the two conditions. In the fast cooling condition, it is thought that the non contact aspect of the hand (dorsal aspect) starts off hot as a result of increased peripheral blood perfusion due to exercise, the contact aspect (palmar aspect) starts to cool immediately upon contact with the material. The dorsal aspect (exposed to air) remain relatively warm throughout the duration of exposure (5 minutes at  $0^{\circ}\text{C}$  or  $-3^{\circ}\text{C}$ ) The contact aspect of the hand quickly cools further to reach 'very cold'. This is different to what happens with the two aspects of the hand during slow cooling. Again, the dorsal aspect of the hand is hot due to exercise when it is introduced into the cold environment, this aspect however, cools to a greater degree than the same aspect in the fast cooling condition, as it is exposed to a colder ambient air for a longer duration. The palmar aspect of the hand in the slow cooling condition however, does not cool to the same degree as the palmar aspect in the fast cooling condition. Instead, it cools on initial contact and then due to the insulative properties of the material, either remains at that temperature after a short period of time or begins to warm up. Obviously, if blood flow is still stopped, this will eventually cool to ambient air temperatures.

## 7.6 Conclusions

- For fast cooling, up to five minutes, the hand blood flow level did not show a clear effect on the decay speed of hand temperature for the conditions investigated.

- No differences in subjective sensations between the occluded and non occluded conditions were observed, though the reliability of the subjective responses during occlusion may be doubted.
- The temperature profiles of contact and non contact areas and their differences between slow and fast cooling suggest that vasoconstriction in the conditions used may be very local to the ventral side of the hand.
- No occurrence of CIVD was observed in these fast cooling conditions.

## **8 Comparison of Blood Flow to the Dominant and Non Dominant Hand**

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### **8.1 Chapter Summary**

Blood flow has been shown to have a significant effect on end skin temperature after slow contact cooling. For this reason it was decided to investigate whether there are any differences in blood flow to the dominant and non dominant hand. It was determined that in the population investigated, there was no difference between resting blood flow values in the dominant and non dominant hands.

### **8.2 Background**

Chapter 6 showed that blood flow has a significant effect on contact cooling during slow cooling. Although this wasn't apparent during fast cooling, it was thought that any differences between blood flow in the dominant and non dominant hand should be investigated to ensure that the European Standard, which was developed using data from the dominant hand, would cover both hands. Due to the effect of blood flow on contact cooling during slow cooling, any differences in blood flow between the dominant and non dominant hand could have a significant impact on the standard.

Generally speaking, a difference between the size of the dominant and non-dominant hand and forearm can be observed. As the dominant hand is generally larger (Jay 2000) it could be expected that heat would be lost more quickly from this hand than from the smaller

non-dominant hand as a result of contact cooling due to the increased surface area. Although the cooling speed of the dominant and non dominant hand have not been analysed and compared in this thesis no significant differences were found in thermal sensation, numbness tingling or pain sensation (chapter 5) between the two hands, and no significant differences in manual dexterity deficits were found. If the heat was lost more quickly from the dominant hand than the non dominant hand as a result of increased surface area, it could be expected that this would be indicated in effects on manual dexterity and subjective sensations. It was thought that apart from the difference in contact area this difference in size might mean that there is higher blood flow (and thus higher heat input) to the dominant arm and hand to maintain the higher muscle mass (mainly in the forearm). It was anticipated that the latter would lead to slower cooling and so less cold sensation. In order to study this, an experiment was devised to determine whether or not there is a difference in blood flow between the dominant and non dominant hand, the hypothesis being that there will be increased blood flow and thus also higher heat input to the dominant hand.

### **8.2.1 Functions of Blood**

Blood has several functions including gas exchange, thermoregulation and transportation of waste. It is necessary for the gas exchange that occurs in the lungs and transports the oxygen throughout the body. It also circulates nourishment and transports water and waste to the kidneys. Blood also aids thermoregulation of the body. Thermoregulation occurs via vasoconstriction (reducing heat loss) or vasodilation (increasing heat loss), closing and opening perfusion of the skin. In addition it operates using a counter current heat exchange system, further enabling an additional reduction in heat loss. It transports heat from the core of the body to the skin surface. The amount of heat lost is controlled by the autonomic regulation of skin blood flow.

### **8.2.2 Blood Flow to the Hand**

The deep palmar arch and superficial palmar arch supply blood to the hands and fingers. The proper digital arteries supply blood to digit 5 (little finger), and the four common digital arteries lead off from the superficial palmar arch, which receives most of its blood from the radial artery. The four common digital arteries also receive a common interosseous artery, which bifurcates into the phalangeal arteries, which run alongside the digits (see figures 4 and 5 in chapter 1.).

### 8.2.3 Physiology of the Hand in the Cold

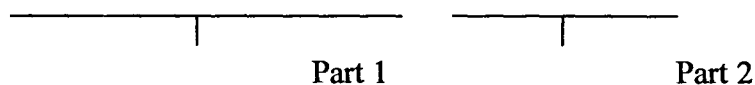
During vasoconstriction, blood flow to the hands can be reduced by as much as 90% when compared to that at normal ambient conditions (Gordon 1974).

In part, the vasoconstrictive responses of the extremities under cold conditions are as a result of the way in which arterial blood returns through the venous system. To prevent excessive heat loss from the core, counter current blood flow, and thus heat exchange occurs between the central arteries and veins (warm arterial blood entering the limb is cooled by returning cooler venous blood). This results in a decreased local  $T_{sk}$  and conservation of heat maintaining core temperature. To this end, arterio-venous anastomoses (AVAs), short vessels with muscular walls joining an artery to a vein, richly innervated with sympathetic nerve fibres, achieve effective blood flow control. During cold exposure, AVA's close as a result of increased sympathetic activity. This reduces blood flow and subsequently the heat input to the hand. Remaining blood flow then returns to the body core via deep veins in close proximity to the arteries. In summary, heat input to the hand is reduced as a result of reduced blood flow and of counter-current heat exchange between arteries and veins (Raman and Roberts 1989). Open AVAs have the opposite effect. The precapillary sphincters together with metarterioles relax and can increase blood flow, by up to seven times, resulting in the blood effectively taking a short cut to the capillary bed. The heat is thus transferred via convection from the deeper organs to the skin, which results in an increased local skin temperature.

The high surface area per unit mass of the fingers results in effective heat loss as a result of blood flow.

The regulation of blood flow to the extremities at low ambient temperatures is primarily determined by the thermal state of the body as a whole. The following equation taken from Havenith (1997) shows how this may be described.

$$\text{Vasoconstriction} = \{A (36.5 - T_{\text{core}}) + B (33.7 - \overline{T_{sk}})\} * 2.0^{(33.7 - T_{sk \text{ local}})}$$



Part 1 shows the central effects of the body on vasoconstriction. Part 2 shows the local effects on vasoconstriction.

However, Chapter 7 indicated that for short term cooling it would appear that Part 2 of the equation has the strongest effect on vasoconstriction. This may effectively results in the dorsal aspect of the hand remaining vasodilated whilst exposed to ambient conditions as a result of both the high T<sub>core</sub> and elevated peripheral blood flow, whilst the palmar aspect of the hand becomes vasoconstricted in response to the contact with the material. For slow cooling however, part one of the equation remains the strongest influence. Rapaport *et al.* (1949) determined that when exposing the hands only to a cold environment that blood flow levels and skin temperature remained high because of the overall thermal state of the body. However, when the body is cooled, vasoconstriction of the hands is evident.

Parsons (1993) stated that blood perfusion and the rate of blood flow has a significant influence on heat transfer. There are many factors that can affect blood flow, including factors specific to the hand. These can include Raynaud's disease, vibration white finger or even something as simple as tight clothing at the wrist. Exercise has also been shown to directly affect blood flow to the body and in particular the hand. Evidence is prevalent on the effect of blood flow on the hand (Havenith 1992, 1995, Enander 1982, Spealman 1945).

Blood flow is the main source of heat input to the hand. This is because there is relatively little muscle in the hand resulting in it being unable to produce large amounts of heat for itself. The amount of heat can be calculated from the following equation taken from Havenith (1992):

$$\text{Hand blood flow} * \text{Heat capacity of blood} \Delta T * \text{Hand volume}$$

The metabolic activity of tissue is related to the amount of blood flowing through a unit mass of tissue in a unit of time.

### **8.3 Methods of Blood Flow Measurement**

There are several reasons why the ability to measure blood flow is important. The measurement of blood flow can give an indication of vascular problems, for example deep vein thrombosis and heart disease. It can also give an indication of the rate of healing after an amputation, or give an indication of skin condition in a patient with severe burns, skin

grafts or ulcers. It is also a useful tool when studying thermoregulation. However, there is no universally accepted method of measuring the flow of blood, although there are several techniques to measure blood flow, which fall into two categories; these are invasive and non-invasive techniques.

### **8.3.1 Invasive techniques**

There are several techniques used for measuring blood flow that would come under the heading of 'invasive techniques'. Intravascular velocity transducers are one method commonly used, and are inserted by surgery into the large arteries. The transducers measure the rate of blood flow or temperature change. This method of measuring blood flow is generally reserved for central body measurements.

The injection of radioactive indicators (e.g. Xenon) is a second invasive method used for determining the rate of blood flow. Xenon is injected into the blood stream, and the rate of clearance or distribution through the body is monitored to give an indication of blood flow.

It was decided that the invasive techniques available were unsuitable for use in this study, both because of the level of skill required to administer the method, and in terms of the demand placed on the participant. For these reasons it was decided to investigate non-invasive techniques.

### **8.3.2 Non-Invasive techniques**

Again, there are several methods available to measure blood flow, which are classed as non-invasive. Whilst investigating the extent of autonomic control of blood flow of the hands and feet, Rapaport *et al.* (1949), measured blood flow by monitoring *skin temperature*. This was found to be effective due to their linear relationship. Limitations of this method however, are extensive. The linear relationship between blood flow and skin temperature only exists up to temperatures of between 32°C and 34°C. It has also been determined (Foster *et al.* 1946; Cooper *et al.* 1949; Fletcher *et al.* 1949), that there is a significant lag effect between the change in blood flow and skin temperature. A subsequent lack of accuracy has been reported.

*Venous occlusion plethysmography* involves occluding the venous outflow of blood whilst not affecting the rate of arterial inflow by inflating the venous occlusion cuff above the

elbow to a pressure of 50- 60mm/Hg. It has previously been determined that a pressure of 50- 60mm/Hg is sufficient to close the veins, but not the arteries. As the blood flows into the arm, through the arteries, it is unable to escape via the veins. This causes the limb to swell. The rate of swelling is a measure of the arterial inflow at that time. The swelling is sensed by a mercury in silastic strain gauge. An assumption that blood flow will be equal throughout the limb is made, so it is also assumed that the volume flow rate is equal throughout the limb volume. This method of measurement allows the results to be compared to other results obtained regardless of a participant's size. This methodology has been used extensively in the past.

*Gravimetric plethysmography*, measures blood flow by measuring the mass increase in a limb as a result of venous occlusion and no arterial occlusion (blood can flow into the arm but can not leave resulting in a net gain). *Photo plethysmography* measures the reflection of infrared light from the skin and subcutaneous tissue. The equipment for this method however is expensive and offers no real advantage over venous occlusion plethysmography for this study.

The use of a *laser Doppler* technique to measure blood flow is also relatively common. Johnson *et al.* (1984) compared laser Doppler velocimetry with plethysmography and found a very high correlation between the two. The main advantage of laser-doppler velocimetry over plethysmography would appear to be that the laser Doppler method also allows measurements at sites not accessible with plethysmography. It also provides a method for continuous measurement. However, the equipment is very expensive and should be evaluated in terms of its required application as it can only measure the blood flow in arteries and venules within 2mm of the skin surface. In addition laser Doppler blood flow measurements are on a relative scale (%) and do not provide absolute blood flow values. Therefore it is difficult to compare different locations.

For this study, it was decided that strain gauge plethysmography was the most suitable measurement of blood flow to use. This decision was based on comfort for participants; time taken to complete the measurement, validity providing an absolute blood flow value and the fact that no specialist training was required to operate the system.

# 8.4 Methods

## 8.4.1 Participants

Ten participants were used for this study, five males and five females.

Table 8.1. Shows Participant Characteristics

Subject	Sex	Age	Height	Weight	Volume of Hand		Palm Length		Palm Width		Third Phalanx Length		Third Phalanx Width	
					R	L	R	L	R	L	R	L	R	L
1	M	27	183	88.7	331	329	10.1	10.1	8.4	8.1	7.6	7.8	2	1.9
2	F	31	171	77.5	312	319	10.7	10.5	8.3	7.8	8.2	7.9	1.9	1.9
3	F	22	170	73	276	269	10.1	10.1	7.9	7.6	7.5	7.8	1.8	1.7
4	F	21	169	65	301	291	9.7	9.6	7.6	7.4	7.6	7.5	1.8	1.7
5	F	21	162	60.5	290	277	9.2	9	8	8	6.7	7.1	1.7	1.7
6	M	25	185	80.4	394	388	11	10.6	8.7	8.7	8.7	8.6	2	2
7	F	23	169	58.3	297	293	11	10.7	8	7.9	7.9	8	1.8	1.7
8	M	22	188	84.7	392	389	11	10.9	8.7	8.7	8.8	8.7	1.9	1.9
9	M	25	179.5	74.8	315	319	10.8	10.9	8.2	8.1	8.3	8.5	1.8	1.7
10	M	23	180	80.3	389	384	10.9	10.7	8.8	8.7	8.5	8.4	2	1.9
Mean		24	175.7	74.3	330	326	10.5	10.3	8.3	8.1	8	8.0	1.9	1.8

## 8.4.2 Design

A within participants repeated measures design was used. All experiments were conducted at the same time of day for each participant, and all participants were asked to eat and drink similarly on each day of the experimentation, to avoid effects of circadian rhythm, or differences in blood flow resulting from eating or exercising. All participants were also asked to abstain from alcohol, caffeine drinks and smoking for twenty-four hours prior to the experiment. Participants were also screened for any circulatory problems or other illnesses/diseases/disorders (e.g. Raynaud's) which might affect peripheral circulation.

It was expected that the cyclic variations that occur in blood flow over periods of about one minute to tens of minutes could be avoided by repeating the measurement over four sessions and by balancing (using a Latin Square) the order of exposure of the dominant or non dominant hand. Therefore any differences observed between the two limbs would be a result of differences that occur naturally between the dominant and non-dominant limbs.

### 8.4.3 Plethysmography

When venous occlusion plethysmography is used to determine forearm skin blood flow normally the hand is fully occluded during the measurement. Generally speaking, blood flow to the hand is quite variable as it is controlled by both thermal and mental influences. So that it is usually cut off by the application of a second cuff during measurement. However, for this study it was decided not to do this, as it was the flow of blood to the hand that was of specific interest. It was expected that as the participant was at rest and thermally neutral, and because the readings were taken immediately after each other and always at the same time of day, the variability between blood flow in the hands due to factors such as vasoconstriction or vasodilation would not be apparent.

The participant entered the room, sat on a stool and rested for five minutes to minimise the effect of blood flow that might occur from walking to the lab. The participant was then asked to rate his/her thermal sensation. The participant then placed the specified arm into a loop of padded rope so that the arm was supported at the wrist and kept at heart level; the padding on the rope ensured the participant's comfort and also increased the surface area in contact with the participant's arm so that the pressure of the arm was distributed over a larger area and therefore decreased. The largest diameter of the participant's forearm was then measured (cm), and a strain gauge was selected which would stretch about two cm when applied. The strain gauge was applied by bringing the loop (of the gauge) around the diameter of the limb and then securing it by fitting the loop into a groove in the end piece. It was ensured that the loop of the strain gauge was applied so that it was parallel, but not touching. The gauge was then secured by placing a piece of tape over the end piece of the gauge ensuring that the tape was not in contact with the mercury part of the equipment. A rapid cuff inflator was required in order to have a clear starting point in the subsequent data. The cuff was required to fully inflate in <0.5 seconds to a pressure of 50-70 mmHg. A workbench programme had previously been designed with a module to trigger valves on a solenoid unit, which ensured that the cuff inflated within the specified time and to the specified pressure automatically. During this period of time, the participant was asked to refrain from moving and talking, as the test is very sensitive to movement. The data was recorded using a workbench for PC programme. Data points were recorded every second. Before the inflation of the cuff, a five second warning was displayed on the screen to alert the participant and experimenter that venous occlusion was about to occur. At this point,

the balance switch was pressed. This returned the tracing to its baseline position (necessary as it is not possible to keep the participant completely still between readings). A calibration spike equal to 1% (blood flow) was made immediately before and after the inflation/deflation of the cuff, as this was required for analysis later on.

Even though the participants were asked not to move or talk, sometimes they fidgeted without realising it, and as the equipment is so sensitive, even moving from a slouch to sitting straight will affect the reading. For this reason, the participants were allowed minor movements between the test periods to ensure they could stay as still as possible for the actual test. This procedure was repeated measuring the blood flow in the remaining arm.

Five curves, which represented blood flow, were produced. The 'best' three curves from these five were then selected. The 'best' curves are indicative of the test periods where the participant did not move or talk.

The curves selected were enlarged and printed separately. A straight edge tangent was then applied by eye to the curve after the initial inflation period of the cuff. Typically, this was the second shallower gradient of the slope on the graph after the sharp gradient immediately apparent after the initial inflation. The first part of the curve is as a result of the cuff artefact where blood is pushed back down the arm because of the rapid inflation of the cuff. Through practise, it was possible to determine the part of the curve to be analysed with relative consistency. The slope of the line was then determined by calculating the change in volume per unit time, using the 1% calibration value obtained by the 1% calibration spike previously described. This then gave the % volume change per minute; equivalent to cc's of flow per 100 ccs of tissue per minute. A typical resting value would be in the region of 1% to 3%/min.

## **8.5 Results**

### **8.5.1 Heat Input**

Average heat input to the hand from blood flow was estimated for the ten participants involved in this study. The calculation below shows the calculation for the right hand of each participant.

$$\text{Heat Input} = \text{Blood flow} * \text{Heat capacity of blood} * T * (T_{\text{blood arterial inflow}} - T_{\text{blood venous outflow}})$$

Where:

Hand Blood flow = plethysmograph value (ml/100ml/min) \* hand volume

Average blood flow = 3.7ml/100ml tissue/minute, Heat capacity of blood = 3.65 J/ml°C,

Average hand Volume = 330ml, Temperature in = approx. 37°C and Temperature out = approx. 17°C

$$\text{Heat Input} = [3.7 \text{ ml/100ml/min} * 330 \text{ ml}] * 3.65 \text{ J/g°C} * [37-17°C]$$

$$\text{Heat Input} = 12.2 \text{ ml/minute} * 3.65 \text{ J} * 20 = 891 \text{ J/Minute} = 14.8 \text{ Watt/Hand}$$

Using the same calculations, the heat input to the left hand was 14.7 Watt/Hand.

### 8.5.2 Dominant Non Dominant Hand

It was determined that there was a skewed distribution of the blood flow. Therefore a non-parametric test was used. Because the data is related, and there are only two samples, it was decided that a Wilcoxin signed rank test would be used. The Wilcoxin signed rank test showed that there was no significant difference between blood flow in the dominant and non-dominant hand. Given the shape of the distribution, performing a transformation on the data was considered, but as discussed previously, a realistic value for resting blood flow would be between 1% and 3% (Hokanson Strain Gauge and Photo Plethysmograph Manual).

It was decided that values over 5% should be treated as outliers. These were removed, and a second analysis was then performed on the data.

The removal of the outliers meant that the data became normally distributed. As the data was interval and related, and all the parametric assumptions were satisfied, it was decided that a repeated measures ANOVA should be used. As can be seen from the ANOVA below, no significant difference in blood flow was observed between the dominant and non-dominant hand.

The following general linear model was used:

```
>model = blood flow = constant + hand + subject + hand* subject
```

Analysis of Variance

Source	Sum-of-Squares	df	Mean-Square	F-ratio	P
HAND	10.004	1	10.004	0.010	0.922
SUBJECT	90248.521	9	10027.613	9.623	0.000
HAND*SUBJECT	16316.454	9	1812.939	1.7400.081	
Error	229253.417	220	1042.061		

Least Squares Means

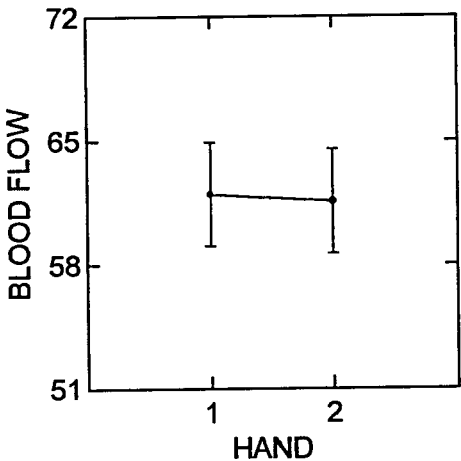


Figure 8.1. Shows the Least Squares Means of the blood flow in Hand 1 (right hand) and Hand 2 (Left Hand)v

## 8.6 Discussion

The amount of heat input to the hand from these ten subjects was relatively low at 14.8 watt/hand, when compared to the maximal effect of blood flow to the hand on heat input which could be estimated at around 49 watt/hand. This was to be expected however, as participants reported a mean thermal sensation of 0 (neutral) prior to the blood flow measurement being taken. As a matter of fact, actual heat input may have been lower than this as counter current heat exchange would reduce the temperature difference between arterial and venous blood.

No significant difference between the amount of blood flow in the dominant arm and non-dominant arm was found. This means that any differences observed between the dominant and non dominant hand in terms of cooling speed and pain sensations are likely to be attributable to other factors, for example hand size or other anatomical or physiological differences. There was however, as expected a significant effect of subject.

It could be possible that experimental noise had a part to play in the lack of significance between the two arms. It could be that the participants did not sit at rest long enough to fully eliminate any effects on blood flow from the walk to the lab or the hot weather. Objective measurements of skin temperature were not taken, but the participant was asked to rate his or her thermal sensation (mean value 0), so it is possible that whilst the participant perceived him or her self to be thermally neutral, they were in fact under thermal strain. Although a pilot study indicated that a five minute rest period slowed the blood flow, it could be that this was not a long enough period.

The method of analysis for this procedure is, in my opinion open to interpretation. Whilst it is stated (Hokanson Strain Gauge and Photo Plethysmograph Manual) that with practise consistent results are achievable, it is not possible using this method to always select the same part of the curve on each curve for analysis. A computer programme or taking the reading after a specified amount of time until a further specified period of time would remove the arbitrariness of this procedure.

It is also possible that there is a difference in blood flow between the dominant and non dominant hand, but that this difference is only apparent during or immediately after exercise, when increased blood flow is required to sustain the muscles.

Given that differences in size between the dominant and non dominant hand have been well documented (Jay 2000), it was unexpected that this sample should have no significant difference between their dominant and non dominant hand in terms of volume ( $p = 0.069$ ). It is anticipated, that had the dominant hand a significantly larger volume, that there would be a significantly increased heat input to the hand. However, it is possible, that this increased heat input to the hand would be negated by the increased surface area of the dominant hand in contact with the cold material when compared to the non dominant hand. The greater surface area exposed would be subject to greater contact cooling. Further experimentation may need to be conducted examining the effects of significantly different volumes occurring as a result of hand dominance on blood flow.

## **8.7 Conclusions**

No significant difference between blood flow to the dominant and non dominant arm as measured by forearm venous occlusion plethysmography were observed.

As hand sizes were not significantly different for the dominant and non dominant hand, also no difference in heat input (blood flow \* volume) was present between the dominant and non dominant hand.

For people with larger dominant hands, heat input may be larger than for the non dominant hand, but it is expected that this is compensated for by the higher contact area.

Therefore there are no implications for the European Standard in terms of setting different limits for each hand at this time.

## **9 Conclusions and Recommendations for Future Work**

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### **9.1 Chapter Summary**

This chapter provides a review of the main findings of this thesis. It also proposes several areas that may be considered for future research.

### **9.2 Background**

The original starting point for this thesis was for the derivation of data for the European Research Project SMT4-CT97-2149. Although this was done in the experiment described in chapter 3, a different slant was taken on the analysis of results, focusing more on the effects of manual dexterity than on time to reach critical temperatures. From this point on, the thesis became focused on the effects of contact cooling on manual dexterity and the effects of blood flow on contact cooling.

### **9.3 Conclusions**

The following conclusions were reached within the constraints of the climates, materials and subject groups tested:

- 1) When considering manual dexterity deficits as a result of contact cooling, when contact with a material with a high contact coefficient is made at temperatures

below 0°C (fast cooling), tissue damage could result before manual dexterity becomes severely affected.

- 2) When full hand contact is made with a cold material with a low contact coefficient (e.g.-nylon at temperatures below -20°C; slow cooling), severe decreases in dexterity will occur before tissue damage is experienced.
- 3) When considering the aspects of manual dexterity most affected as a result of contact cooling, it was determined, that fine motor tasks and strength tasks were most affected. It is thought this is a result of changes in synovial fluid viscosity, muscle strength and nerve conduction velocity.
- 4) Speed and Strength tests were found to highlight deficits occurring as a result of full hand contact cooling, for both the fast and slow contact cooling conditions.
- 5) For the participant group studied there are no significant differences in manual dexterity decrements between the dominant and non dominant hand as a result of fast or slow contact cooling except for strength in the slow cooling condition.
- 6) There are no significant differences, in terms of subjective sensations of pain, numbness tingling and thermal sensation experienced, as a result of full hand contact cooling, between the dominant and non dominant hand for either slow or fast cooling.
- 7) Therefore, the European Standard, which was derived from data based on the dominant hand, is suitable to protect the intended population.
- 8) The difference in hand skin temperature as a result of the occlusion of blood flow compared to a high blood flow state was first apparent in digit 5 (little finger) and then spread to the to other contact areas.
- 9) These results imply that in populations where the blood flow to the hand is likely to be reduced, and in populations where vasoconstriction is likely to occur (thereby

reducing bloodflow) special considerations should be made in situations where contact cooling is likely to occur, as cooling times are significantly reduced, leading to an increased risk of tissue damage.

- 10) The differences observed were for high versus no blood flow. Differences may be less for vascular patients compared to normal blood flows. This would be an area for future research.
- 11) For fast cooling (up to five minutes in duration) the hand blood flow level did not show a significant effect on the decay speed of hand temperature for the conditions used (stainless steel and aluminium at 0 and -3). It is likely this is because of the quick superficial nature of contact cooling that occurs as a result of contact with a material of a high contact coefficient at temperature at 0°C and below.
- 12) No differences in subjective sensations (thermal, numbness, tingling or pain) between the occluded and not occluded condition were observed in fast cooling, although reliability of subjective sensations during occlusion may be doubted.
- 13) The temperature profiles of contact and non contact areas and their differences between slow and fast cooling, suggest that vasoconstriction in the conditions used, may be very local to the ventral side of the hand.
- 14) No occurrence of CIVD was observed in the fast cooling conditions detailed in Chapter 7.
- 15) No significant difference between the resting blood flow in the dominant and non dominant hand as measured by venous occlusion plethysmography was observed.
- 16) As hand sizes and skin blood flows were not significantly different for the dominant and non dominant hand in the experimental population, there was consequently no difference in heat input (blood flow \*hand volume) to the dominant and non dominant hand. For people with larger dominant hands, heat input may be larger

than for the non dominant hand, but it is expected, that this is compensated for by the higher contact area.

#### **9.4 Future Research**

The findings detailed in the previous chapters give rise to further issues, that could be investigated. Some of these areas are detailed below and their ergonomic implications assessed.

Blood flow was found to have an effect on slow contact cooling and significantly reduced cooling times as a result of occlusion. Further to this, the effect of contact pressure of the whole hand in contact with the bar could be investigated. Jay (2000) showed that pressure was a factor in the contact cooling time of the index finger pad and speculated that reduced cooling times were as a result of the blood being pushed out of the finger pad through pressure. The effects of whole hand pressure as a result of holding and lifting a material in the air has not been investigated and would be of ergonomic interest, as it has the potential to directly affect the safety of manual workers and therefore has implications for the standard proposed by research group SMT4-CT97-2149.

Further the dominant - non dominant hand comparison did not include groups who perform heavy manual labour with associated callus formation. This may affect dominant-non dominant hand differences.

The effects of age were not addressed in these studies. The population investigated on the whole was young (eldest participant was 36). In the literature review, the effects of age on the skin were discussed. It is felt that more elderly people may be at increased risk of contact cooling as a result of skin differences that occur amongst other factors as amongst other effects epidermal thickness decreases with age. The effects of race and gender should also be investigated as both these have been shown in the past and discussed in the literature review as having an effect on thermoregulatory responses. In terms of ergonomic interest, society is moving towards an ageing population, in the U.K. Certainly, this will result in people working longer as a result of insufficient pension provisions. For these reasons it is important to consider the safety of older people as they will be working longer and making up an increasing percentage of the working population.

In chapter 8, the effects of a larger dominant hand when compared to the non dominant hand were briefly discussed. It was surmised that any additional heat input to the dominant hand resulting from a larger hand volume would be counterbalanced by the accompanying larger contact area. This however has not been investigated.

Finally, the effects of contact cooling on a hot body, induced by exercise would be interesting to investigate and to see what effect this has on the speed of cooling especially if the participant was sweating. This would be a likely scenario to occur in industry, as typically work in cold stores etc can induce sweating, although regular changes of clothing are encouraged, through heavy manual work and a high level of clothing insulation.

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# Appendix 1

## GENERIC HEALTH SCREEN FOR STUDY VOLUNTEERS

It is important that volunteers participating in research studies are currently in good health and have had no significant medical problems in the past. This is to ensure (i) their own continuing well-being and (ii) to avoid the possibility of individual health issues confounding study outcomes.

**Please complete the questions in this brief questionnaire to confirm fitness to participate:**

**If YES to any question, please describe briefly in the spaces provided (eg to confirm problem was/is short-lived, insignificant or well controlled.)**

**1 At present, do you have any health problem for which you are:**

*(Please tick as appropriate)*

(a) on medication, prescribed or otherwise

Yes ☐ No ☐

(b) attending your general practitioner

Yes ☐ No ☐

(c) on a hospital waiting list

Yes ☐ No ☐

**2 In the past two years, have you had any illness which required you to:**

*(Please tick as appropriate)*

(a) consult your GP

Yes ☐ No ☐

(b) attend a hospital outpatient department

Yes ☐ No ☐

(c) be admitted to hospital

Yes ☐ No ☐

**3 Have you ever had any of the following:**

*(Please tick as appropriate)*

(a) Convulsions/epilepsy

Yes ☐ No ☐

(b) Asthma

Yes ☐ No ☐

(c) Eczema

Yes ☐ No ☐

(d) Diabetes

Yes ☐ No ☐

(e) A blood disorder

Yes ☐ No ☐

(f) Head injury

Yes ☐ No ☐

(g) Digestive problems

Yes ☐ No ☐

(h) Heart problems

Yes ☐ No ☐

(i) Problems with bones or joints

Yes ☐ No ☐

(j) Disturbance of balance / co-ordination

Yes ☐ No ☐

(k) Numbness in hands or feet

Yes ☐ No ☐

(l) Disturbance of vision

Yes ☐ No ☐

(m) Ear / hearing problems

Yes ☐ No ☐

(n) Thyroid problems

Yes ☐ No ☐

- (o) Kidney or liver problems
- (p) Allergy to nuts
- (q) Migraines

Yes	<input type="checkbox"/>	No	<input type="checkbox"/>
Yes	<input type="checkbox"/>	No	<input type="checkbox"/>
Yes	<input type="checkbox"/>	No	<input type="checkbox"/>

(Please tick as appropriate)

**Optional questions for female participants**

- (a) are your periods normal/regular?
- (b) are you on "the pill"?
- (c) could you be pregnant?
- (d) are you taking hormone replacement therapy (HRT)?

Yes	<input type="checkbox"/>	No	<input type="checkbox"/>
Yes	<input type="checkbox"/>	No	<input type="checkbox"/>
Yes	<input type="checkbox"/>	No	<input type="checkbox"/>
Yes	<input type="checkbox"/>	No	<input type="checkbox"/>

**Thank you for your co-operation!**

**Declaration Of Consent**

I, ..... hereby volunteer to be an experimental participant in a thermal environment experiment during the period of / on .....200 .....

My replies to the above questions are correct to the best of my belief and I understand that they will be treated with the strictest confidence by the experimenter. The purpose of the experiment has been explained by the experimenter and I understand what will be required of me.

I understand that I may withdraw from the experiment at any time and that I am under no obligation to give reasons for withdrawal or attend again for experimentation. I also understand that the experimenter is free to withdraw me from experimentation at any time.

I undertake to obey the laboratory regulations and the instructions of the experimenter regarding safety, participant only to my right to withdraw as declared above.

Signature of Participant ..... Date .....

Signature of Experimenter ..... Date .....

