

---

This item was submitted to [Loughborough's Research Repository](#) by the author.  
Items in Figshare are protected by copyright, with all rights reserved, unless otherwise indicated.

## **Finger skin cooling on contact with cold materials: an investigation of male and female responses during short-term exposures with a view on hand and finger size**

PLEASE CITE THE PUBLISHED VERSION

<http://www.springerlink.com/content/1439-6319/>

PUBLISHER

© Springer-Verlag

VERSION

SMUR (Submitted Manuscript Under Review)

LICENCE

CC BY-NC-ND 4.0

REPOSITORY RECORD

Jay, Oliver E., and George Havenith. 2019. "Finger Skin Cooling on Contact with Cold Materials: An Investigation of Male and Female Responses During Short-term Exposures with a View on Hand and Finger Size". figshare. <https://hdl.handle.net/2134/2563>.

This item was submitted to Loughborough's Institutional Repository by the author and is made available under the following Creative Commons Licence conditions.



CC creative commons  
COMMONS DEED

**Attribution-NonCommercial-NoDerivs 2.5**

**You are free:**

- to copy, distribute, display, and perform the work

**Under the following conditions:**

 **Attribution.** You must attribute the work in the manner specified by the author or licensor.

 **Noncommercial.** You may not use this work for commercial purposes.

 **No Derivative Works.** You may not alter, transform, or build upon this work.

- For any reuse or distribution, you must make clear to others the license terms of this work.
- Any of these conditions can be waived if you get permission from the copyright holder.

**Your fair use and other rights are in no way affected by the above.**

This is a human-readable summary of the [Legal Code \(the full license\)](#).

[Disclaimer](#) 

For the full text of this licence, please go to:  
<http://creativecommons.org/licenses/by-nc-nd/2.5/>

# **Finger skin cooling on contact with cold materials: An investigation of male and female responses during short-term exposures with a view on hand and finger size**

**Ollie Jay<sup>1,2</sup>✉ and George Havenith<sup>1</sup>**

<sup>1</sup> Human Thermal Environments Laboratory, Department of Human Sciences, Loughborough University, Leicestershire, U.K. LE11 3TU.

<sup>2</sup> Laboratory for Exercise and Environmental Physiology, 8888 University Drive, School of Kinesiology, Simon Fraser University, Burnaby, British Columbia, CANADA, V5A 1S6.

Author Email: [Ojay@sfu.ca](mailto:Ojay@sfu.ca)

Author Fax no: +44 (0) 1509 223940

**Abstract.** This study investigates the independent effects of hand anthropometry and gender upon contact cooling responses. Subjects were selected for matching hand/finger size between genders, with equal variation between individuals of each group. Fourteen volunteers (7 male, 7 female) participated, touching blocks of aluminium and stainless steel using the first phalanx of the index finger with a contact force of 1.0N and 9.8N, at surface temperatures of  $-2^{\circ}\text{C}$  and  $-10^{\circ}\text{C}$ . Conditions were selected in order to elicit varying rates of skin cooling upon contact. Contact temperature ( $T_C$ ) of the finger-pad was measured over time using a T-type thermocouple. Overall, no significant difference was found between the cooling responses of males and females. In order to investigate whether differences in hand anthropometry correlated with contact cooling response, a multiple regression approach was used. Analyses of the residual variance in contact cooling data after the effects of material type, surface temperature and finger contact force had been accounted for, showed that, under slow cooling conditions (over 45 seconds to reach  $T_C = 1^{\circ}\text{C}$ ), hand size correlated significantly with contact cooling response only when represented by index finger volume ( $p < 0.05$ ), and gender did not. Whilst under fast cooling conditions (below 25 seconds to reach  $T_C = 1^{\circ}\text{C}$ ), hand size did not correlate significantly with contact cooling response at all, but gender had a significant effect ( $p < 0.001$ ). Under slow cooling conditions, a larger finger (and most cases hands) provides a higher heat content thus giving a slower skin cooling speed. Under fast cooling conditions, the significantly longer time required for males to reach a  $T_C$  of  $1^{\circ}\text{C}$  despite matching hand and finger size is attributed to higher epidermal insulation provided by the thicker stratum corneum typically found in males, combined with the higher starting skin temperature observed in the “slightly cool” environment.

**Keywords.** Cold injury, skin freezing, contact, hand size, gender differences

# Introduction

The European Union sponsored COLDSURF project (SMT4-CT97-2149) was established in 1998 in order to derive a safety standard to protect workers in cold environments from discomfort, numbness, pain and ultimately skin damage caused by bare hand contact with cold surfaces. The data collected from this extensive project was used to develop an empirical predictive model of fingertip contact cooling with limits set to protect 75% of the population (Malchaire *et al.* 2002). However a large amount of inter-individual variation was found suggesting that particular groups may not be proportionally represented within the protected population. Jay and Havenith (2004a) compared skin cooling of males and females, representative for their gender in terms of hand anthropometry. They observed that female skin cooled significantly faster under slow cooling conditions (>45 seconds to reach 0°C) that elicited cooling of the deeper dermal tissues. However no differences between genders in cooling speed were reported under fast cooling conditions (<30 second to reach 0°C) that only elicited cooling of the superficial tissue layers. Subsequent analysis found that finger skin contact cooling speed under slow cooling conditions was significantly related to hand/finger size, with larger hands and fingers requiring greater heat transfer to attain a given finger skin temperature (contact temperature), thus cooling slower. However as the subject's hand anthropometry was representative for their gender, with males therefore having larger hand dimensions, gender and hand size were confounded. Conclusive evidence of the effects of hand/finger size upon finger skin contact cooling speed independent of gender could therefore not be derived.

Hand size has been found to affect skin cooling in a number of studies. Rissanen *et al.* (2000) found that whole-hand cooling under slow cooling conditions correlated with hand volume and palm size and during finger contact, Chen *et al.* (1994) found that finger morphology is a predictor of skin cooling for contact with aluminium at temperatures between +7°C and -7°C.

Many gender differences do exist that could have an effect upon finger skin contact cooling. The skin itself has been found to differ in mechanical properties and thickness. Thickness of the stratum corneum of the volar fingertips has been found to be thinner in women than in men (Fruhstorfer *et al.* 2000) and a significant difference between genders has been reported in collagen and elastic fibre density in 45 skin biopsies taken from limbs or the trunk (Vitellaro-Zuccarello *et al.* 1994). Tur (1997) summarised the differences in skin physiology between men

and women: Skin thickness in young subjects (27-31 years) is greater in men than in women across the entire body except for the lower back (Seidenari *et al.* 1994); Skinfold thickness in younger subjects (17-24 years) is lower in the limbs of women (Davies *et al.* 1988) and skinfold compression is less in the limbs of women in younger subjects (Hattori *et al.* 1993).

Other gender differences concern blood flow. Bollinger and Schlumpf (1976) found a lower rate of arterial inflow through the fingers in women than in men and that arterial inflow in response to cooling decreases more greatly in women than in men causing cooler limb temperatures. Cooke *et al.* (1990) found finger blood flow to be more than double in men than women and skin perfusion more than triple. However, whilst changes in blood flow have been found to affect starting finger skin temperature before finger-pad contact cooling, the cooling behaviour of the finger skin during contact is not affected by differences in blood flow to the finger for contact forces above that of capillary pressure, typically 2.6-3.3kPa (20-25 mmHg) (Jay and Havenith, 2004b).

As differences in finger skin contact cooling at the usually observed contact pressures of 5.0-33.0kPa (35-250 mmHg) cannot be attributed to the effects of blood flow, further investigation is required into the relationship of the well documented gender differences in hand structure and skin properties with the evident difference between the finger skin cold contact response of males and females.

The aim of the present study is to compare the fingertip cooling responses of males and females to short-term cold contact exposure and to study whether this response can be described in terms of gender differences or is only related to hand anthropometry. For this purpose, experiments were performed where male and female participants touched cold materials over a range of surface temperatures representing fast and slow cooling conditions using high and low finger contact forces. The hand sizes of both gender groups were matched, but within groups variation in hand size was present.

# Methods

## Subjects

Fourteen participants (7 men aged  $24.8 \pm 5.8$  years and 7 women aged  $24.3 \pm 5.0$  years) volunteered for the study. Potential subjects were excluded from the study if they had in the past suffered frost-bite, any other related cold injuries or suffered from vascular disease. None of the subjects were smokers. They were instructed to not drink tea or coffee within an hour before the beginning of experimentation, or consume alcohol the evening prior to any experimental session. Subject groups were selected such that average hand and finger dimensions were similar for both males and females.

## Experimental design

Participants were asked to touch two smooth surfaced materials (Aluminium and Stainless steel) at two different surface temperatures ( $-2^{\circ}\text{C}$  and  $-10^{\circ}\text{C}$ ) and at two touching force levels (1.0N and 9.8N, with a separate session for each subject at each temperature. The material, surface temperature and touching force level were presented in a balanced design such that the effect of order was avoided. Each exposure was repeated three times during the same session with a 5-minute re-warming period in between.

## Equipment and measurements

### *Instrumentation*

Mean hand characteristics were determined as follows: Volumes of the hand and index finger were measured using weight of water displacement by submerging the hand/finger in water up to the base of the processus styloideus and proximal phalanx respectively. Lengths of the index finger and its 1<sup>st</sup> phalanx were measured using a sliding rule, from finger tip to the base of the proximal and distal phalanx respectively. Finger depth and width were measured using a sliding rule, depth from the base of the fingernail to the centre of the finger-pad without compressing the distal pulp, and width across the line of the centre of the finger-pad again without compression of finger tissue. Finger contact areas were calculated by scanning a fingerprint at the appropriate pressure into a customised computer programme (Jay and Havenith, 2004a). All measurements were repeated until three reproducible measurements were attained (i.e. within 2.5% of the mean).

Two types of contact material blocks (9.5 x 9.5 x 9.5cm) were used for the study, Aluminium and Stainless Steel. These were selected in order to represent different thermal properties and were tested at pre-selected temperatures in order to provide a range of skin cooling rates whilst preventing frostbite (Jay and Havenith, 2004a). The thermal properties of the contact materials are given in Table 1 and expressed in terms of thermal penetration coefficient ( $b$ ) (BSI 1978; Yoshida *et al.* 1989) which is defined as:

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

where:  $k$  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 specific heat ( $\text{J}\cdot\text{Kg}^{-1}\cdot\text{K}^{-1}$ ).

### *Insert Table 1*

For the purpose of regulating the material temperatures, each block was placed inside a modified HOTPOINT “Iced Diamond” 87610 kitchen freezer, with a window and central access point incorporated into the door design. The required temperature was achieved inside the cool-box using a P.I.D temperature control module that replaced the existing thermostat, thus allowing the freezer to regulate with better accuracy and stability ( $\pm 0.5$  °C) than the existing thermostat.

In order to allow the subject to regulate the finger contact force during contact, the blocks were placed on a balance inside the freezer, appropriate compensating weights were then added to the balance tray with the test material in order to achieve the required finger contact force. Contact force was regulated using feedback provided by an analogue pointer method that facilitated the judgement of the amount of force required to obtain the correct force level.

For the purpose of measuring skin contact cooling, T-type thermocouples (copper/constantan) of 0.2mm diameter (time constant <0.5 seconds) were attached to the palmar side of the 1<sup>st</sup> phalanx of the index finger of the non-dominant hand using ‘3M Blenderm’ surgical tape. The base of the sensor tip was attached to the finger just below the 1<sup>st</sup> phalanx, allowing the sensor to be totally exposed to the skin surface on one side, and the touched surface on the other without tape in between. This measured the effective temperature between the skin contact area and the material surface – the ‘contact temperature’. The local skin cooling of the contact area was monitored using a WorkBench PC for Windows 3.00.15 programme in conjunction with a 16-bit

Strawberry Tree DATAshuttle™, model DS-16-8-TC-AO (Strawberry Tree Inc., Sunnyvale, CA, USA).

### *Procedure*

Pre-cooling period: Each participant rested for a period of 30 minutes in an air-conditioned preparation room (used to achieve the desired body thermal state) and was asked to rate his or her whole-body thermal sensation on a thermal sensation scale (ISO 7730, 1994). These were recorded at 5 minute intervals with the environmental conditions within the room adjusted in order to induce the thermal sensation equivalent to a PMV of  $-1$  (slightly cool). The mean conditions of the room over all experimental sessions were  $T_a = 18.6 \pm 1.2^\circ\text{C}$ ,  $R_h = 40.5 \pm 5.1\%$  which should induce a mean thermal sensation of slightly cool according to the PMV index (ISO 7730, 1984). A PMV of  $-1$  was chosen in order to achieve a state of vasoconstriction. Clothing insulation was standardised at around 0.4 - 0.5 clo (cotton underwear, socks and t-shirt; jeans and trainer/shoes).

Contact cooling period: After this pre-cooling period, each subject touched, with the 1<sup>st</sup> phalanx of the index finger of the non-dominant hand, the appropriate material block at the required surface temperature with a given finger contact force. The skin cooling behaviour of the contact area was monitored throughout the exposure until one of the following withdrawal criteria was reached: a contact temperature ( $T_C$ )  $0.5^\circ\text{C}$  or below; a test duration of 180 seconds; a typical sensation of frostnip about which subjects were instructed (burning/tingling); a sensation of intolerable pain or any other reason for which the subject perceived withdrawal to be necessary.

### **Analysis**

For the purpose of analysing the contact cooling data, the time taken to reach a contact temperature of  $1^\circ\text{C}$  ( $T_1$ ) after initial contact was used ( $T_C$  sampling rate = 5Hz). This was considered the most appropriate point for analysis as this was a temperature point consistently reached by all of our subjects before the designated withdrawal criteria of  $T_C = 0.5^\circ\text{C}$ . Using this analysis point did not require any extrapolation and thereby eliminated a potential source of error.

The previous study by Jay and Havenith (2004a) observed two distinct cooling response patterns. A “Slow” cooling condition elicited a skin cooling pattern that followed a distinct “bi-phasic” curve (see figure 1). The first steep part primarily represents only the cooling of the superficial skin layer and thermocouple dynamics. The shallow second part represents the cooling of the deeper dermal layers of the fingertip (Jay and Havenith, 2004a). A “Fast” cooling condition elicited a skin cooling pattern that showed only the initial steep part of the curve (figure 1) seen in the “Slow” cooling. In this case the cooling is so fast that the withdrawal criteria were reached by cooling of the superficial skin before cooling could affect the deeper skin layers. Cold induced vasodilation (CIVD) was not a concern for any of the conditions tested as maximal test duration for this study was 3 minutes, CIVD is typically not observed for 5-10 minutes after the start of local cold exposure of the extremities (Daanen, 2003).

### *Insert Figure 1*

As the previous study by Jay and Havenith (2004a) found a confounding effect of cooling speed of the given condition when investigating the effect of hand size on finger-pad contact cooling response, fast and slow cooling conditions were treated separately in the present study. “Fast” and “Slow” cooling conditions were defined by observing finger skin contact cooling response. If on average over the individual condition, the time analysis point ( $T_1$ ) was reached in 25 seconds or less, the condition was classified as a “Fast” cooling condition, as the cooling occurring would be predominantly of the superficial epidermal layers of the skin. If on average over the individual condition,  $T_1$  was reached after 45 seconds or longer the condition was classified as a “Slow” cooling condition, as the cooling occurring would include the deeper dermal layers of the fingertip.

Based on these criteria, all conditions at  $-10^{\circ}\text{C}$  and Aluminium at  $-2^{\circ}\text{C}$  with a finger contact force of 9.8N were classified as “Fast” cooling conditions, and all Stainless Steel exposures at  $-2^{\circ}\text{C}$  and Aluminium at  $-2^{\circ}\text{C}$  with a finger contact force of 1.0N were classified as “Slow” cooling conditions.

For the purpose of investigating the relationship between skin cooling time and the variation in hand measurements, a stepwise general regression analysis was used. This incorporated the three parameters that defined each given condition (material, surface temperature and finger contact

force) and subsequently analysed the residual variance for the effects of hand/finger size (as defined by the hand measurements taken) and gender. The model tested is described below.

$$\text{Time to reach } [T_C = 1^\circ\text{C}] = \beta_0 + \beta_1 \times [\text{Material Property}] + \beta_2 \times [\text{Material surface temperature}] + \beta_3 \times [\text{Finger contact force}] + \beta_4 \times [\text{Hand size}] + \beta_5 \times [\text{Gender}]$$

The thermal properties of the contact material in the equation are represented by the natural logarithm of the thermal penetration coefficient to linearise its effect. Gender was represented by a dummy variable of “1” for female, “2” for male.

The data collected was further analysed using t-test, analyses of variance and co-variance studying the relationships between individual parameters (e.g. material, finger contact force, surface temperature etc.) and cooling time. All analyses were performed using the statistical software package SYSTAT (Systat Inc., Evanston, IL, USA). For significance,  $p \leq 0.05$  was accepted.

# Results

## Physical and hand measurements

The subject's physical measurements and anthropometrics of the non-dominant hand are detailed in Table 2. Subjects were specifically selected for this study in order to provide a male and female group similar in terms of hand size, therefore by design, a range of different hand sizes was present within each group with no differences present between the male and female groups.

*Insert Table 2*

## Skin cooling data

Starting finger skin temperature ( $T_{C0}$ ) varied considerably between subjects. Overall,  $T_{C0}$  was found to be significantly lower for female participants ( $30.7 \pm 3.3^\circ\text{C}$ ), than the male participants ( $31.8 \pm 3.1^\circ\text{C}$ ) ( $p < 0.01$ ). However, in the limited observations within each condition there was no significant difference in  $T_{C0}$  of male and female responses.

Mean values for  $T_1$ , the time taken after contact to reach a finger contact temperature of  $1^\circ\text{C}$ , separated by gender for each condition are given in Table 3.

*Insert Table 3*

### *Effect of Gender*

An analysis of variance (MIXED ANOVA, repeated measures with gender as between groups factor) was performed on the times taken to reach a contact temperature of  $1^\circ\text{C}$  ( $T_1$ ) over all 8 conditions tested. Overall, it was found that despite mean  $T_1$  times for females being shorter than males in 7 out of the 8 conditions, gender ( $F(1,12)=1.089$ ,  $p=0.317$ ) did not have a significant effect upon finger skin contact cooling time.

### *Differences of skin cooling time in relation to hand size*

In order to avoid the confounding effect of cooling speed (given by the varying test conditions) previously found (Jay and Havenith, 2004a), fast and slow cooling conditions were treated separately. Initial analysis suggested no significant difference between the skin contact cooling times of the male and female subject groups, therefore their skin cooling data were combined in

order to investigate whether the cooling times ( $T_1$ ) were related to the variation in hand measurements present between subjects. However, gender was included as a parameter in further analysis in order to identify any potential interaction effects it may present. The stepwise general linear model (GLM) described in the methods was used.

#### *GLM Results – Slow cooling conditions*

The multiple regression analyses of the slow cooling data showed that of the “physical parameters” both contact material type and finger contact force had a highly significant effect on  $T_1$  ( $p < 0.001$ ). Material temperature was the same in these conditions and did therefore not contribute to the prediction.

Subsequent analyses of the residual variance in the cooling responses for the effect of hand size indicators showed that only hand size when represented by finger volume correlated significantly with the residual variance in  $T_1$  ( $p = 0.017$ ). An example of this correlation of finger volume with  $T_1$  is shown in figure 2. None of the other hand measurements were found to significantly affect  $T_1$  under the slow cooling conditions. The p-values for the effect of these measurements upon  $T_1$  are given in Table 4, showing that fingertip depth and hand volume also showed a trend effect on finger cooling speed.

Following the steps described above, gender was not found to correlate significantly with the residual variance in  $T_1$  after the physical parameters and hand/finger size were introduced. None of the interactions of gender with any of the model parameters were found to be significant.

*Insert Table 4*

*Insert Figure 2*

#### *GLM Results – Fast cooling conditions*

The multiple regression analyses of the fast cooling data showed that all the “physical parameters” of contact material type, material surface temperature and finger contact force had a highly significant effect upon  $T_1$  ( $p < 0.001$ ) and were all included in the stepwise regression model.

Subsequently, hand size was not found to significantly correlate with the residual variance in  $T_1$  under fast cooling conditions, when represented by any of the hand/finger measurements taken ( $p>0.05$ ). However, it was found that gender did have a significant effect upon  $T_1$  ( $p<0.001$ ). Despite similar hand sizes, males cooled significantly slower than females. A subsequent comparison between genders for fast cooling conditions only, shows a mean  $T_1$  value of  $19.4\pm 17.2$  seconds for male participants compared to a mean  $T_1$  value of  $11.7\pm 10.2$  seconds for female participants (two-sample t-test,  $p=0.002$ ).

# Discussion

## Physical hand measurements

Results showed that subjects were successfully selected for matching hand size and similar variation between genders. The physical measurements taken of the non-dominant hand showed that there was no significant difference between the males and females in this study in any of the hand or finger dimensions. Maximum and minimum values for each gender were either identical or very similar between males and females.

## Skin cooling data

Despite the equal pre-test conditioning of the subjects in terms of rest period and environmental conditions, the starting skin temperature of the fingertip ( $T_{C0}$ ) for males was on average 1.1 °C higher than that of the female participants. The same difference between male and female starting skin temperature was found in the previous study by Jay and Havenith (2004a) and is attributed to a lower arterial blood inflow to the fingers of women (Bollinger and Schlumpf, 1976) providing a lower heat input to the fingers at rest.

As the background of the work being conducted concerns the *protection* of both males and females from discomfort, pain, numbness and skin damage (Holmér *et al.* 2001), it was initially determined that the time to reach a given finger contact temperature ( $T_C$ ) for the occurrence of these phenomena (15, 7 and 0 °C respectively) would be used to analyse the cooling data obtained (Jay and Havenith, 2004a). However, for the present study the time taken to reach a  $T_C$  of 1°C was used. Firstly as the criteria of 15 and 7°C were reached too fast and secondly in order to avoid unnecessary extrapolation that would be needed to calculate time to 0°C due to variations in end point. Despite large individual differences, the method used to represent the skin cooling occurring ( $T_1$ ) would appear to be sufficiently discriminative. Material type, surface temperature and finger contact force were all found to have a highly significant effect upon finger skin cooling under both fast and slow cooling conditions. This is consistent with the findings of previous contact cooling studies (Jay and Havenith, 2004a; Jay, 2002; Powell, 2002; Geng *et al.* 2000; Chen *et al.* 1992; Havenith *et al.* 1992).

Jay and Havenith (2004a) found that for a representative male and female group in terms of hand sizes (i.e. males with larger hand dimensions than females), no difference in finger skin cooling time was apparent for fast cooling conditions, but there were for slow cooling conditions. In the

present study, using a male and female subject group of equal hand sizes, initial analysis testing all data together found no significant difference between the finger skin cooling time ( $T_1$ ) of males and females. However, when separating the data into fast and slow cooling conditions for the purpose of analysing the effect of hand/finger size upon skin cooling response, it was found that whilst gender continued to show no significant effect upon  $T_1$  under the slow cooling conditions tested, gender did have a highly significant effect upon  $T_1$  under the fast cooling conditions tested, with males showing longer skin cooling times (slower cooling).

### *Slow cooling conditions*

Under slow cooling conditions, the findings of the present study suggest that by eliminating the differences in hand and finger dimensions, the effect of gender upon finger skin contact cooling time is removed. Furthermore, the variation observed in  $T_1$  is significantly correlated with finger volume, the greater the finger volume, the longer the finger skin cooling time. A larger finger (and in most cases hands) has a higher heat content thus giving a longer cooling time. This is in agreement with the findings of Jay and Havenith (2004a) who found that hand size had a greater predictive power than gender under slow cooling conditions but at that time were unable to derive a conclusive verdict due to the confounding effect of hand size with gender in their study.

Burse *et al.* (1979) stated that women are at a greater risk to cold injury due to the geometry of their thinner extremities resulting in a greater heat outflow for the same circulatory heat input per unit tissue mass. Whilst on average, women do have thinner extremities (i.e. smaller hand/finger size) within a representative group of the general population, the findings of the present study suggest that it is primarily the tissue mass of the contact finger that dictates the rate of skin cooling and not any further gender effect such as differences in blood flow. The fact that arterial inflow to the fingers of women being normally only about half of that of men (Bollinger and Schlumpf, 1976) does affect starting finger skin temperature ( $T_{C0}$ ) but does not significantly affect skin cooling rate under the slow cooling conditions tested. This is supported further by the findings of Jay and Havenith (2004b) who in a separate study reported no effect of blood flow upon finger skin contact cooling behaviour for finger contact pressures above 20-25mmHg (2.6-3.3 KPa). The lowest pressures employed in the present study were approximately 30-35mmHg (4.0-4.7 kPa) and it is assumed that capillaries are compressed and thus closed at these pressures.

In the present study, only finger volume was found to correlate significantly with skin cooling time, however a trend was apparent for the physical hand measurements describing the tissue

mass of the contact fingertip. Fingertip depth ( $p=0.060$ ) relates directly to fingertip tissue mass, and hand volume ( $p=0.091$ ) is highly correlated to finger volume. Physical hand measurements describing primarily “hand shape”, such as finger length and phalanx length were not significant predictive factors, i.e. long fingers may also be thin as well as thick, so no clear relation of lengths with heat content is present.

The ideal measurement for the representation of tissue mass of the fingertip would be that of the soft volar tissue of the fingertip. This can be estimated using the linear relationship found between volar tissue of the fingertip and fingertip volume (Murai *et al.* 1997). Fingertip volume was calculated by multiplying 1<sup>st</sup> phalanx length, fingertip width, fingertip depth and an estimated shape ratio of 0.95. The subsequent calculations of soft volar tissue for each participant correlates significantly with finger skin cooling time ( $T_1$ ) in the present study ( $p=0.03$ ).

#### *Fast cooling conditions*

Under fast cooling conditions, a significant difference was found between the finger skin cooling times ( $T_1$ ) of the males and females in the present study despite the absence of differences in hand/finger size. This is incongruent with the earlier findings of Jay and Havenith (2004a). However half of the fast cooling conditions tested in that particular study were metals (aluminium and stainless steel) at  $-17^{\circ}\text{C}$ , which elicited skin cooling at such a rate that the withdrawal criteria of  $T_C \leq 0.5^{\circ}\text{C}$  was reached within 0-2 seconds. Consequently it is likely that the cooling was too quick for individual variation to be apparent in terms of gender.

When considering this difference in skin cooling time between males and females, the thermal interaction of the different components of the skin system as a whole must be considered and this will be dependent upon the thermophysical properties of these components. Under fast cooling conditions, the most relevant and extensively cooled component will be that of the outer layer of the epidermis, a corneal layer composed of fully keratinised, flat, fused cells bound together by synthesised lipids. These are essentially dead cells with very low water content and no heat input from any vascular structures. A consequence of the low water content of the epidermal layer is its low thermal conductivity, a factor that ranked highest in importance when predicting skin burning in response to heat sources (Ng and Chua, 2002). A thicker cornified epidermal layer therefore essentially provides a greater degree of thermal insulation, which may result in a longer finger skin cooling time in response to contact cooling. Fruhstorfer *et al.* (2000) found that

cornified epidermis (stratum corneum) is significantly thicker in the fingertips of males than females and it is suggested that the longer finger skin cooling times ( $T_1$ ) found for males in the present study are a consequence of this.

In conclusion, it is apparent from the present study that by eliminating the differences in hand and finger dimensions usually found between a representative group of males and females, the effect of gender upon finger skin contact cooling time under the given conditions is removed under slower cooling conditions where cooling of the deeper epidermal and dermal layers and subcutaneous tissue occurs. Under fast cooling conditions where contact duration is sufficiently long for individual variation to be apparent (i.e.  $\approx 5$  seconds) but where primarily only cooling of the epidermal layers occurs, males show a significantly longer finger skin contact cooling time than females. This is attributed to the thicker stratum corneum usually found in males providing greater superficial insulation against cold surfaces, combined with the higher starting skin temperature observed in the slightly cool environment. Consequently for applied purposes, the modelling of fingertip contact cooling for the protection of males and females under slower cooling conditions would require the measurement of finger dimensions, whereas under fast cooling conditions it is essential that gender is included as a parameter to represent the different epidermal characteristics.

*Acknowledgement.* This research was sponsored by the European Union (Contract SMT4-CT97-2149). The experiments performed comply with current United Kingdom law.

## References

1. Bollinger A and Schlumpf M, (1976). Finger blood flow in healthy patients of different age and sex and in patients with primary Raynaud's disease. *Acta Chirurgia Scandinavica* 465 : 42-7.
2. BSI. (1978). Safety of household and similar electrical appliances. BS 3456, part 101. British Standards Institute, London.
3. Burse RL, (1979). Sex differences in human thermoregulatory response to heat and cold stress. *Hum Factors*, 21 : 687-699.
4. Chen F, Nilsson H, Holmér I, (1992). Cooling of the finger pad touching different material surfaces. In: Lotens, W.A. and Havenith, G. (eds) *Proceedings of 5<sup>th</sup> International Conference on Environmental Ergonomics* , Maastricht, pp 60-61.
5. Chen F, Nilsson H, Holmér I, (1994). Finger cooling by contact with cold aluminium surfaces – effects of pressure, mass and whole body thermal balance. *Eur J Appl Physiol*, 69(1):55-60
6. Cooke JP, Creager MA, Osmundson PJ and Shepherd JT, (1990). Sex differences in control of cutaneous blood flow. *Circulation*, 82(5):1607-1615
7. Daanen HA, (2003). Finger cold-induced vasodilation: a review. *Eur J Appl Physiol*, 89(5): 411-26.
8. Davies BN, Greenwood EJ and Jones SR, (1988). Gender differences in the relationship of performance in the handgrip and standing long jump tests to lean limb volume in young adults. *Eur J Appl Physiol*, 58:315-320
9. Fruhstorfer H, Abel U, Garthe C-D and Knüttel A, (2000). Thickness of the stratum corneum of the volar fingertips, *Clinical Anatomy*, 13: 429-433.

10. Geng Q, Holmér I and Cold surfaces research group, (2000). Finger contact cooling on cold surfaces: Effect of pressure. In: J Werner, M Hexamer (Eds), Shaker Verlag, Aachen. Proceedings of 9<sup>th</sup> International Conference on Environmental Ergonomics, Dortmund, Germany, pp. 185-188
11. Hattori K and Okamoto W, (1993). Skinfold compressibility in Japanese university students. *Okajimas Folia Anat Jpn*, 70:69-78
12. Havenith G, Van de Linde EJG, Heus R, (1992). Pain and thermal sensation and cooling rate of hands while touching cold materials. *Eur J Appl Physiol* 65 : 43-51
13. Holmér I, Havenith G, Hartog E den, Rintamäki H, Malchaire J, Geng Q, Jay OE, Powell SL, Rissanen S, (2001). Temperature limit values for cold touchable surfaces. Final report on the project SMT4-CT97-2149. European Union
14. ISO 7730, (1994). Moderate Thermal Environment – Determination of the PMV and PPD indices and specification of the conditions for thermal comfort. Geneva: International Standards Organisation.
15. Jay OE and Havenith G, (2002). Skin Contact with Cold Materials: A comparison between the fingerpad responses of the dominant and non-dominant hand for short-term exposures. In: Y Tochihara (Ed), 10<sup>th</sup> International Conference on Environmental Ergonomics, Fukuoka, Japan, pp 259-262
16. Jay O and Havenith G, (2004a). Skin cooling on contact with cold materials: A comparison between male and female responses during short-term exposures. *Eur J Appl Physiol*, 91(4): 373-381.
17. Jay O and Havenith G, (2004b). Skin cooling on contact with cold materials: The effect of blood flow during short-term exposures. *Ann Occup Hyg*. 48(2): 129-137.
18. Malchaire J, Geng Q, Den Hartog E, Havenith G, Holmer I, Piette A, Powell SL, Rintamaki H, Rissanen S, (2002). Temperature limit values for gripping cold surfaces. *Ann Occup Hyg* 46(2) : 157-63.

19. Murai M, Lau H-K, Pereira BP and Pho RWH, (1997). A cadavar study on volume and surface area of the fingertip, *Journal of Hand Surgery*, 22A: 935-941.
20. Ng EY, Chua LT, (2002). Prediction of skin burn injury. Part 2: Parametric and sensitivity analysis. *Proc Inst Mech Eng [H]*, 216(3): 171-183.
21. Powell SL, (2002). Contact cooling and its effects upon manual dexterity; Doctoral Thesis, Loughborough University, UK. December, 2002.
22. Rissanen S, Rintamäki H and Hassi J, (1998). Individual variations in finger temperature responses to contact cooling in indoor workers. 8th International Conference for Environmental Ergonomics (ICEE8) Abstracts (Not Published).
23. Rissanen S, Rintamäki H and Cold surfaces research group, (2000). Individual variation during slow and rapid contact cooling. In: J Werner, M Hexamer (Eds), Shaker Verlag, Aachen. Proceedings of 9<sup>th</sup> International Conference on Environmental Ergonomics, Dortmund, Germany, pp. 189-191.
24. Seidenari S, Pagnoni A and Di Nardo A, (1994). Echographic evaluation with image analysis of normal skin: Variations according to age and sex. *Skin Pharmacology*, 7:201-209.
25. Tur E, (1997). Physiology of the skin-differences between men and women. *Clinics in Dermatology*, 15: 5-16.
26. Vitello-Zuccarello L, Cappelletti S, Dal Pozzo Rossi V and Sari-Gorla M, (1994). Stereological analysis of collagen and elastic fibres in the normal human dermis: Variability with age, sex and body region. *The Anatomical Record*, 238:153-162.
27. Yoshida A, Matsui I, Taya H, (1989). References on contact with hot and cold surfaces, tactile warmth and warmth of floors. Technical Report ISO/TC159/SC5/WG1/187, International Standardisation Organisation, Geneva.

**Table 1.** Thermal properties of the materials tested

Material	Density ( $\rho$ )	Thermal Conductivity (k)	Specific Heat (mass) (c)	Thermal Diffusivity ( $a=k\rho^{-1}c^{-1}$ )	Thermal Penetration coefficient
	$\text{Kg m}^{-3}$	$\text{W m}^{-1} \text{K}^{-1}$	$\text{J Kg}^{-1} \text{K}^{-1}$	$10^{-6} \text{m}^2 \text{s}^{-1}$	$\text{Jm}^{-2} \text{s}^{-1/2} \text{K}^{-1}$
Aluminium	2770	180	900	28.80	21180
Steel	7750	14.8	461	4.20	7270

*Properties of materials tested by VTT, Finland, June 14, 1999.*

**Table 2.** Physical measurements and hand characteristics of the non-dominant hand for male and female participants

Subj. (No.)	Gender (M/F)	Age (Yrs)	Height (cm)	Weight (Kg)	Handed (L / R)	Finger volume (cm <sup>3</sup> )	Hand volume (cm <sup>3</sup> )	1 <sup>st</sup> phalanx length (cm)	Finger length (cm)	1 <sup>st</sup> phalanx depth (mm)	1 <sup>st</sup> phalanx width (mm)	Finger contact area (cm <sup>2</sup> ) (1.0N)	Finger contact area (cm <sup>2</sup> ) (9.8N)
1	M	25	175	86.5	R	19	388	2.5	7.8	13	17	2.60	2.98
2	M	19	182	79.9	R	15	356	2.4	7.0	12	16	2.63	2.88
3	M	35	172	70.1	R	18	369	2.5	7.1	13	16	2.83	3.10
4	M	20	167	100.1	R	14	350	2.3	6.5	12	14	2.70	2.93
5	M	29	171	70.6	R	17	324	2.4	7.0	13	17	2.85	3.25
6	M	20	182	96.6	R	20	402	2.7	7.5	13	17	3.28	3.65
7	M	26	174	73.1	R	14	315	2.5	7.2	13	15	2.68	3.08
<b>Mean</b>		<b>25 ±6</b>	<b>174 ±6</b>	<b>82.4 ±12.3</b>	-	<b>17 ± 2</b>	<b>358 ± 32</b>	<b>2.5 ± 0.1</b>	<b>7.2 ± 0.4</b>	<b>13 ± 1</b>	<b>16 ± 1</b>	<b>2.79 ± 0.23</b>	<b>3.12 ± 0.26</b>
1	F	20	187	103.8	L	20	391	2.5	7.3	13	16	2.78	3.28
2	F	23	176	63.5	R	14	300	2.4	6.8	12	14	2.30	2.58
3	F	21	187	81.5	R	20	386	2.8	8.1	14	16	2.98	3.48
4	F	32	172	78.0	R	16	330	2.6	7.5	13	16	2.45	2.73
5	F	19	175	79.9	R	18	375	2.8	7.8	13	20	2.95	3.43
6	F	25	173	79.7	L	19	360	2.5	7.2	13	16	2.90	3.38
7	F	30	168	69.4	R	15	289	2.4	7.4	13	16	2.40	3.05
<b>Mean</b>		<b>24 ±5</b>	<b>177 ±7</b>	<b>79.4 ±12.6</b>	-	<b>17 ± 2</b>	<b>347 ± 41</b>	<b>2.6 ± 0.2</b>	<b>7.4 ± 0.4</b>	<b>13 ± 1</b>	<b>16 ± 2</b>	<b>2.68 ± 0.28</b>	<b>3.13 ± 0.35</b>

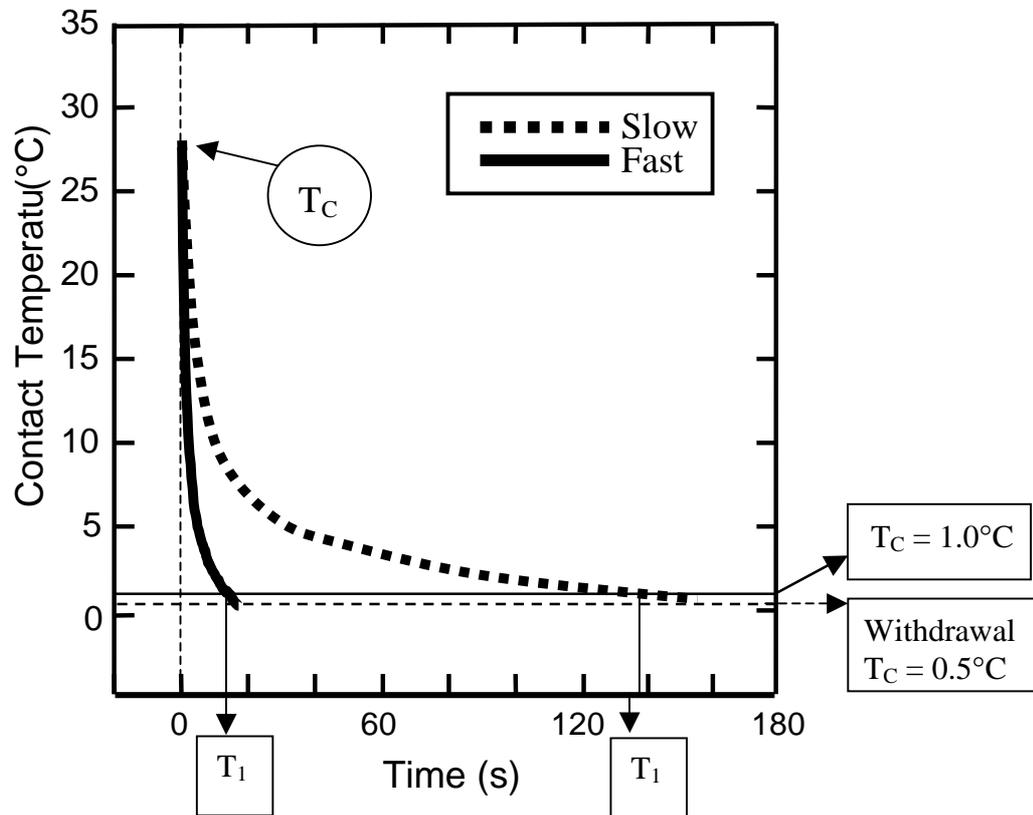
**Table 3.** Mean skin cooling times ( $T_1$ ) in seconds and standard deviations for males (M) and females (F) for finger contact under “Fast” and “Slow” cooling conditions. AL denotes Aluminium, SS denotes Stainless Steel

	<b>AL -10°C (9.8N)</b>	<b>SS -10°C (9.8N)</b>	<b>AL -10°C (1.0N)</b>	<b>SS -10°C (1.0N)</b>	<b>AL -2°C (9.8N)</b>	<b>AL -2°C 1.0N</b>	<b>SS -2°C 9.8N</b>	<b>SS -2°C 1.0N</b>
M	6.2±4.4	12.8±6.0	19.8±18.8	29.3±20.1	29.1±16.4	57.4±51.0	77.7±24.9	134.9±51.5
F	4.6±3.0	8.3±3.3	8.3±3.8	17.3±8.5	19.4±16.6	49.9±21.0	69.5±12.2	161.2±68.5
<b>Mean</b>	<b>5.5±3.8</b>	<b>10.6±5.3</b>	<b>14.2±14.8</b>	<b>23.3±16.3</b>	<b>24.4±17.3</b>	<b>55.6±39.4</b>	<b>73.5±19.4</b>	<b>148.0±60.9</b>
	<b>Fast</b>	<b>Fast</b>	<b>Fast</b>	<b>Fast</b>	<b>Fast</b>	<b>Slow</b>	<b>Slow</b>	<b>Slow</b>

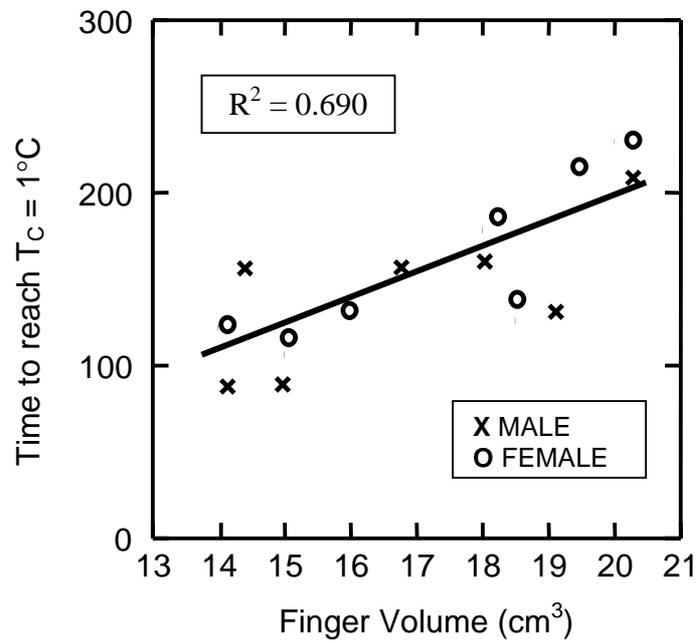


**Table 4.** Significance levels for each individual hand measurement when included in regression equation for  $T_1$ , after physical parameters for condition were entered first, under “Slow” cooling conditions. Significance ( $p \leq 0.05$ ) denoted by an asterisk (\*)

	P-value
Finger volume	0.017*
Fingertip depth	0.060
Hand volume	0.091
Fingertip width	0.253
Phalanx length	0.325
Finger length	0.748



**Figure 1.** A comparison between examples of a skin cooling curve recorded during a “Slow” and during “Fast” cooling condition, with withdrawal criteria and analysis point ( $T_1$ ) also demonstrated



**Figure 2.** A regression plot of the time to reach a T<sub>c</sub> of 1°C against finger volume for Steel at -2°C with a finger contact force of 1.0N