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ORIGINAL ARTICLE

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# Finger skin cooling on contact with cold materials: a comparison between male and female responses during short-term exposures

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**Abstract** This study compares male and female contact cooling responses in order to ascertain whether a particular sex is at a greater risk to cold injury. Ten volunteers (five male, five female) participated, touching blocks of four different materials (aluminium, stainless steel, nylon and mahogany wood) with finger contact forces of 1.0 N, 2.9 N and 9.8 N, at a range of surface temperatures (−35°C to +5°C) appropriate for the thermal properties of the material. Contact temperature ($T_C$) of the finger-pad was measured over time using a T-type thermocouple. Under fast cooling conditions (below 10 s to reach $T_C$=0.5°C), no significant difference was found between the cooling responses of males and females ($P>0.05$) for the 12 conditions tested. Under slow cooling conditions (above 10 s to reach $T_C$=0.5°C), females were found to have significantly faster skin cooling than males ($P<0.05$) for 18 of the 24 conditions tested. In order to investigate whether differences in hand anthropometry between these representative groups of males and females were related to differences in contact cooling response under slow-cooling conditions, a general linear model approach was used. Subsequent analyses of the residual variance in contact cooling data after the effects of material type, finger contact force and surface temperature had been accounted for showed that both sex and hand size correlated significantly with contact cooling response ($P \leq 0.001$) with hand size showing the stronger impact and possibly being the determining factor. Conclusive proof of the latter would require an additional experiment using males and females of equal hand dimensions instead of representative groups as used here. This study showed females to be at a higher risk during contact with cold objects.

**Keywords** Cold injury · Contact · Hand size · Sex differences · Skin freezing

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## Introduction

Typically, industry workers are exposed to and may touch, either accidentally or intentionally, many surfaces of different materials (e.g. machine parts, walls). For environments containing hot surfaces, standards are available to determine the temperature limits for these surfaces in order to minimise safety risks (EN 563:1994; Safety of machinery: temperature of touchable surfaces). However, no such standard is available for cold surfaces and for those working in such an environment, accidental finger skin contact exposure and the resultant cooling could pose a health and safety risk in terms of discomfort, pain, numbness and skin damage (Enander 1986, 1989; Havenith et al. 1995).

Data was collected for the derivation of a cold surfaces safety standard (European Union project SMT4-CT97-2149), the overall aim being to use the data to develop a predictive model of fingertip contact cooling to protect 75% of the population (Malchaire et al. 2002). However, a large inter-individual variation in contact cooling responses was found. This indicated that the existing standard provided minimal flexibility, in terms of accounting for individual groups that may be at greater or lower risk, and therefore are not covered by the data collected.

Burse (1979) found that in extreme cold, women are at a severe disadvantage due to their heat loss-to-production (surface-to-mass) ratio being far greater than their male counterparts. Despite their greater percentage of body fat at the subcutaneous level, women have little advantage as the relative size of their active body mass (producing heat) is less. Furthermore, this added insulation does not provide an advantage in preventing frost-bitten extremities, as it does not cover the body regions most at risk—the hands and feet. Further, Bollinger and Schlumpf (1976) found that women reduce their arterial inflow more than men in response to direct air cooling to the finger, thus making them even more susceptible to cold injury.

A study by Chen et al. (1992) found that gender had no significant effect upon finger-pad cooling time when touching aluminium, plastic and wood at a range of temperatures, but this was for three-fingered contact, with the contact force (9.8 N) distributed (potentially unevenly) across the contact fingers, which may have caused noise in the data. A further study by Chen et al. (1994a) investigating cold contact with aluminium at –1°C, −5°C and –14°C found that there were no significant differences between male and female subjects for any of the time constants derived from analysis, neither was there a difference in final skin temperatures. However, the study did find that males took longer to reach threshold limit values under conditions that elicited slow skin cooling rates whereas females took longer to reach threshold limit values under conditions that caused faster skin cooling rates. It is thus possible that the extent to which cold-contact response differs between gender is dependent upon the skin cooling speeds dictated by the conditions tested (i.e. material and surface temperature).

Secondary to the gender effect it may be questioned whether other differences between 'representative' males and females play a role similar to the whole body surface-to-mass area difference. Such contributing factors could be hand size or blood flow differences (Havenith et al. 1992).

In summary, previous research has shown that individual variation in contact cooling response is considerable and that some of this variation may be attributable to (1) sex and (2) hand morphology. However, these findings have been inconsistent and inconclusive due to the range of conditions tested and methods used. Research on differences in whole-body cooling and thermoregulatory response due to sex is extensive and well documented. However, this is not the case for contact cooling.

For the purpose of ascertaining relevant criteria or risk indicators for withdrawal during experimentation it was required to review the literature for studies relating to dysfunction of the hands caused by low skin temperature. Occurrences of pain have been reported at a range of skin temperatures; however, specifically for contact skin temperatures it has been found that the onset of pain occurs within the range 14–23°C (Havenith et al. 1992, 1995). Marked deterioration in tactile discrimination was found to occur at finger skin temperatures below 8°C and a considerable degree of numbness was found at skin temperatures of around 7–8°C (Provins and Morton 1960). Skin in air has been found to freeze at skin temperatures below −10°C, due to supercooling of the finger tissue (Wilson and Goldman 1970; Wilson et al. 1976). For skin in contact with cold metal, skin freezing was observed to occur at skin temperatures of −2.2°C (Lewis and Love 1926). The estimated theoretical freezing point of skin without the presence of supercooling was found to be −0.6°C (Keatinge and Evans 1960).

The aim of this study is to compare the fingertip cooling responses of males and females to short-term, cold-contact exposure. For this purpose, experiments were performed in which male and female participants with representative hand sizes for their gender touched various cold materials over a range of surface temperatures and contact forces.

## Methods

### Subjects

Ten participants (five men aged 21–26 years and five women aged 22–26 years) volunteered for the study. Potential subjects were excluded from the study if they had in the past suffered frostbite, any other related cold injuries or suffered from vascular disease. None of the subjects were smokers. They were instructed not to drink tea or coffee during the hour before the beginning of experimentation, or consume alcohol the evening prior to any experimental session. The subjects were all right-handed and had both their physical characteristics (Table 1) and hand characteristics (Table 4) measured. Mean hand characteristics were determined as follows: circumference of the 1st phalanx of the index finger was measured using string and rule. Volumes of the hand, index finger, 1st phalanx of the index finger were measured using water displacement by submerging the hand/finger in to water up to the base of the processus styloideus, proximal phalanx and distal phalanx, respectively. Lengths of the index finger and its 1st phalanx were measured using a sliding rule. Finger contact area and hand surface area were calculated by scanning a fingerprint at the appropriate pressure and hand-print into a customised computer programme (Holmér et al. 2001). Subject groups were selected such that hand sizes were representative of normative values for these population groups (People Size Pro 2000 software; Open Ergonomics, Loughborough, UK; http://www.openerg.com/psz/onestop.htm#quest5).

### Experimental design

Subjects were asked to touch four smooth-surfaced materials (aluminium, stainless steel, nylon and mahogany wood) at five different surface temperatures, a separate session for each subject at each temperature. The material, surface temperature and the three touching force levels (1.0 N, 2.9 N and 9.8 N) 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-min re-warming period in between.

**Table 1** Mean physical characteristics for male and female participants. Values are mean (SE)

| | Age (years) | Height (cm) | Weight (kg) |
|---|---|---|---|
| Male | 22.2 (2.4) | 184.2 (7.3) | 93.1 (12.4) |
| Female | 24.8 (5.9) | 167.2 (3.0) | 70.2 (10.6) |
| Overall | 23.5 (4.5) | 175.7 (10.4) | 81.7 (16.2) |

Equipment and measurements

Each subject rested for a period of 30 min in an air-conditioned preparation room (used to achieve the desired thermal environment) and was asked to rate his or her whole-body thermal sensation on a predicted mean vote (PMV) scale (ISO 7730, 1994; Moderate thermal environment—determination of the PMV and PPD indices and specification of the conditions for thermal comfort). These were recorded at 5-min intervals with the environmental conditions within the room adjusted in order to induce the desired PMV of –1 (slightly cool). The mean conditions of the room over all experimental sessions were $T_a$ = 19.1 (1.1)ºC, RH = 44.1 (4.8)% [mean (SE)]. 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).

Each subject touched, with the 1st phalanx of the index finger of the non-dominant hand, blocks (9.5×9.5×9.5 cm) of the four different materials which were chosen to represent a wide range of thermal properties as detailed in Table 2 (properties of material were tested by VTT, Finland, 14 June 1999). The thermal properties are expressed in terms of thermal penetration coefficient (*b*) (BSI 1978; Yoshida et al. 1989) which is defined as:

$$b = \sqrt{k \cdot \rho \cdot c}$$

(units = $\mathrm{Jm^{-2}\ s^{-1/2}\ K^{-1}}$), where $k$ is thermal conductivity ($\mathrm{W\ m^{-1}\ K^{-1}}$), $\rho$ is density ($\mathrm{kg\ m^{-3}}$) and $c$ is specific heat ($\mathrm{J\ kg^{-1}\ K^{-1}}$).

The material temperatures to be used were derived from pilot studies conducted at partner institutions (National Institute for Working Life, Sweden; Université Catholique de Louvian, Belgium; TNO Human Factors Research Institute, The Netherlands). This data provided information on the expected cooling speeds and safe temperatures for a range of materials. Based on this data the conditions were designed such that frost-nip risks were minimal and the skin cooling was slow enough to be controlled (Holmér et al. 2001). The experimental conditions are detailed in Table 3.

The materials were placed on a balance inside a modified Hotpoint Iced Diamond 87610 kitchen freezer, with a window and central access point incorporated into the door design. The required material surface temperature was achieved inside the coolbox using a P.I.D temperature control module which replaced the existing thermostat, thus allowing the freezer to regulate at lower temperatures (below –20°C) and with better accuracy and stability (± 0.5°C). Appropriate compensating weights were placed in the balance tray with the test material in order to achieve the required finger contact force. Contact force was regulated using feedback provided by three indicator lights (too low, correct, too high) linked to the balance tray.

For the purpose of measuring skin contact cooling, T-type thermocouples (copper/constantan) of 0.2 mm diameter (time-constant < 0.5 s) were attached to the palmar side of the 1st phalanx of the index finger of the non-dominant hand using 3 M Blenderm surgical tape. The base of the sensor tip was attached to the finger just below the 1st 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, Sunnyvale, Calif., USA).

Withdrawal criterion was the occurrence of one of the following: a contact temperature below 0.5°C; a test duration of 300 s; a typical sensation of frost-nip 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

It was considered most relevant for occupational practice to analyse the time after contact at which numbness or frost-nip would occur: 7°C for numbness (Provins and Morton 1960) and 0°C for skin freezing (Keatinge and Evans 1960).

The data collected was analysed using 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 was performed using the statistical software package SYSTAT (Systat, Evanston, Ill., USA). For significance, $P \leq 0.05$ was accepted.

## Results

### Physical hand measurements

The mean hand measurements of the non-dominant hand are detailed in Table 4. It was found that all female hand measurements were significantly smaller than the male participants (two-sample *t*-test, $P \leq 0.05$).

### Skin cooling data

Starting finger skin temperature ($T_ø$) varied considerably between subjects. Overall, $T_ø$ was found to be significantly lower for female participants [26.8 (3.0)°C] than the male participants [27.9 (2.9)°C] ($P < 0.001$).

**Table 2** Thermal properties of the materials tested

| Material | Density ($\rho$) ($\mathrm{kg\ m^{-3}}$) | Thermal conductivity ($k$) ($\mathrm{W\ m^{-1}\ K^{-1}}$) | Specific heat (mass) (c) ($\mathrm{J\ kg^{-1}\ K^{-1}}$) | Thermal diffusivity ($a = k\rho^{-1}c^{-1}$) ($10^{-6}\ \mathrm{m^{-2}\ s^{-1}}$) | Thermal penetration coefficient ($\mathrm{J\ m^{-2}\ s^{-1/2}\ K^{-1}}$) |
|---|---|---|---|---|---|
| Aluminium | 2,770 | 180 | 900 | 28.80 | 21,180 |
| Steel | 7,750 | 14.8 | 461 | 4.20 | 7,270 |
| Nylon | 1,200 | 0.34 | 1,484 | 0.19 | 780 |
| Wood | 560 | 0.22 | 2,196 | 0.18 | 520 |

**Table 3** Description of fast- and slow-cooling conditions. *S* Slow, *F* fast

| | + 5°C | −10°C | −17°C | −25°C | −35°C |
|---|---|---|---|---|---|
| Material | Stainless steel (S)<br>Aluminium (S) | Stainless steel (F)<br>Aluminium (F)<br>Nylon (S) | Stainless steel (F)<br>Aluminium (F)<br>Nylon (S) | Nylon (S)<br>Wood (S) | Nylon (S)<br>Wood (S) |

**Table 4** Mean hand characteristics and standard deviation of the non-dominant hand for male and female participants

| | 1st Phalanx circumference (cm) | 1st Phalanx volume ($cm^3$) | Finger volume ($cm^3$) | Hand volume ($cm^3$) | 1st Phalanx length (cm) | Finger length (cm) | Hand surface area ($cm^2$) | Finger contact area ($cm^2$) (1.0 N) | Finger contact area ($cm^2$) (2.9 N) | Finger contact area ($cm^2$) (9.8 N) |
|---|---|---|---|---|---|---|---|---|---|---|
| Male | 5.7 (0.2) | 5.3 (0.9) | 24.4 (6.6) | 468 (102) | 2.8 (0.3) | 7.7 (0.4) | 179.5 (18.9) | 2.4 (0.2) | 2.8 (0.2) | 3.2 (0.3) |
| Female | 4.6 (0.1) | 2.8 (0.4) | 15.2 (1.3) | 305.4 (36.1) | 2.4 (0.1) | 7.0 (0.2) | 146.3 (7.7) | 1.8 (0.1) | 2.1 (0.1) | 2.3 (0.2) |
| *P* | 0.010 | 0.002 | 0.011 | 0.020 | 0.049 | 0.016 | 0.014 | 0.002 | 0.001 | 0.001 |

However, within each condition there was no significant difference between $T_{ø}$ of male and female participants.

Highly different cooling rates were observed as a consequence of the thermal properties of the test material and its surface temperature. Typically, two different cooling patterns were found. The first, slower cooling, produced a distinct "bi-phasic" curve (see Fig. 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 2002). The second pattern (Fig. 2) only showed the steep part of the curve seen in the slow cooling. In this case the cooling was so fast that the withdrawal criteria were reached before cooling could affect the deeper skin layers. It was determined that in order to avoid any confounding effect of depth of skin cooling, all conditions would be broadly separated into "fast" and "slow" conditions. A fast or slow cooling condition was defined by observing finger skin contact cooling response. If a withdrawal criterion was reached within 10 s the curve was classified as fast. If a clear shallow part was observed, the curve was classified as slow. Typically the

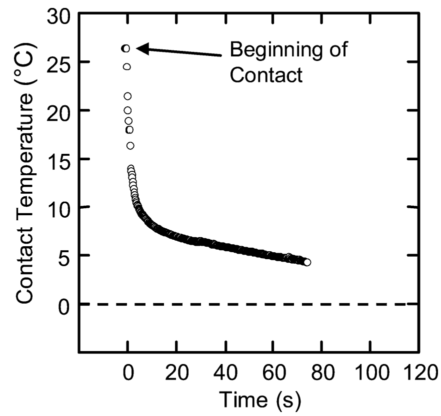


**Fig. 1** An example of a skin cooling curve recorded during a slow-cooling condition exposure

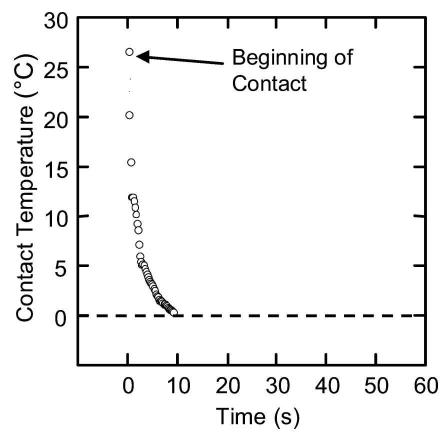


**Fig. 2** An example of a skin cooling curve recorded during a fast-cooling condition exposure

duration of these exposures were between 45 and 300 s. The rate under which each condition fell is detailed in Table 3.

Although the initial goal was to analyse all curves for the times to reach a contact temperature of 7°C or 0°C, the latter would require a substantial amount of extrapolation in most slow cooling conditions, introducing a large source of error. It was therefore concluded that the time taken to reach a contact temperature of 7°C ($T_7$) would be used for the time analysis of slow cooling conditions and the time taken to reach a contact temperature of 0°C ($T_0$) would be used for the time analysis of fast cooling conditions. In those cases where withdrawal occurred before the appropriate analysis point, extrapolation was performed using SYSTAT 7.0.

## Effect of sex

It was immediately apparent from the data that for the majority of slow cooling conditions tested in the study there was a considerable difference between the skin cooling times of the male and female participants, with the female's finger skin cooling much quicker than that of the males. An example is shown in Fig. 3. However, this ''effect'' of gender was lost for the fast cooling conditions, an example is shown in Fig. 4.

With the data separated between fast and slow cooling conditions, an analysis of variance (mixed ANOVA, repeated measures with sex as between-groups factor) was performed on each set. Under slow cooling conditions, it was found that sex [$F_{(1,8)} = 6.760$, $P < 0.05$] had a significant effect upon the time taken to reach a contact temperature of 7°C ($T_7$). Under fast cooling conditions, it was found that sex [$F_{(1,8)} = 0.077$, $P = 0.788$] did not have a significant effect upon the time taken to reach a contact temperature of 0°C ($T_0$). No interaction effects were found between any of the factors analysed (surface temperature, material type, finger contact force and sex) for either fast or slow cooling conditions.

The $T_0$ (fast cooling) and $T_7$ (slow cooling) values for males and females for finger contact with each separate material are detailed in Tables 5 and 6. Of all the 24 slow cooling conditions analysed, 18 showed females to cool significantly quicker than males. Of the 12 fast cooling conditions analysed, 8 showed males to cool quicker than females; however, these differences were marginal in most cases and no significant trend was apparent.

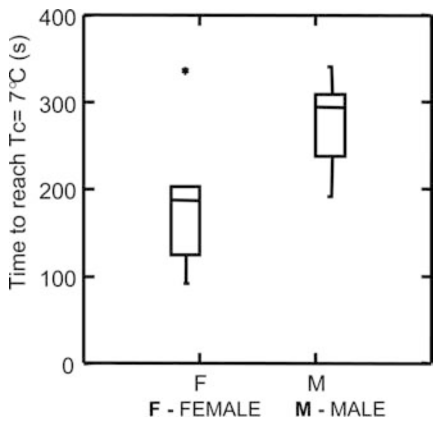


**Fig. 3** Box plot comparing male and female skin cooling times for wood at −25°C, 9.8 N contact force [medians: male ($M$) = 286 s, female ($F$) = 187 s]

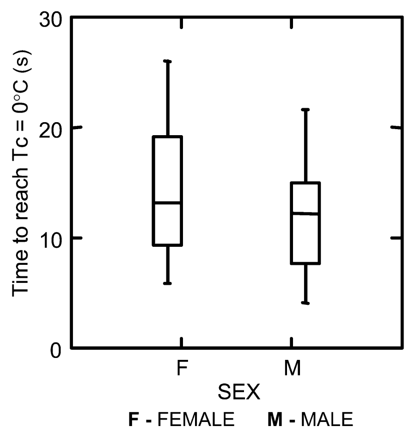


**Fig. 4** Box plot comparing male and female skin cooling times for steel at −4°C, 9.8 N contact force (medians: $M = 12.2$, $F = 13.2$)

**Table 5** Mean skin cooling times (in seconds) with standard deviations for males and females for finger contact with aluminium and steel under each temperature condition

| | Force | Sex | +5°C ($T_7$) | −10°C ($T_0$) | −17°C ($T_0$) |
|---|---|---|---|---|---|
| Aluminium | 1.0 N | M | 59.8 (69.4)* | 3.3 (4.7) | 1.2 (1.2) |
| | | F | 29.6 (20.2) | 3.9 (3.5) | 1.3 (1.2) |
| | 2.9 N | M | 44.2 (62.9)* | 2.9 (4.9) | 1.2 (0.9)* |
| | | F | 10.6 (8.6) | 2.4 (2.1) | 0.7 (0.3) |
| | 9.8 N | M | 15.2 (5.8)* | 0.9 (0.2) | 0.6 (0.3) |
| | | F | 5.4 (3.0) | 2.1 (1.4)* | 0.8 (0.3) |
| Steel | 1.0 N | M | 151.0 (117.7) | 5.0 (5.5) | 1.1 (0.5) |
| | | F | 138.4 (77.7) | 4.2 (1.9) | 2.0 (1.3)* |
| | 2.9 N | M | 105.6 (16.5)* | 6.9 (9.3)* | 1.2 (0.6) |
| | | F | 79.2 (62.2) | 2.4 (1.4) | 1.6 (0.8) |
| | 9.8 N | M | 95.2 (72.5) | 2.0 (0.8) | 1.2 (0.4) |
| | | F | 93.2 (24.9) | 3.2 (2.1)* | 1.4 (0.8) |

*Significantly greater value

**Table 6** Mean skin cooling times (in seconds) with standard deviations for males and females for finger contact with nylon and wood under each temperature condition

| | Force | Sex | −10°C ($T_7$) | −17°C ($T_7$) | −25°C ($T_7$) | −35°C ($T_7$) |
|---|---|---|---|---|---|---|
| Nylon | 1.0 N | M | 432.2 (44.7)* | 330.4 (69.1)* | 177.2 (66.6) | 96.6 (54.5)* |
| | | F | 323.0 (52.5) | 176.2 (111.6) | 160.0 (103.9) | 54.8 (49.7) |
| | 2.9 N | M | 413.0 (142.5)* | 294.0 (83.8)* | 226.4 (64.8)* | 74.2 (47.4)* |
| | | F | 357.8 (45.1) | 210.4 (92.5) | 126.8 (59.9) | 42.0 (39.3) |
| | 9.8 N | M | 429.8 (74.9)* | 253.8 (77.4)* | 145.2 (32.9)* | 98.6 (74.3)* |
| | | F | 327.3 (97.3) | 177.0 (85.9) | 94.3 (32.4) | 61.4 (37.8) |
| Wood | 1.0 N | M | - | - | 300.3 (54.7) | 200.4 (106.5) |
| | | F | - | - | 282.3 (200.7) | 215.2 (79.8) |
| | 2.9 N | M | - | - | 290.2 (99.4)* | 210.0 (113.5) |
| | | F | - | - | 240.0 (73.5) | 195.6 (58.6) |
| | 9.8 N | M | - | - | 274.6 (59.8)* | 286.6 (58.6)* |
| | | F | - | - | 188.6 (93.9) | 207.2 (60.5) |

*Significantly greater value

Differences of skin cooling time in relation to hand size

The subjects were selected for this study in order to provide a representative group in terms of hand size; therefore, by design there was a difference in hand measurements between the male and female participants, with females having significantly smaller hand and finger dimensions.

In order to investigate whether the skin cooling times are related to the differences in hand measurements between males and females observed under the longer slow cooling conditions tested, individual cooling times ($T_7$) were plotted against individual hand measurements such as finger volume. Examples of the linear regression plots obtained are detailed in Figs. 5 and 6. It can be seen that skin cooling time under slow cooling conditions is significantly related to individual hand/finger measurements with skin cooling time increasing with hand and finger size.

Large variation was present in some conditions and sample size was only small for this analysis. Hence, a stepwise general linear model (GLM) was used in order to analyse all of the slow cooling conditions together, thereby increasing the statistical power. The GLM 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 sex.

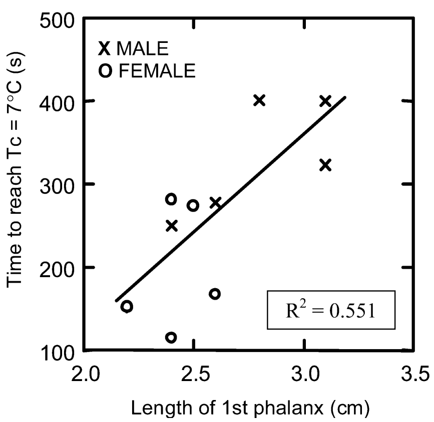


**Fig. 5** A regression plot of time to reach a contact temperature ($T_C$) of 7°C against length of 1st phalanx for nylon; −17°C, 1.0 N ($P$=0.014)

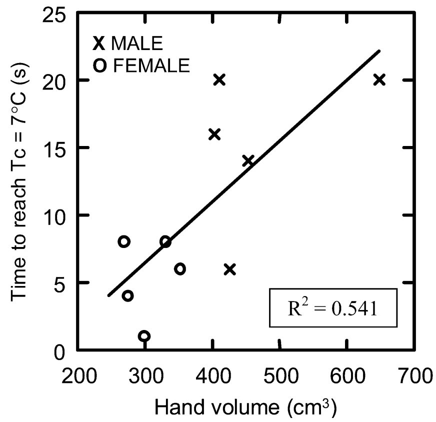


**Fig. 6** A regression plot of time to reach a $T_C$ of 7°C against hand volume for aluminium; +5°C, 9.8 N ($P$=0.015)

The model tested is described below and the extent to which each parameter affected skin cooling time was determined by using an interactive forward stepwise method, including the parameters found to have a significant effect:

$$\textit{Time to reach}[T_C = 7^\circ C] = \beta_0 + \beta_1 \times [\text{Materialproperty}] + \beta_2 \times [\text{Material surface temperature}] + \beta_3 \times [\text{Fingercontactforce}] + \beta_4 \times [\text{Handsize}] + \beta_5 \times [\text{Sex}]$$

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. Sex was represented by a dummy variable of "1" for female, "2" for male.

The skin cooling times ($T_7$) of the 233 cases of finger contact under the slow cooling conditions tested were investigated and contact material ($\beta\beta_1$) and surface temperature of the contact material ($\beta_2$) were all found to have a highly significant effect upon skin cooling time ($P \leq 0.001$) and were all included in the stepwise regression model. Finger contact force ($\beta_3$) did not significantly contribute to the residual variance in $T_7$ ($P = 0.105$).

Subsequent analyses of the residual variance for the effect of hand size indicators and sex showed that both correlated significantly with the residual variance in $T_7$ (finger volume: $P < 0.001$; sex: $P = 0.001$).

Finger volume was found to have a greater partial correlation coefficient and greater significance, it was therefore included in the model above sex. The inclusion of finger volume in the model removed the correlation of sex with the residual variance in $T_7$ ($P = 0.952$). If sex was included first in the model above finger volume, finger volume continued to show a significant correlation with the residual variance in $T_7$ ($P = 0.020$); however, when both were included in the model, sex again lost its significance. Sex and hand size, as stated earlier, are highly correlated. However, for these data the model has shown hand size to have a greater effect upon skin cooling time ($T_7$) under the slow cooling conditions tested in this study.

This greater effect of hand size upon finger skin cooling time was found to be the case when represented by hand volume ($P < 0.001$), finger volume ($P < 0.001$), 1st phalanx volume ($P = 0.001$), hand area ($P < 0.001$), 1st phalanx circumference ($P = 0.001$), and finger pad contact area ($P < 0.001$). However, this was not found to be the case with finger length ($P = 0.629$) and 1st phalanx length ($P = 0.250$).

Whilst a number of hand/finger measurements have been found to significantly affect finger skin cooling time, more than one of these measurements cannot be included in the model simultaneously, as all measurements are highly correlated due to the fact that they have been measured from the same hand.

## Discussion

### Physical hand measurements

Subjects were not selected for matching hand size, but to represent the average male and female. The physical hand measurements taken of the non-dominant hand showed that the males in this study had significantly larger measurements in all hand and finger dimensions than the female participants. A comparison to normative data using People Size Pro 2000 software (Open Ergonomics, Loughborough, UK) showed that the two measurements that can be compared (1st phalanx circumference and finger length) are very close to that of the normative data of 1st phalanx circumference, be it slightly higher for both the males and the females: (M) 5.7 (0.2) cm versus 5.4 (0.4) cm for reference, (F) 4.6 (0.1) versus 4.5 (0.3) cm for reference, and finger length: (M) 7.7 (0.4) cm versus 7.6 (0.5) cm for reference, (F) 7.0 (0.2) cm versus 6.9 (0.4) cm for reference. This suggests that our participants provide a sufficient representation of the normal male and female population.

### Skin cooling data

The starting skin temperature of the fingertip ($T_{ø}$) for males was on average 1.1°C higher than that of the female participants. The 30-min moderate whole-body cooling occurring before exposure allowed a baseline whole-body thermal state to be achieved, this was reflected in an actual mean vote of "slightly cool". Despite the preparation room environmental conditions being the same for both male and female participants, the effect of the conditions upon starting skin temperature were slightly different. This can be explained by the data of Bollinger and Schlumpf (1976) who observed that arterial inflow to the fingers of women is normally only about half of that of men, and women reduce their arterial finger inflow much more than men in response to cooling, therefore giving lower skin temperatures.

The work being conducted is concerned with *protecting* workers of both sexes from discomfort, pain, numbness and skin damage. The temperatures at which these phenomena occur are the same for both males and females; therefore, for the purpose of comparison it is logical to investigate the times taken for these temperature thresholds to be reached, despite a difference in starting skin temperature between the two subject groups.

Despite large individual differences, the method used to represent the skin cooling occurring ($T_7$ or $T_0$ depending upon cooling condition) would appear to be sufficiently discriminative. Material type and surface temperature were found to have a significant effect upon finger skin cooling under both fast and slow cooling conditions. Finger contact force was found to have a significant effect upon finger skin cooling under fast-cooling conditions, but not under slow-cooling conditions (however, there was a trend suggesting that cooling was quicker with greater finger contact force). The effects of finger contact force on contact cooling response were not as strong in the present study as with previous investigations (Geng et al. 2000; Holmér et al. 2000); however, it did appear that skin cooling time did decrease as finger contact force increased (as expected) in most cases. The method used for regulating pressure in the present study was not optimal and may have resulted in more noise in the data; however, this did not in anyway affect the comparison of contact cooling responses between males and females.

There were no significant differences apparent due to sex for the fast cooling conditions, but there were for slow cooling conditions. This difference between cooling time of males and females is supported by data collected by Geng et al. (2001). Though they did not report the gender effect their tabular data show a substantial difference in skin cooling time to reach a contact temperature of 7°C between males and females for finger contact with aluminium and steel at surface temperatures of +2°C and −4°C, but the differences were no longer observed at surface temperatures of −10°C and −17°C. The latter provided a faster cooling rate potentially being too quick for any individual variation to be apparent in terms of sex.

In the present study, the slow-cooling conditions of metals at +5°C and all non-metals conditions elicited the cooling of the deeper epidermal and dermal layers and subcutaneous tissue, producing a smaller temperature gradient throughout the contact finger, i.e. at a given finger skin temperature, the deeper tissues of the fingertip will be cooler under slow-cooling conditions. The female participants were found to cool quicker under these conditions and the subsequent analyses found this to be significantly affected by hand and finger size. This is supported by the finding of Chen et al. (1994b) where a factorial analysis of the Newtonian cooling parameters derived from finger contact with aluminium at surface temperatures of +7°C, 0°C and −7°C showed that finger morphology factors significantly contributed to the description of the skin cooling occurring.

Burse (1979) stated that when considering cold injury to the extremities, women are at greater risk when working in the cold. The geometry of women's thinner extremities results in a greater heat outflow for the same circulatory heat input per unit tissue mass. This appears to be the case in the present study, where a larger finger (and in most cases hand) has a higher heat content thus giving a longer cooling time. Interestingly, this appears to be further reflected by the hand measurements that were *not* found to have a significant effect upon finger skin cooling time (finger length and 1st phalanx length). This seems to suggest that the shape of hand and finger is a determining factor in skin cooling time. Female fingers may be similar in length to male fingers but more slender (as described by finger volumes and 1st phalanx circumferences). The differences in hand and finger shape between males and females are described by the correlation found between hand and finger measurements for both sexes. As expected, finger length is a bad predictor of finger volume for both sexes (M: $r=0.46$, F: $r=0.49$), reflecting males having thicker fingers than females with similar finger lengths. Hand volume is a good predictor of finger volume for both sexes (M: $r=0.91$, F: $r=0.88$), with males having thicker hands accompanied by thicker fingers and females having more slender hands and fingers.

Sex and hand/finger size are highly correlated, and therefore their effects as parameters in a model describing skin cooling time (as represented by partial correlation coefficients) have a similar influence. It was found that hand/finger size had a slightly greater predictive power than sex and therefore the emphasis has been on describing the differences between the responses of males and females simply as a result of differences in hand and finger morphology. However, in order to derive conclusive evidence of the effects of hand size independent of sex, finger skin contact cooling responses must be drawn from an experimental group selected to discriminate between the hand size and sex effect, composed of males and females with similar hand and finger dimensions and not for a representative group of males and females as in the current experiment.

In conclusion, it is apparent from the present study that for practical purposes (i.e. a representative group of males and females in terms of hand size), that females show significantly faster cooling of the finger skin than males when in contact with the cold solid materials tested under slower cooling conditions, where cooling of the deeper epidermal and dermal layers and subcutaneous tissue occurs. However, no differences in skin contact cooling times were found between sexes for the fast cooling conditions (below 10 s to reach $T_0$) tested, where only cooling of the epidermal layer occurs. The difference between male and female skin cooling responses under slow cooling conditions is tentatively attributed to the differences found in hand/finger size, structure and shape; however, conclusive proof would require an additional experiment using males and females of equal hand dimensions.

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