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Skin Cooling on Contact with Cold Materials: The Effect of Blood Flow During Short-term Exposures

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This study investigates the effect of blood flow upon the short-term (<180 s) skin contact cooling response in order to ascertain whether sufferers of circulatory disorders, such as the vasospastic disorder Raynaud's disease, are at a greater risk of cold injury than people with a normal rate of blood flow. Eight female volunteers participated, touching blocks of stainless steel and nylon with a finger contact force of 2.9 N at a surface temperature of –5°C under occluded and vasodilated conditions. Contact temperature (T_c) of the finger pad was measured over time using a T-type thermocouple. Forearm blood flow was measured using strain gauge plethysmography. Contact cooling responses were analysed by fitting a modified Newtonian cooling curve. A significant difference was found between the starting skin temperatures for the two blood flow conditions ($P < 0.001$). However, no effect of blood flow was found upon any of the derived cooling curve parameters characterizing the skin cooling response ($P > 0.05$). It is hypothesized that the finger contact force used (2.9 N) and the resultant pressure upon the tissue of the contact finger pad restricted the blood supply to the contact area under both blood flow conditions; therefore, no effect of blood flow was found upon the parameters describing the contact cooling response. Whilst the findings of this study are sufficient to draw a conclusion for those in a working environment, i.e. contact forces below 2.9 N will seldom be encountered, a further study will be required to ascertain conclusively whether blood flow does affect the contact cooling response at a finger contact force low enough to allow unrestricted blood flow to the finger pad. Further protocol improvements are also recommended.

Keywords: blood flow; cold injury; contact; finger pressure; skin freezing

INTRODUCTION

The accidental touching of cold surfaces is commonplace in an industrial setting and for those working in such an environment, accidental skin contact exposure and the resultant skin cooling could pose a health and safety risk in terms of discomfort, pain, numbness and skin damage (Enander, 1986, 1989). Despite the presence of a standard to determine the temperature limits of hot surfaces in order to minimize safety risks (EN, 1994), no such standard was available for environments containing cold surfaces. This issue was addressed by the collection of data 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 who, therefore, may not be covered by the data collected.

Peripheral blood flow can vary greatly depending upon the thermal state of a given person, which is a function of activity level, climate and clothing insulation. These are largely dictated by the task required of the worker. The effect of varying states of blood flow upon the skin cooling response during short-term or accidental cold contact has not yet been quantified. Understanding the effects of blood flow upon contact cooling is of great importance when considering the protection of numerous individual groups in a working environment. The cold contact responses of sufferers of circulatory disorders, such as the vaso-

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spastic disorder Raynaud's disease, which is characterized by excessive vasoconstriction of the cutaneous circulation of the extremities (Coffman, 1989), may be greatly affected should blood flow have an influence upon fingertip contact cooling.

A study by Chen *et al.* (1994b) incorporated a 3 min 'body warming' step activity preceding index finger contact with aluminium and found that this had a significant effect upon the rate of contact cooling of the finger pad when compared with a 'body cooling' condition. Havenith *et al.* (1992) investigated the cooling responses for whole hand contact gripping cold bars and observed that a 30 min step activity that raised rectal temperature by 0.4°C, preceding cold contact exposure, had a significant effect upon the rate of skin cooling. More recent work by Geng *et al.* (2000) studied the change in skin surface contact temperature of the index finger touching cold surfaces. They hypothesized that the effects of differences in finger contact pressure were in part attributed to 'finger blood flow reducing, or even stopping with higher pressures'.

The influence of ambient temperature on the effect of segment skin temperature has been summarized by Montgomery (1974). At a given skin temperature the blood flow through a body segment tends to be higher with increasing ambient temperature. The absolute effect of ambient temperature on hand blood flow is less pronounced at lower skin temperatures than at a skin temperature above 32°C. Above 35°C, the effect of ambient temperature on forearm blood flow, at a given skin temperature, tends to decrease. The rate in segmental blood flow with skin temperature above 32°C is higher in a warm environment than a cold one.

From the literature it is evident that many factors have an influence upon peripheral blood flow. However, the effects of differences in blood flow upon contact cooling remain unclear. It is deemed necessary to investigate this further in order to account for circulatory affected groups when deriving protective values for cold surfaces in a working environment.

The aim of this study was to compare the finger pad cooling responses of an occluded and a non-occluded hand to short-term cold contact exposure and to study whether this response is related to differences in blood flow state. For this purpose, experiments were performed where subjects touched materials at different temperatures under occluded and, to maximize possible differences, vasodilated conditions.

MATERIALS AND METHODS

Subjects

Eight participants (all females aged 19–24) 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 within 1 h before the beginning of the experiment or consume alcohol the evening prior to any experimental session. All subjects had their physical characteristics and hand characteristics measured. These measurements are detailed in Tables 1 and 2, respectively. Blood pressure was measured using a Speidel and Keller automatic blood pressure monitor (wrist version), the specification accuracy being ±3 mmHg and ±5% of pulse reading. Body surface area was estimated using DuBois surface area (A_D) (DuBois and DuBois, 1916).

Experimental design

Subjects were asked to touch two materials (stainless steel and nylon) at a surface temperature of –5°C with a finger contact force of 2.9 N (equivalent to producing 300 g on a weight scale). Cold contact responses were investigated under both occluded and free-flow conditions, a separate session for each subject under each blood flow condition. The material and blood flow condition were presented in a balanced design such that an effect of order was avoided. Each exposure was repeated three times during the same session with a 5 min rewarming period in between.

Table 1. Mean physical characteristics for participants in the study

Subject no.	Age (yr)	Height (cm)	Weight (kg)	DuBois surface area (m^2)	Resting blood pressure (mmHg)
1	23	174	64.3	1.76	104/53
2	21	161	57.6	1.60	118/72
3	24	167	64.5	1.72	119/78
4	19	169	69.0	1.79	138/88
5	22	163	61.2	1.66	100/60
6	21	165	73.0	1.54	127/73
7	20	162	64.4	1.68	119/72
8	21	173	62.1	1.74	113/87
Mean ± SD	21 ± 2	167 ±5	65.5 ± 4.4	1.69 ± 0.07	117/73 ± 12/12

Table 2. Mean hand characteristics of the non-dominant hand for participants in the study

No.	First phalanx circumference (cm)	Finger volume (cm^3)	Hand volume (cm^3)	First phalanx length (cm)	Finger length (cm)	Finger contact area (cm^2) (2.9 N)	Hand surface area (cm^2)
1	3.8	15	275	3.0	7.5	2.6	179
2	4.6	15	280	3.5	7.7	2.0	167
3	5.0	13	283	2.9	7.7	2.2	157
4	4.5	19	311	2.9	7.7	2.7	141
5	4.7	13	260	4.7	7.3	2.8	129
6	4.1	11	264	3.2	7.1	2.2	144
7	4.7	15	296	2.7	8.0	2.9	142
8	5.0	10	241	2.7	7.1	2.2	133
Mean ± SD	4.6 ± 0.4	14 ± 3	276 ± 21	3.2 ± 0.7	7.5 ± 0.3	2.5 ± 0.3	149 ± 17

Table 3. Thermal properties of materials tested

Material	Density (ρ) (kg/m^3)	Thermal conductivity (k) (W/m/K)	Specific heat (mass) (c) (J/kg/K)	Thermal diffusivity ($a = k/\rho/c$) (10^{-6} m^2/s)	Thermal penetration coefficient ($J/m^2/s^{1/2}/K$)
Steel	7750	14.8	461	4.20	7270
Nylon	1200	0.34	1484	0.19	780

Equipment and measurements

Each subject touched, with the first phalanx of the index finger of the non-dominant hand, blocks (9.5 × 9.5 × 9.5 cm) of stainless steel and nylon. The thermal properties of the materials are detailed in Table 3 (properties of the materials 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 $b = (k \cdot \rho \cdot c)^{1/2}$ ($J/m^2/s^{1/2}/K$), where k is thermal conductivity (W/m/K), ρ is density (kg/m^3) and c is specific heat (J/kg/K).

The test materials and surface temperature were selected such that contrasting rates of cooling were obtained at the same temperature (fast and slow) (Jay and Havenith, 2003).

Prior to cold contact exposure, the desired blood flow state was obtained in order to achieve an occluded or vasodilated condition.

Vasodilated blood flow state procedure

Upon arrival, the subject's forearm blood flow was measured using an EC4 Hokanson SGP mercury strain gauge plethysmograph. Five measurements were taken and saved to a PC over a 5 min period using a customized WorkBench PC for Windows 3.00.15 program. Upon completion of the measurements the subject was required to cycle on an ergometer for 30 min with 5 min rests every 5 min after the initial 10 min of exercise. The required metabolic rate of ~140 W/m^2 (mean 139 ± 6 W/m^2) was performed in an environmental chamber with mean environmental conditions of T_a = 34.6 ± 0.9°C and relative humidity = 31.9 ± 4.5%, with a clothing insulation of 0.3 clo (cotton underwear, socks, shorts, trainers and T-shirt). After a 30 min period since initial exposure had elapsed, the subject was transferred (walked) next door to a heated preparation room (mean environmental conditions T_a = 30.1 ± 1.3°C, relative humidity = 32.2 ± 4.1%). For the purpose of this transfer the subject's clothing insulation was increased to ~0.6 clo (cotton underwear, socks, shorts, trainers and T-shirt + tracksuit trousers and sweatshirt). Forearm blood flow was measured again, following which the subject was instrumented for the contact cooling exposure. Forearm blood flow was once again measured at the end of the session.

Occluded blood flow state procedure

Upon arrival, each subject sat in a test room with a standard clothing insulation of 0.4–0.5 clo (cotton underwear, socks and T-shirt; jeans and trainers/shoes) and at normal room temperature (T_a = 19.1 ± 1.2°C, relative humidity = 33.1 ± 2.0%). The subject's non-dominant arm was elevated above heart level for 30 s, after which a blood pressure cuff was placed around the wrist just below the styloid process of the ulna and inflated to 200 mmHg to stop all blood flow to the hand. The cold contact exposure was performed and upon conclusion of each exposure the cuff was deflated. The procedure was performed for each cold contact exposure for this condition.

Contact cooling procedure

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 (Jay, 2002). The

required material surface temperature was achieved inside the cool box using a PID temperature control module to override the existing thermostat, thus allowing the freezer to regulate at lower temperatures (below –20°C) and with greater 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 of 2.9 N (300 g weight produced on a balance). Contact force was regulated using feedback provided by an analogue pointer 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 first 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 first 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' (T_c). Starting finger skin temperature was determined before contact by pinching the thumb against the thermocouple on the forefinger. This temperature represents an average of thumb and finger skin temperatures, thereby eliminating any effects of the ambient temperature on the partially exposed sensor. Local skin cooling of the contact area was monitored using a WorkBench PC for Windows 3.00.15 program in conjunction with a 16 bit Strawberry Tree DATAshuttle™, model DS-16-8-TC-AO, with cold junction compensation (Strawberry Tree Inc., Sunnyvale, CA).

The withdrawal criterion was the occurrence of one of the following: a contact temperature of 0.0–0.5°C; 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; an exposure duration of 180 s.

Analysis

The observed contact cooling was analysed by fitting a mathematical model to each separate cooling curve. The model used was a modified Newtonian cooling curve, a function describing the skin cooling as a second order exponential decay, with the curve being treated in two stages (Chen *et al.*, 1992, 1994a). Stage A is dominated by one time constant (τ_1) and stage B by a second (τ_2) (see Fig. 1).

$$T_c(t) = T_F + (T_o - T_F) \cdot (A \cdot e^{-t/\tau_1} + B \cdot e^{-t/\tau_2})$$

where $T_c(t)$ is the contact temperature at time t, T_F is the final skin temperature, T_o is the starting skin temperature, t is the cold contact exposure time, τ is the time constant of the cooling process, A is the proportion of the cooling process dominated by τ_1 and B is the proportion of the cooling process dominated by τ_2.

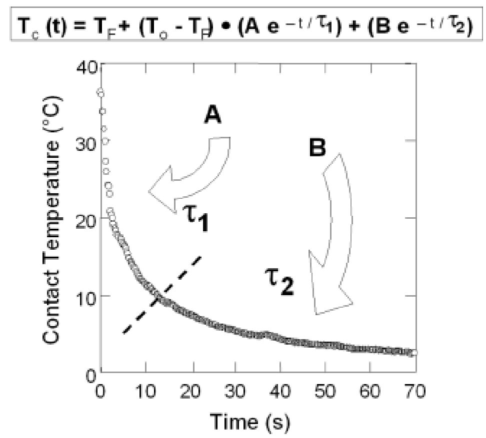

Fig. 1. Diagram describing the modified Newtonian cooling curve.

All modelling was performed using the statistical software package SYSTAT 8.0 (Systat Inc., Evanston, IL).

Statistics

The data collected was analysed using analyses of variance and covariance studying the relationships between individual parameters and the skin cooling occurring. All analyses was performed using the statistical software package SYSTAT (Systat Inc.). For significance, $P < 0.05$ was accepted.

The Loughborough University Ethical Advisory Committee approved the study.

RESULTS

Starting finger skin temperature (T_o) before cold contact exposure varied considerably between blood flow conditions. Of the 45 cooling exposures recorded under the occluded condition, mean T_o was 26.3 ± 1.3°C, compared with a mean T_o of 33.7 ± 1.6°C for the 44 cooling exposures recorded under the vasodilated condition. An analysis of variance (ANOVA) with a *post hoc* test showed that there was a significant difference in starting skin temperature between the two blood flow conditions ($P < 0.001$).

The modelling process characterized each curve with five parameters: A, B, τ_1, τ_2 and predicted T_F for each exposure. The mean values of these parameters for the occluded and vasodilated conditions for both the stainless steel and nylon exposures are detailed in Table 4. Mean adjusted r^2 values of the mathematical model used for the fitting of the cooling curves observed over all conditions are also detailed.

Effect of blood flow

Forearm blood flow measurements taken under the vasodilated condition showed that peripheral cutaneous vasodilation was occurring due to the exercise performed in the climatic chamber (T_a = 34.6°C, relative humidity = 32%). On arrival, strain gauge plethysmography measured a mean forearm blood flow of 5.3 ml/min/100 ml, compared with a mean reading of 14.0 ml/min/100 ml after thermal chamber exercise and 12.9 ml/min/100 ml at the end of the session.

An ANOVA was performed on the finger pad contact cooling data for both stainless steel and nylon comparing the contact cooling responses under occluded and vasodilated conditions. A *post hoc* test was carried out by treating 'subjects' as a random factor; the main fixed effect of 'blood flow condition' was tested against its interaction with 'subjects', using the interaction as the error term. For significance, $P < 0.05$ was accepted.

No significant differences were found between the occluded and vasodilated responses for any of the equation parameters for stainless steel or nylon.

An overall ANOVA was also performed using the data from both conditions together. No significant differences were found between the occluded and vasodilated finger pad contact cooling responses for any of the equation parameters. However, all equation parameters were found to be significantly different when compared between materials ($P < 0.001$), with nylon being dominated by a longer second time constant (τ_2) and stainless steel being dominated by a shorter first time constant (τ_1). After the *post hoc* test, no significant differences were found between the occluded and vasodilated conditions for all equation parameters ($P > 0.05$). An example of the cooling curves observed under both blood flow conditions is demonstrated in Fig. 2 for stainless steel and Fig. 3 for nylon.

Table 4. Mean individual equation parameters for occluded and free-flow conditions for finger contact with stainless steel and nylon

Parameter	Blood flow condition	–5°C stainless steel	–5°C nylon
τ_1	Occluded	1.79 ± 0.73	3.13 ± 1.43
τ_1	Vasodilated	1.66 ± 1.16	2.53 ± 1.86
τ_2	Occluded	19.33 ± 8.77	382.2 ± 151.3
τ_2	Vasodilated	16.23 ± 9.04	347.6 ± 136.1
A	Occluded	0.59 ± 0.11	0.31 ± 0.11
A	Vasodilated	0.60 ± 0.18	0.37 ± 0.13
B	Occluded	0.29 ± 0.11	0.59 ± 0.06
B	Vasodilated	0.39 ± 0.09	0.56 ± 0.09
T_f (°C)	Occluded	–0.37 ± 0.95	4.67 ± 3.57
T_f (°C)	Vasodilated	0.46 ± 0.99	7.41 ± 3.72
r^2	Occluded	0.988	0.991
r^2	Vasodilated	0.992	0.973

Differences between τ_1 and τ_2

For both blood flow conditions and both materials it was found that τ_1 was significantly shorter than τ_2 ($P < 0.001$).

DISCUSSION

The second order Newtonian cooling model used for the analysis was found to be a very accurate mathematical model for the data obtained. An almost perfect fit to the observed values was obtained for both materials under both occluded and vasodilated

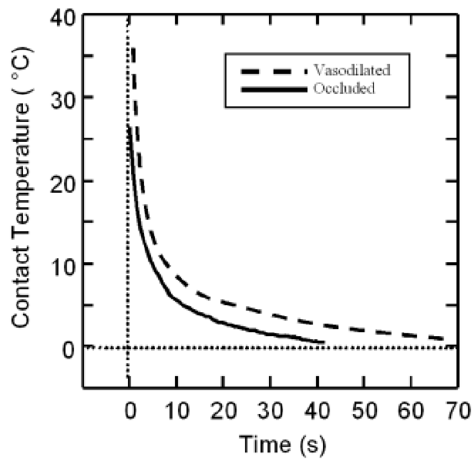

Fig. 2. An example of a comparison between the skin cooling response for vasodilated and occluded blood flow conditions for contact with stainless steel.

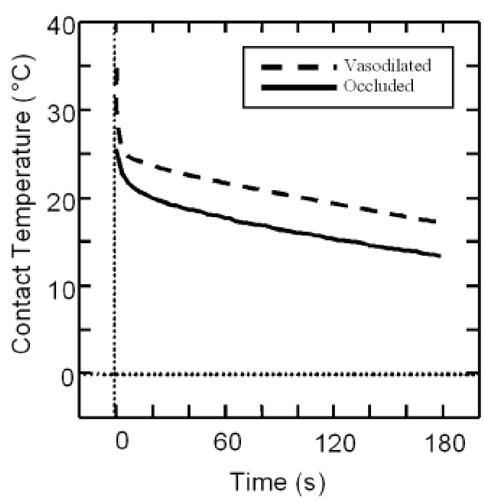

Fig. 3. An example of a comparison between the skin cooling response for vasodilated and occluded blood flow conditions for contact with nylon.

conditions. This is reflected in the overall adjusted r^2 values for stainless steel of 0.988 and 0.992 and for nylon of 0.991 and 0.973 for the occluded and vasodilated conditions, respectively.

The time constants derived from the model would appear to describe different aspects of the cooling process and this is shown by the highly significant difference between the two for both materials. The first time constant (τ_1) was short, and this represents cooling of the very superficial epidermal layer and primarily thermocouple dynamics (Chen *et al.*, 1994a). The second time constant (τ_2) was longer, representing the cooling of the deeper dermal layers of the fingertip. For stainless steel, the cooling process was overall a lot quicker and was dominated to a greater extent by the shorter, first time constant, which is reflected in the value of parameter *A* being greater for both blood flow conditions. The larger thermal penetration coefficient of stainless steel elicited a faster skin cooling response, in comparison with nylon, where the cooling process was considerably slower. It can be seen that both the first and second time constants for nylon were significantly longer and that the overall cooling process was dominated to a greater extent by the very long second time constant. This effect of material upon the equation parameters is supported by the findings of Chen *et al.* (1992) where wood, nylon and aluminium had a significant effect upon the finger skin cooling process.

As this study was conducted with the aim of investigating any possible effects of blood flow upon contact cooling responses, comparing a maximal blood flow condition with that of an occluded hand was considered the optimal way in which to observe any potential differences. Despite this, it was found that there were no significant differences in the parameters describing the contact cooling responses of the finger pad of the index finger of the non-dominant hand between the occluded and vasodilated conditions for contact with both stainless steel and nylon.

An effect of blood flow condition was found upon starting finger temperature before contact, with the increased tissue heat content of the fingertip as a consequence of exercise giving a significantly higher starting temperature for the vasodilated condition. Whilst this difference in starting finger temperature did not affect the rate of contact cooling, it can be observed from Figs 2 and 3 that a given contact temperature would be reached appreciably quicker under the occluded condition. Despite this, which may be of practical value, i.e. a person with a lower starting finger temperature would reach a given critical value in a shorter time, the effect of blood flow is only upon the starting temperature and not the rate of cooling during contact with the cold materials used in this study.

However, a number of points can be raised in terms of the methodology used in this study and whether particular aspects could have potentially masked any effects of blood flow upon the finger skin cooling responses.

Considering the two stages of the cooling process as discussed above, no differences were anticipated in the first time constant between the occluded and vasodilated condition. The short, first time constant (1.7–3.2 s) primarily represents thermocouple dynamics and superficial cooling of the epidermal layers; the majority of these layers are non-vascularized and therefore any heat input due to blood flow is expected to be minimal. However, the longer second time constant (16–382 s) represents cooling of the deeper dermal layers, all of which are richly vascularized with capillary loops immediately under the epidermal layer and networks of arterioles in the deeper layers (Baran and Dawber, 1994). Surprisingly, this particular part of the cooling process was also found not to be significantly affected by the two blood flow conditions tested in this study. A possible cause for this could be found in the force of the finger pad on the contact material, which may have restricted the blood flow of the finger skin tissue.

The effect of pressure applied to the fingertip on blood flow through the fingertip has been discussed by Mascaro and Asada (2001), who report that forces between 0.3 and 1 N progressively restrict the venous return of blood in the fingertip. As the touch force reaches 1 N, the veins of the fingertip are completely blocked and further increases in touch force, to a limit of ~4 N, begin to push all blood out of the tip of the finger, resulting in a widening white band at the front of the nail. This effect of touch pressure is also apparent for the skin of the finger pad. Figure 4 shows the effect of a gradual increase in pressure upon the visible blood supply to the skin of the finger pad, with increasing white discolouration of the contact skin area with pressure.

Geng *et al.* (2000) found significant differences between the finger pad contact cooling response between force levels of 0.98, 2.94 and 9.81 N, with cooling rate increasing with pressure. They partly attributed this to finger blood flow reducing or even stopping at higher pressure levels.

From this literature it becomes apparent that the finger contact force level used for contact in this particular study (2.9 N) may have restricted the blood supply to the skin area being cooled. It is especially likely that the vascularized layers that are closest to the skin surface, those supplied by capillary loops, may have been occluded.

Blood pressure in humans is typically 35 mmHg at the start of the capillary network and reduces from 35 to ~18 mmHg as the blood moves through the capillary beds towards the venous system (Martini, 1998). More specifically for the fingertips, blood pressure in

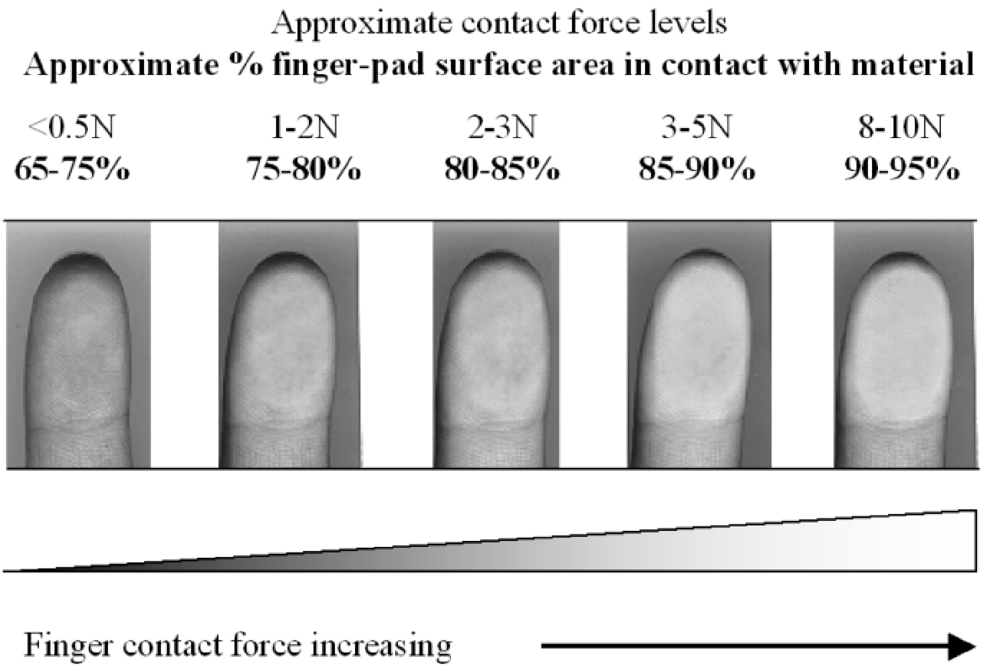

Fig. 4. Visible effects of approximate finger contact force levels upon the blood supply to the skin of the finger pad of the index finger.

human nailfold capillaries has been found to be 18–19 mmHg at rest and unaffected for short periods of exercise, suggesting the presence of a protective mechanism minimizing the transmission of increases in systemic blood pressure to this capillary bed (Shore *et al.*, 1993). Hahn and Shore (1994) found that local rapid cooling of the fingertip caused a trend of reducing mean capillary blood pressure of the nailfold from 16.7 to 15.1 mmHg.

For the purpose of comparing the capillary blood pressures reported in the literature above with the pressures exerted by the finger contact force in the present study, the actual pressure of the contact area of the fingertip of the participants used in the present study was calculated. This was achieved by dividing the finger contact force (~3 N) by the finger contact area (see Table 2). The approximate value for this was calculated as 12 000 N/m^2, which can be converted to 90 mmHg. This far exceeds any of the capillary blood pressure values reported in the literature and thus provides strong evidence that blood supply to the finger pad may be restricted. For the purpose of further study, a finger pressure of ~20 mmHg (contact force ~0.5 N) would be recommended to ensure that capillary blood flow of the finger pad was not obstructed.

Further aspects of the experimental protocol may have masked potential differences between contact cooling response of the occluded and vasodilated hand. Havenith *et al.* (1992) found that a change in starting skin temperature affected the shape of a first order Newtonian cooling curve in longer exposures. Whilst this problem was suggested to be addressed by the using a two time constant Newtonian equation (Chen *et al.*, 1994a), such a great difference in starting skin temperatures between the two blood flow conditions in the present study could affect the shape of the subsequent cooling curves. This problem could be addressed by heating the participant in both cases, occluded and vasodilated, thus giving similar pre-test skin blood flows and starting finger skin temperatures.

Blond and Madsen (2000) found that elevation of the upper limb was required for at least 30 s for a 45% mean reduction in blood volume caused by exsanguination. Warren *et al.* (1992) reported that advice within the literature regarding duration and angle of arm elevation required to empty the blood from the arm is confusing, with recommendations ranging from 20 s to 5 min. As far back as 1864, investigations accompanying the invention of the tourniquet recommended that the limb should be elevated for 4 min before tourniquet application in order to create a bloodless surgical field. Warren *et al.* (1992) studied volume changes of the upper limb and found that for maximal exsanguination, an arm elevation at 90° for 5 min is recommended. The 30 s elevation in the present study is considerably shorter than the majority of the durations suggested in the literature. It is conceivable that occlusion after 30 s of elevation

may result in considerable pooling of warm blood in the finger, which could mask any differences in blood flow effects on short-term cold contact due to heat input from pooled blood slowing the contact cooling process. The total heat content of this blood is low, however, and should not have affected the longer exposures.

Kerslake (1949) suggested that an arterial occlusion cuff should be applied to the wrist and inflated to a pressure of 240 mmHg in order to occlude hand circulation. Despite the occlusion cuff in the present study being inflated to ~200 mmHg depending upon the resting systolic blood pressure, it is conceivable that a certain degree of leakage of blood under the occlusion cuff into the hand may have occurred under the occluded condition, although visually the hands showed clear evidence of occlusion. Aspects to be considered when selecting an occlusion pressure include the fact that whilst higher pressures may confer greater safety, discomfort is also related to pressure. However, the duration of cuff application is relatively short for this work and generally a pressure 50–100 mmHg above the pulse occlusion pressure is recommended. Some advocate a pressure of 200–260 mmHg for the upper limb (2.5 × systolic pressure) (Dhar, 2001). The highest systolic blood pressure in the present study was 138 mmHg, 62 mmHg below the occlusion pressure used (200 mmHg). This should have been sufficient to occlude blood flow for all cases. However, it may be considered that an occlusion pressure of ~240 mmHg should be used in order to ensure blood flow occlusion for all participants in future studies.

CONCLUSIONS

In conclusion, the findings from the present study suggest that no effect of blood flow upon the contact cooling response of the index finger pad of the non-dominant hand during short-term exposure exists. However, it is hypothesized that the finger contact force used (2.9 N) and the resultant pressure upon the tissue of the contact finger pad restricted the blood supply to the contact area under both blood flow conditions. It could be argued that for practical purposes, finger contact forces below this would seldom occur in a working environment and therefore blood flow is shown to be irrelevant for these short-term contact exposures. However, from a physiological viewpoint, in order to determine whether the potential effects of blood flow upon finger contact cooling response were masked in the present study, a further study is recommended. This further study should incorporate a lower finger contact force, allowing unrestricted blood flow to the finger pad and an improved methodology (i.e. equal starting skin temperatures and higher occlusion cuff pressure).

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