Differences in finger skin contact cooling response between an arterial occlusion and a vasodilated condition

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Jay, Ollie, and George Havenith. Differences in finger skin contact cooling response between an arterial occlusion and a vasodilated condition. J Appl Physiol 100: 1596–1601, 2006. First published September 22, 2005; doi:10.1152/japplphysiol.00760.2005.—To assess the presence and magnitude of the effect of skin blood flow on finger skin cooling on contact with cold objects against the background of circulatory disorder risks in occupational exposures, this study investigates the effect of zero vs. close-to-maximal hand blood flow on skin contact cooling response at a contact force used during the contact cooling exposures in this study. Participants were required to exercise in a hot room for $\geq 30$ min for cutaneous vasodilation to occur (increase in rectal temperature of $1^\circ$C). Under the vasodilated condition, forearm blood flow rate rose as high as 16.8 ml$\cdot$100 ml$^{-1}$$\cdot$min$^{-1}$. Under the occluded condition, the arm was exsanguinated, after which a blood pressure cuff was secured on the wrist inducing arterial occlusion. Contact temperature of the finger pad during the subsequent cold contact exposure was measured. No significant difference was found between the starting skin temperatures for the two blood flow conditions, but a distinct difference in shape of the contact cooling curve was apparent between the two blood flow conditions, with Newtonian cooling observed under the occluded condition, whereas a rewarming of the finger skin toward the end of the exposure occurred for the vasodilated condition. Blood flow was found to significantly increase contact temperature from 40 s onward ($P < 0.01$). It is concluded that, at a finger contact force compatible with capillary perfusion of the finger pad ($\sim 0.5$ N), circulating blood provides a heat input source that significantly affects finger skin contact cooling during a vasodilated state.

arterial occlusion; blood flow; cold contact; circulatory disorders; skin cooling

FOR WORKERS IN COLD ENVIRONMENTS, the frequent contact of bare hands with cold objects and the resultant skin cooling presents a health and safety risk in terms of discomfort, pain, numbness, and skin damage (10–12). Data were collected for the derivation of a cold surfaces safety standard with the overall aim being to use the data to develop a predictive model of fingertip contact cooling (22). However, due to the large interindividual variation found in the contact cooling responses, it was hypothesized that individual groups may not be covered by the model and could therefore potentially be at a greater risk than predicted. One such population under consideration were those with reduced heat input to the fingers such as those who have suffered vascular damage from repeated and frequent use of handheld vibrating tools resulting in vibration white finger or the vasospastic disorder Raynaud’s disease, both of which are characterized by excessive cutaneous vasoconstriction in the extremities (5) resulting in cessation of arterial flow in the digital vessels during exposure to the cold (32). Such is the effect of the heightened sympathetic response in Raynaud’s patients that only brief local cooling ($-15^\circ$C air, 60 s) is sufficient to reduce skin temperature ($T_{sk}$) at the pulp of the finger to significantly lower levels than in controls (21). The increased risk associated with this greater degree of finger skin cooling may be further augmented during contact with cold surfaces, especially in Raynaud’s patients experiencing full digital occlusion.

Jay and Havenith (14) investigated the effects of blood flow on the contact cooling response of the index finger pad of the nondominant hand during short-term cold exposure. They found no apparent effect of blood flow when comparing contact cooling responses during a vasodilated condition, achieved by cycling intermittently for 30 min at a metabolic rate of 140 W/m$^2$ in the heat (ambient temperature $= 34.6 \pm 0.9^\circ$C; relative humidity $= 31.9 \pm 4.5\%$), with those of an arterial occlusion condition, achieved by inflating a blood pressure cuff to 200 mmHg around the wrist while the participants were at room temperature. A criticism of their study was that participants were not in the same physiological starting condition for the occluded (thermonutral) and nonoccluded (heat + exercise) condition. Furthermore, it was reasoned that the finger contact force used during the contact cooling exposures in this particular study (2.9 N) and the resultant pressure on the tissue of the contact finger pad ($\sim 90$ mmHg) may have restricted the capillary blood supply to the contact area during both blood flow conditions, thus confounding any effect of arterial occlusion on skin contact cooling rate. It has since been demonstrated that a substantial decrease in laser-Doppler cutaneous blood cell velocity of the fingertip occurs with increasing finger contact force, with a reduction in blood flow of $\sim 70\%$ observed at a contact force of 2.9 N compared with the lowest force measured of 0.5 N (15). For the purpose of further developing analytical models of finger/hand cooling, it remains pertinent to determine whether skin cooling rate is influenced by blood flow state and the concomitant differences in heat inflow to the hand during cold contact at lower finger contact forces.

Examples of previous models, which would require data regarding the effect of blood flow for validation and further development, include a whole-hand simulation of skin cooling...
during the gripping of cold cylinders of various materials (20), a lumped-parameter model of a cold-stressed fingertip that incorporated heat transport by blood perfusion (27), a similar model as the latter but now including arteriovenous heat exchange (28).

The aim of this study was to determine whether any effect of blood flow exists on skin cooling behavior during contact with a cold object and to produce data for development and/or validation of finger cooling models. For this purpose, two extremes of blood flow were chosen: cutaneous vasodilation of the hand vs. hand arterial occlusion with subsequent contact cooling exposures at a finger contact force sufficient to allow cutaneous blood perfusion [0.5 N (15)]. We hypothesized that heat input from capillary perfusion of the finger pad during cutaneous vasodilation of the hand significantly slows short-term skin contact cooling of the fingertip.

METHODS

Participants

After obtaining approval from the Loughborough University Ethical Advisory Committee, six normotensive male participants [age: 21 yr (SD 2); height: 184 cm (SD 3); weight: 88.0 kg (SD 14.7); Dubois surface area: 2.10 m² (SD 0.16)] volunteered for the study. Potential subjects were excluded from the study if they had in the past suffered frostbite or any other injuries related to cold or any vascular disease. None of the participants were smokers. They were instructed not to drink tea or coffee within 1 h of the beginning of experimentation or consume alcohol the evening before any experimental session. A 20-min preexperiment session was conducted for each participant to provide complete familiarization with the experimental protocol, including training of the regulation of the desired finger contact force using the balance inside the cool box. The pretest session was completed once the participant achieved a learning plateau defined as three consecutive attempts of successfully maintaining a finger contact force of 0.5 N with a sufficient degree of accuracy (i.e., ±0.05 N).

Experimental Design

Participants were asked to touch aluminium at a surface temperature of −2°C with a finger contact force of 0.5 N, which was sufficient to allow capillary perfusion of the finger pad (15). Cold contact responses were investigated under an “occluded” and “vasodilated” condition. The blood flow conditions were presented in a balanced design such that the effect of order was avoided. Each blood flow condition was tested on a separate day, with each cold contact exposure being repeated three times during the same session.

Equipment and Measurements

Instrumentation. Core (internal) body temperature was measured using a rectal thermistor (Grant Instruments, Barrington, Cambridge, UK) inserted to a minimum depth of 10 cm. Mean body T<sub>a</sub> was measured using skin thermistors (Grant Instruments) at the four-point Ramanathan measurement sites: shoulder, triceps, thigh, and calf (25). All thermistors were recorded on an 8-bit GRANT squirrel data logger (Grant Instruments, Loughborough, UK). The base of the sensor tip was attached to the palmar side of the first phalanx of the index finger of the nondominant hand using surgical tape (Blenderm, 3M, Loughborough, UK). The base of the sensor tip was attached to the finger just below the first phalanx, allowing the sensor tip and first part of the wire (1.0 cm in length) 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, i.e., the contact temperature (T<sub>c</sub>) (30).

All local contact cooling T<sub>a</sub> and FBF measurements were monitored using a WorkBench personal computer 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, Sunnyvale, CA).

Participants wore a standardized clothing insulation of ~0.3 clo (cotton underwear, socks, shorts, trainers, and T-shirt).

Procedure. After instrumentation, either a vasodilated or occluded blood flow condition was achieved before the contact cooling exposure.

VASODILATED CONDITION. Preexperimental FBF was measured, after which each participant was required to cycle on an ergometer for a minimum of 30 min at an approximate metabolic rate of 180 W/m² in a thermal neutral environment. Mean environmental conditions of this room were ambient temperature = 37.1°C (SD 2.2), relative humidity = 42.5% (SD 7.8). On reaching a rise in rectal temperature (T<sub>re</sub>) of 1.0°C from resting values, cycling was stopped and postexercise FBF was measured again (in an identical way to the preexperimental method). After the postexercise blood flow measurements were completed, the contact cooling procedure began within 15–20 s as described below using the cool box equipment situated in the same experimental room. After completing the first contact cooling exposure, the participant cycled for a further 10 min to remain in a vasodilated state. The postexercise blood flow measurement and contact cooling procedure was repeated followed by another 10-min cycling period, another blood flow measurement, and a third contact cooling exposure.
OCCLUDED CONDITION. Preeexperimental FBF measurement and cycling protocol were performed in an identical manner to the vasodilated condition. Mean environmental conditions of the experimental room were ambient temperature = 38.2°C (SD 2.1), relative humidity = 41.1% (SD 6.9). On reaching a rise in Tre of 1.0°C from resting values, cycling was stopped. The participant’s nondonminant hand blood content was then emptied via exsanguination by elevating the arm at a 90° angle to the horizontal for 2 min (31). Blood flow to the hand was subsequently occluded using a blood pressure cuff secured on the wrist just below the styloid process of the ulna, inflated to 240 mmHg (6). The cold contact exposure was then performed as described below. On completion of the cold contact exposure, the cuff was deflated. The participants cycled for a further 10 min, and the occlusion procedure was repeated with a further 2-min exsanguination followed by a second cold contact exposure. Another 10 min of cycling, 2 min of exsanguination, occlusion, and a third cold contact exposure followed.

Contact Cooling Procedure

Each participant touched, with the first phalanx of the index finger of the nondominant hand, the aluminium block at a temperature of −2°C with a finger contact force of 0.5 N. The skin cooling behavior of the contact area was continuously monitored throughout the exposure until one of the following withdrawal criteria were met: a TC of 0.5°C [freezing point of human finger skin = −0.6°C (16)]; an exposure duration of 180 s; a typical sensation of frostnip about which participants were instructed (burning/tingling); a sensation of intolerable pain or any other reason for which the participant perceived withdrawal to be necessary. It was ensured that, before the next contact cooling exposure, Tre of the finger pad was within 0.5°C of the previous preexposure value.

Statistical Analyses

To investigate the effect of arterial occlusion on skin cooling, the TC observed at six time points throughout the contact cooling exposure were used for analysis. These points were selected to ensure that all parts of the cooling process and, therefore, the cooling at all tissue depths were studied. These times were 0, 20, 40, 60, 120, and 180 s (Tre, T20, T40, T60, T120, and T180, respectively).

The differences in Tre and mean Tsk after the initial precontact cooling cycling protocol, the subsequent 10-min cycling between the three contact cooling exposures, and between blood flow conditions were analyzed using t-tests. The mean Tc at the predetermined time points were analyzed using a repeated-measures analysis of variance to study the relationship between blood flow condition (i.e., vasodilated or occluded) and the skin cooling occurring. A repeated-measures analysis of variance was also used to establish any differences in finger skin Tc between the three repeated contact cooling exposures within each time point used for analysis.

Table 1. Body thermal response to exercise

<table>
<thead>
<tr>
<th>Finger-Cooling Trial</th>
<th>Tre, °C</th>
<th>Chest, °C</th>
<th>Shoulder, °C</th>
<th>Thigh, °C</th>
<th>Calf, °C</th>
<th>Tsk, °C</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Occluded</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Base</td>
<td>37.1 (SD 0.2)</td>
<td>34.6 (SD 1.3)</td>
<td>34.0 (SD 0.5)</td>
<td>33.9 (SD 0.8)</td>
<td>34.4 (SD 2.4)</td>
<td>34.2 (SD 0.3)</td>
</tr>
<tr>
<td>1</td>
<td>38.0 (SD 0.1)</td>
<td>36.7 (SD 0.6)</td>
<td>36.4 (SD 0.6)</td>
<td>37.3 (SD 0.7)</td>
<td>37.3 (SD 0.6)</td>
<td>36.9 (SD 0.4)</td>
</tr>
<tr>
<td>2</td>
<td>38.1 (SD 0.3)</td>
<td>36.9 (SD 0.7)</td>
<td>36.6 (SD 0.6)</td>
<td>37.4 (SD 0.7)</td>
<td>37.6 (SD 1.2)</td>
<td>37.0 (SD 0.5)</td>
</tr>
<tr>
<td>3</td>
<td>38.2 (SD 0.2)</td>
<td>37.1 (SD 0.6)</td>
<td>36.5 (SD 0.5)</td>
<td>37.3 (SD 1.1)</td>
<td>37.7 (SD 0.8)</td>
<td>37.0 (SD 0.6)</td>
</tr>
<tr>
<td><strong>Vasodilated</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Base</td>
<td>37.1 (SD 0.3)</td>
<td>34.9 (SD 0.8)</td>
<td>34.3 (SD 0.9)</td>
<td>33.8 (SD 1.0)</td>
<td>33.8 (SD 0.8)</td>
<td>34.3 (SD 0.5)</td>
</tr>
<tr>
<td>1</td>
<td>38.0 (SD 0.2)</td>
<td>36.8 (SD 0.7)</td>
<td>36.4 (SD 0.6)</td>
<td>37.2 (SD 0.9)</td>
<td>37.5 (SD 1.1)</td>
<td>36.9 (SD 0.5)</td>
</tr>
<tr>
<td>2</td>
<td>38.1 (SD 0.2)</td>
<td>36.5 (SD 0.7)</td>
<td>36.4 (SD 0.8)</td>
<td>37.1 (SD 0.6)</td>
<td>37.9 (SD 0.6)</td>
<td>36.9 (SD 0.7)</td>
</tr>
<tr>
<td>3</td>
<td>38.3 (SD 0.2)</td>
<td>36.9 (SD 0.6)</td>
<td>36.5 (SD 0.8)</td>
<td>37.2 (SD 0.8)</td>
<td>37.9 (SD 0.9)</td>
<td>37.0 (SD 0.6)</td>
</tr>
</tbody>
</table>

Values are means (SD); n = 6/group. Tre, rectal (internal) body temperature; Chest, Shoulder, Thigh, Calf, 4-point Ramanathan skin temperature sites; Tsk, mean weighted skin temperature (0.3Chest + 0.3Shoulder + 0.2Thigh + 0.2Calf).

RESULTS

The body thermal response of the participants in terms of mean Tre and body Tsk before experimentation and during the three contact cooling exposures are detailed in Table 1. Mean metabolic rate during the precontact cooling cycling protocol before the first contact cooling exposure was 178 W/m² (SD 7), which is classed as “moderate work” (23).

Tre and mean Tsk were significantly raised by the precontact cooling cycling protocol before the first contact cooling exposure (P < 0.001). No significant difference was found in either Tre or Tsk across any of the subsequent contact cooling exposures, and there was no significant difference in either Tre or Tsk between the vasodilated and occluded conditions.

The mean FBF rate under the vasodilated condition was 3.7 ml·100 ml⁻¹·min⁻¹ (SD 0.5) before the initial precontact cooling cycling protocol compared with 16.3 (SD 0.8), 16.8 (SD 0.7), and 16.0 ml·100 ml⁻¹·min⁻¹ (SD 0.5), directly before the first, second, and third contact cooling exposure, respectively. FBF rate was significantly increased in response to the precontact cooling cycling protocol before the first contact cooling exposure (P < 0.001) and was found to remain elevated throughout the session, with no significant difference in FBF occurring across any of the subsequent contact cooling exposures.

Contact Cooling Data

An example of the skin cooling response under both the occluded and vasodilated condition is given in Fig. 1. The mean values for T0, T20, T40, T60, T120, and T180 for all participants are given in Table 2. Under the occluded condition, the experimental withdrawal criteria were met for 2 of 18 exposures before 60 s of contact; for 9 of 18 exposures before 120 s of contact; and for 16 of 18 exposures before 180 s of contact. Of these total cases, a sensation of frostnip (tingling/burning) was reported on 6 occasions and a TC of ≤0.5°C was met on 10 occasions. No data for T180 under the occluded condition are therefore reported in Table 2. Under the vasodilated condition, the withdrawal criteria were met for 4 of 18
exposures between 120 and 180 s of contact. These were all cases of a sensation of frostnip.

There was no significant difference in starting finger skin contact temperature (T₀) [35.7°C (SD 1.6)] before the occluded contact cooling measurements compared with those recorded before the vasodilated contact cooling measurements [36.5°C (SD 0.7)]. Tₐ under the vasodilated condition were found to be significantly higher than those under the occluded condition for T₄₀ (P < 0.01) and T₆₀ (P < 0.001). The critical level of significance was lost for T₁₂₀ due to the reduced number of cases for the occluded condition (9 withdrawals); however, a strong trend was still evident (P = 0.019 for a Bonferroni-corrected significance level of 0.01). No statistical comparison could be made between the occluded condition and vasodilated condition for T₁₈₀ due to the large number of cases absent for the occluded condition (16 withdrawals).

No significant difference was found in finger skin Tₐ between the three repeated contact cooling exposures for any of the analysis points under both the occluded and vasodilated condition.

DISCUSSION

The experimental protocol was successful in eliciting comparable initial thermal states of the body under both experimental conditions (i.e., Tₑ and Tₕ not significantly different between each blood flow condition). Thus body heat content was the same for both conditions, and therefore the potential confounding effect of differences in the thermal state of the body experienced in earlier work (14) was avoided in the present study, allowing a more straightforward analysis of the effect of skin blood flow on finger skin contact cooling behavior.

The treatment conditions for the study, full occlusion vs. vasodilation, were successfully created. Due to the increased body core temperature [mean Tₑ for both conditions was above 38.0°C; mean increase in Tₑ from baseline was 0.9°C (SD 0.1)], the FBF before contact showed a more than a fourfold increase over baseline under all three repeated contact cooling exposures.

During the occluded condition, a 2-min arm elevation period followed by the inflation of a wrist occlusion cuff to 240 mmHg appeared effective in eliminating the presence of both pooling of blood in the hand and further blood flow to the hand, as the hand skin surface appeared pale in coloration. However, only minimal (if any) discomfort was experienced by the participant.

Table 2. Contact temperatures for each time analysis point

<table>
<thead>
<tr>
<th>Participant</th>
<th>T₀  °C</th>
<th>T₂₀  °C</th>
<th>T₄₀  °C</th>
<th>T₆₀  °C</th>
<th>T₁₂₀  °C</th>
<th>T₁₈₀  °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Occluded</td>
<td>35.5 (SD 0.5)</td>
<td>5.1 (SD 1.7)</td>
<td>3.5 (SD 2.2)</td>
<td>3.0 (SD 2.0)</td>
<td>4.1*2</td>
<td>2.9 (SD 0.8)</td>
</tr>
<tr>
<td>1 Vasodilated</td>
<td>37.4 (SD 1.2)</td>
<td>6.0 (SD 1.1)</td>
<td>4.3 (SD 0.9)</td>
<td>4.1 (SD 0.9)</td>
<td>4.1 (SD 0.8)</td>
<td>4.9 (SD 0.4)</td>
</tr>
<tr>
<td>2 Occluded</td>
<td>37.7 (SD 1.0)</td>
<td>4.3 (SD 0.3)</td>
<td>2.9 (SD 0.8)</td>
<td>1.9 (SD 1.1)</td>
<td>2.0*2</td>
<td>2.9 (SD 0.6)</td>
</tr>
<tr>
<td>2 Vasodilated</td>
<td>36.9 (SD 0.7)</td>
<td>5.3 (SD 0.9)</td>
<td>4.0 (SD 1.1)</td>
<td>3.2 (SD 0.9)</td>
<td>2.9 (SD 0.6)</td>
<td>4.2 (SD 1.4)</td>
</tr>
</tbody>
</table>

Values are mean contact temperatures for each time analysis point: T₀, T₂₀, T₄₀, T₆₀, T₁₂₀, and T₁₈₀ (finger-pad contact temperature after 0, 20, 40, 60, 120, and 180 s, respectively). Contact temperature values are means (SD) of the 3 repetitions. * and accompanying number represents the number of exposures, terminated before analysis point due to reaching withdrawal criteria. P values are for differences between conditions (occluded vs. vasodilated).
There was a fundamental difference in the shape of finger skin contact cooling curve observed between the occluded and vasodilated conditions. The occluded condition consistently showed Newtonian cooling (12). The vasodilated condition, however, showed a non-Newtonian skin cooling behavior with a gradual rewarming response of the finger skin-material interface occurring on 13 occasions from a total of 18 exposures. The contact time before onset of rewarming varied, with one case occurring between 40 and 60 s, eight cases occurring between 60 and 120 s, and five cases occurring between 120 and 180 s.

It is evident that the effect of forearm arterial occlusion on the finger skin contact cooling behavior is cumulative and hence dependent on contact cooling time. T20 values were not significantly affected by blood flow condition. During this initial period of contact, primarily superficial skin cooling occurs. The superficial skin layers are located in the epidermis and are not vascularized. The TC observed after 40, 60, and 120 s were all found to be influenced by blood flow condition. The cooling occurring during this period represents that of the deeper dermal layers (12–14), all of which are richly vascularized beginning with the capillary loops immediately under the epidermis, down to networks of arteriololes deeper in the dermis (1, 33).

Comparisons between blood flow conditions were not possible after 180 s due to the number of occasions the withdrawal criteria were met under the occluded condition. However, the results confirm that, under the vasodilated condition, heat input from blood flow into the fingertip provided a greater amount of heat to the surface of the contact material and is sufficient to cause an increase in Tc after ~60–120 s of exposure. This was not a cold-induced vasodilated response as no cyclic function was apparent in any test and cold-induced vasodilation is known not to occur before 3 min of exposure (7, 8). The lack of heat input from blood flow during the occluded condition facilitated continued finger skin cooling. Despite the lack of T120 and T180 data under the occluded condition, the increased number of occasions that the withdrawal criteria were met further suggests that there were no other avenues of further significant heat input (e.g., metabolism) and hence the cooling occurring appears to be Newtonian (12).

Jay and Havenith (14), using a fingertip pressure of ~90 mmHg at a 2.9-N finger contact force, suggested that, to explain their observation of an absence of a blood flow effect, the pressure used may have restricted blood supply to the finger pad due to the collapse of the capillaries at the tip of the finger and those in the pulp of the palmar side of the fingertip. A subsequent study (15) has shown that a finger contact force of 2.9 N indeed reduces laser-Doppler cutaneous blood cell velocity by ~70% compared with a lighter finger contact force of 0.5 N. The finger contact force used in the present study was therefore chosen to provide sufficient capillary perfusion, allowing any potential effects of forearm arterial occlusion on finger skin contact cooling behavior to be apparent. The actual fingertip pressure at 0.5 N for the participants in the present study was 15.2 ± 2.4 mmHg, which is below the capillary pressure of men reported in the literature (18.1 ± 2.3 mmHg (29)) and therefore should have not disrupted skin blood flow of the finger pad during finger contact (15). The difference in findings of the effect of blood flow on contact cooling between the two studies suggests that the lighter finger contact force used in the present study was sufficient to allow blood flow to the finger pad and its resultant heat input to affect the contact cooling behavior of the finger’s skin, whereas under the higher pressure of the earlier study heat input was too small to produce statistically significant differences within the test constraints.

Since only one material was tested at one temperature in the present study, the data represent skin cooling at only one cooling speed. Different finger skin cooling speeds elicited by different materials at different surface temperatures provide varying thermal gradients throughout the fingertip (12–14). The test material and temperature used were selected specifically to elicit a maximum cooling of the deeper (vascularized) dermal layers within the time restriction imposed (i.e., ≤3 min). This is evident in the fact that Tc under many of the cold contact exposures closely approached the withdrawal criteria. Thermal conditions that elicit cooling rates faster than this produce more pronounced cooling of the nonvascularized epidermal layers and less cooling of the deeper tissues of the finger; thus one would expect less effect of blood flow.

The Downloaded blood flow of the finger pad is dependent on local and whole body factors. The local factor with greatest influence is finger contact force: the greater the finger contact force, the deeper the tissues that are occluded by contact pressure. For low finger contact forces that allow blood flow near the skin surface of the finger pad (≤1.0 N), blood flow is governed by whole body factors (exercise, body temperature). It has been previously demonstrated that a clear relationship exists between body heat content, finger blood flow, and finger temperature during −25°C air exposure (4). The present findings add that, with equal body heat contents, different contact cooling behaviors are observed with different states of hand (and therefore finger) blood flow: the greater the hand/finger blood flow, the smaller the rate of finger skin cooling when in contact with cold surfaces. Furthermore, if different hand/finger blood flow states were to occur due to unequal body heat contents (4), interventions that have been shown to provide greater body heat content and consequently a greater finger blood flow (3), such as heating of the torso, would therefore be potentially beneficial for workers exposed to cold surfaces in the workplace. For groups predicted to be at risk, other factors may modulate this central effect on hand or finger blood flow. Hence the findings of the present study are relevant when considering the effects of blood flow as a function of gender, age, and especially sufferers of circulatory disorders (e.g., Raynaud’s syndrome). In the case of the latter, not only will the episodic digital ischemia in response to exposure to a cold environment potentially result in a lower finger Tsk before contact (21), a greater rate of skin cooling on contact with a cold surface may subsequently occur, therefore presenting a greater risk of cold tissue injury.

The contact force/pressure used in the present study (0.5 N; 13–18 mmHg) is comparatively light, and such forces applied directly to the fingertip only may seldom occur in the working environment. However, the same pressure applied to the whole hand, e.g., as it would occur in gripping or carrying, would be equivalent to a force or weight of 43 N or 4.4 kg, which will occur on a regular basis.

It must be considered when discussing the application of the findings of the present study that the blood flow levels tested were chosen to maximize any possible effects and hence were vastly different, presenting a best- vs. worst-case scenario (i.e.,
16 ml·100 ml⁻¹·min⁻¹ vs. zero blood flow). In comparison, a typical resting blood flow for Raynaud’s sufferers is ~0.5–1.0 ml·100 ml⁻¹·min⁻¹ (2), whereas typical blood flow of the healthy population is ~2–3 ml·100 ml⁻¹·min⁻¹ at rest (9, 18) and 7–8 ml·100 ml⁻¹·min⁻¹ after a 5-min sustained handgrip at a force of 10% of a maximal voluntary contraction (17).

In terms of heat inflow by hand to the hand, values are estimated (12) by multiplying the above blood flow rates by mean hand volume of 418 ml, specific heat of blood of 3.64 J·ml⁻¹·°C⁻¹ (26), a temperature difference of incoming and outflowing blood of 37 to 10°C (change = 27°C), and an effective ratio of the counter current heat exchange of 0.6 (24). The heat inflow to the hand is calculated to be 0 W for the occluded condition in the present study, 1.2 W for a sufferer of a circulatory disorder (or a maximally vasoconstricted hand in the cold of a healthy person at rest), 9.2 W for a normothermic healthy person at rest, 18.5 W for a healthy person exercising submaximally, and 40 W for the vasodilated condition in the present study. Despite the difference in blood flow, and therefore cold contact response not being expected to be as great for the groups predicted to be at risk as that which was found in this study, it is evident that for modeling purposes it is essential that skin blood flow is included as a parameter, ideally as a function of finger contact pressure.

In conclusion, at a low finger contact force (0.5 N) in a vasodilated person, it was found that arterial occlusion of the hand had a significant effect on contact cooling of the index finger pad of the nondominant hand. Under the occluded condition, skin cooling appeared Newtonian, whereas under the vasodilated condition a rewarming effect of the finger was apparent after ~60–120 s of contact. The TC of the finger pad was found to be lower under the occluded condition from 40 s of contact onward. Before 180 s of exposure, withdrawal criteria were met on 16 of 18 occasions under the occluded condition, but only on 4 of 18 occasions under the vasodilated condition. After 120 s of contact duration, the onset of frostbite risk (TC = 0.5°C) is reached in 50% of cases under occlusion, whereas a rewarming effect of the finger skin appears to occur after ~60–120 s of contact, continuing as a parameter, ideally as a function of finger contact pressure.

REFERENCES