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Skin and core temperature response to partial- and whole-body heating and cooling

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Abstract

1. Human subjects were exposed to partial- and whole-body heating and cooling in a controlled environmental chamber to quantify physiological and subjective responses to thermal asymmetries and transients.

2. Skin temperatures, core temperature, thermal sensation, and comfort responses were collected for 19 local body parts and for the whole body.

3. Core temperature increased in response to skin cooling and decreased in response to skin heating.

4. Hand and finger temperatures fluctuated significantly when the body was near a neutral thermal state.

5. When using a computer mouse in a cool environment, the skin temperature of the hand using the mouse was observed to be 2–3 °C lower than the unencumbered hand.

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Keywords: Core temperature; Skin temperature; Human thermoregulation; Localized heating; Localized cooling

1. Background

Most humans subjected to thermal comfort studies (e.g., Nevins et al., 1966; McNall et al., 1967; Fanger, 1972; Rohles and Wallis, 1979; de Dear et al., 1993) have related subjective perceptions to environmental conditions, but not to skin and core temperatures. A few fundamental sensation and pleasantness studies have included such measurements (Frank et al., 1999; Cabanac, 1969; Attia and Engel, 1981; Mower, 1976; Hensel, 1982), but their test conditions do not apply to realistic everyday environments. Our goal is to model human physiological and subjective response in the types of non-uniform and transient environments typically encountered in buildings and automobiles. We have already developed a sophisticated physiological model of human thermoregulatory response (Huizenga et al., 2001), but this model is not currently capable of predicting subjective response to complex environments. Since thermal sensation originates in skin and core temperature receptors, we need to correlate local and overall sensation and comfort to the corresponding skin and core temperatures under such complex environmental conditions. This suggested an experiment in which controlled combinations of local skin temperatures and their rates of change were produced in the subjects while they responded to thermal sensation and comfort questions. This experiment could also coincidentally yield physiological information about the response of skin and core temperatures to heating and cooling stimuli. The responses of the hand and fingers would be of particular interest because of their functional importance and their prominence in regulating the body's heat dissipation. This paper presents the key physiological observations from the experiment; the sensation and comfort results are described in Zhang (2003).

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2. Methods

2.1. Experiment procedure

We performed 109 human subject tests in a controlled environmental chamber at the University of California, Berkeley. The following categories of tests are reported here.

(1) *Uniform/stable*. These tests established the physiological temperatures corresponding to neutral, warm, and cold sensations. The chamber was controlled to specific temperatures from 20 to 32 °C. To determine neutral, the air in the chamber was kept at a temperature slightly cooler than neutral, allowing the subjects to precisely select their

neutral condition by adjusting the output of heating lamps.

(2) *Non-uniform/transient*. We applied cooling or heating separately to 19 individual body parts until they approached steady-state sensation. The body parts were: head, face, neck, breathing, chest, back, pelvis, left and right upper arms, left and right lower arms, left and right hands, left and right thighs, left and right lower legs, left and right feet.

(3) *Uniform/transient*. Subjects stepped between two chambers controlled to different temperatures.

Subjects spent 15 min in a circulating water bath to precondition their body to a warm, cold, or neutral state before testing began. After leaving the bath, we attached thermocouples to measure skin temperature at 28 locations every 5 s (21 locations fixed as in Fig. 1; 7 locations varied depending on the specific test). Core temperature was measured every 20 s using a Cor-Temp[TM][TM] ingestible thermometer pill (HTI Technologies, Inc.). We administered a computerized questionnaire to assess subjects' local and overall sensation and comfort (Fig. 2). The questions were repeated at a varying time step from 1 to 3 min throughout the test. The subjects performed work of their choice at a computer during the tests.
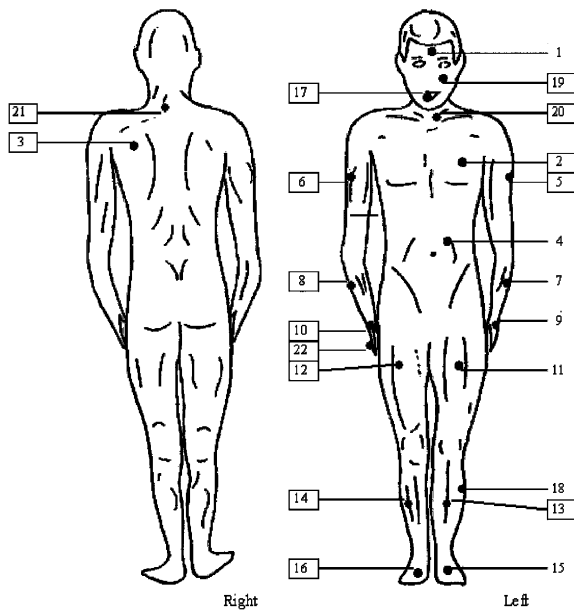
2.2. Local cooling/heating apparatus

We used air sleeves to cool or heat individual areas of subjects' bodies (Fig. 3). Cooling and heating by air does not exert pressure on the skin as with a contact method such as a water suit, and permits a more natural variation of skin temperature across a given body part. To eliminate the perception of air movement caused by ruffling skin hair, subjects wore a leotard (0.32 clo) and cotton socks (0.55 clo) under the air sleeve. In addition, males wore briefs and females briefs and bra. The air sleeves were attached to the borders of each body part with Velcro strips sewn on to the leotard. To prevent

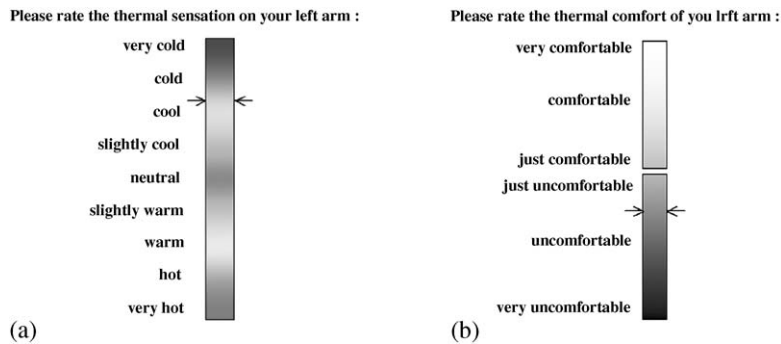Fig. 1. Skin temperature measurement locations (after Mitchell and Wyndham 1969).

Fig. 2. Subjective voting scales: (a) thermal sensation and (b) comfort. The same scales were also used to collect responses for overall thermal sensations and comfort.

local spot heating or cooling near the sleeve entrance and exit, we designed manifolds in the air sleeves that disperse the air around the circumference of the sleeves. Airflow through the sleeves was sufficiently high to typically maintain less than a 1 °C temperature difference between the air entering and leaving the sleeve.

3. Results

3.1. Uniform/stable conditions

We exposed subjects to neutral, warm and cold environments for a period of 80–120 min. Figs. 4 and 5 show typical results from these tests.

Under neutral conditions, subjects' core and average skin temperatures (calculated based on the 7-site method of Hardy and DuBois, 1938) were very stable during 2 h exposures, fluctuating within 0.1 °C. In the example test shown in Fig. 4, the core temperature became extremely stable 30 min after the test began and the mean skin temperature became stable within 10 min. The slightly

higher initial core temperature was caused by the metabolic exertion of putting on the leotard and thermocouples before the test started. The skin temperature distribution across the whole body from all 7 neutral condition tests are averaged and shown in Fig. 5. The maximum skin temperature variation among all body parts was about 3 °C, with the forehead and front-of-neck being the warmest (35.8 °C) and the calf the coolest (32.7 °C). The foot skin temperature was not the lowest in these tests because the socks provided higher insulation than the leotard.

In an 80 min warm condition test (31.5 °C) the core temperature was very stable, gradually decreasing less than 0.1 °C (Fig. 4). The mean skin temperature increased 0.6 °C during this period. Across the whole body, the total range of skin temperatures was 2.7°, from the highest of 36.8 °C for the front-of-neck to 34.1 °C for the calf (Fig. 5).

In a 2 h cold condition test (15.6 °C), the core temperature increased slightly (0.15 °C) while the mean skin temperature decreased by 1 °C (Fig. 4). The skin temperatures of the extremities decreased substantially,

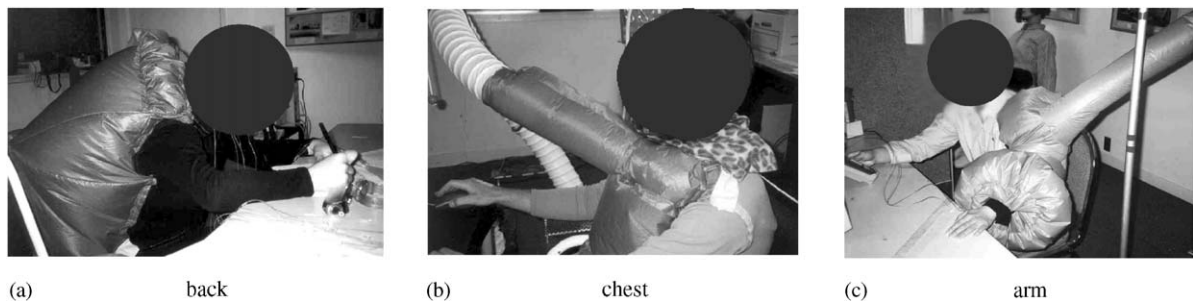(a)   back   (b)   chest   (c)   arm

Fig. 3. Air sleeves for three example body parts. A total of 19 body parts were heated and/or cooled during the tests.
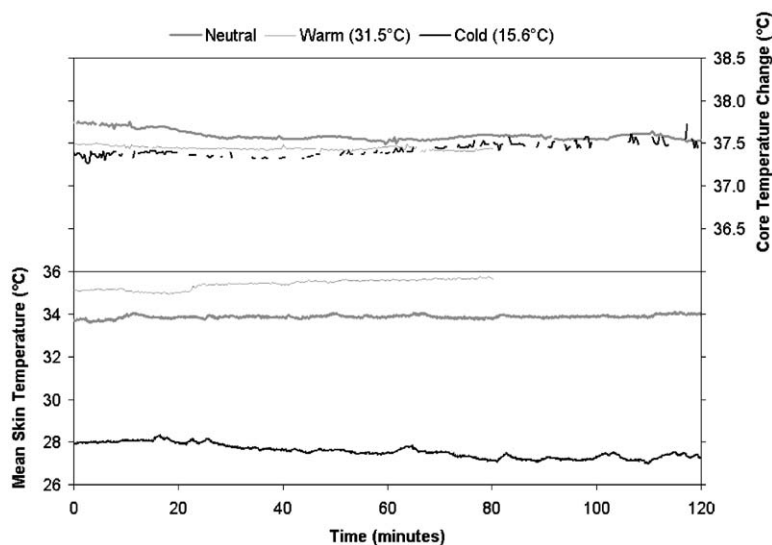

Fig. 4. Core and mean skin temperature of a neutral, warm, and cold condition test.

but the forehead and trunk remained reasonably constant. Across the whole body, the total range of skin temperature was substantial (13 °C, Fig. 5), with the neck the warmest, and finger and foot the coldest.

It is interesting that under neutral conditions, the hand and finger skin temperatures fluctuated considerably (Fig. 6), up to 1 °C for the hand and 2 °C for the finger. A similar observation was made by Humphreys

et al. (1999) and appears to be due to the fact that the body is actively using hand vasodilation and constriction to regulate heat loss to around the neutral setpoint. These variations in hand and finger skin temperature were not subjectively perceived. They did not appear in the warm or cold condition tests, when the hands were well-dilated or constricted, respectively.

A different effect was seen in the cold tests, however. When the finger skin temperature was near 18 °C (the pain threshold), there were sudden large increases in hand (2 °C) and finger (4 °C) skin temperatures (Fig. 7), which lasted more than 20 min. These increases are caused by arteriovenous anastomoses (AVA) action. In the periods between these increases, the hand and finger temperatures did not fluctuate, but decreased steadily.

Because the subjects in our tests occupied their time using a computer and a mouse, it gave us the opportunity to observe an effect of muscular activity on finger temperature. During the cold tests, the extremity blood vessels were constricted, and extremity skin temperatures were low. Muscular movement in these circumstances promotes blood circulation and therefore increases skin temperature. Mouse operation restricts finger motion significantly compared to an unencumbered hand. Table 1 shows that the right finger skin temperature was 2–3 °C lower than that of the left in cold test environments (15.6 and 19 °C) when the right hand was operating the computer mouse. In neutral and warm environments, use of the mouse caused a much smaller difference in finger temperature.

We did an additional test of the effects of motion on hand and finger temperatures (Fig. 8). Skin temperature was measured for the 2nd and 4th fingers, the palm, and
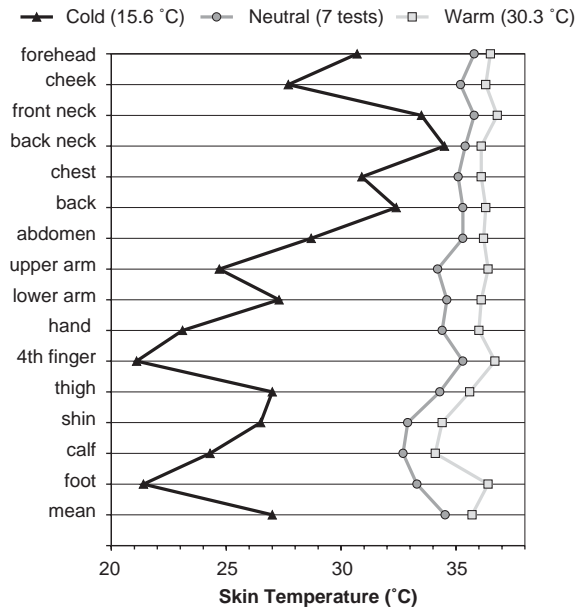

Fig. 5. Skin temperature distribution under neutral, cold, and warm environments.
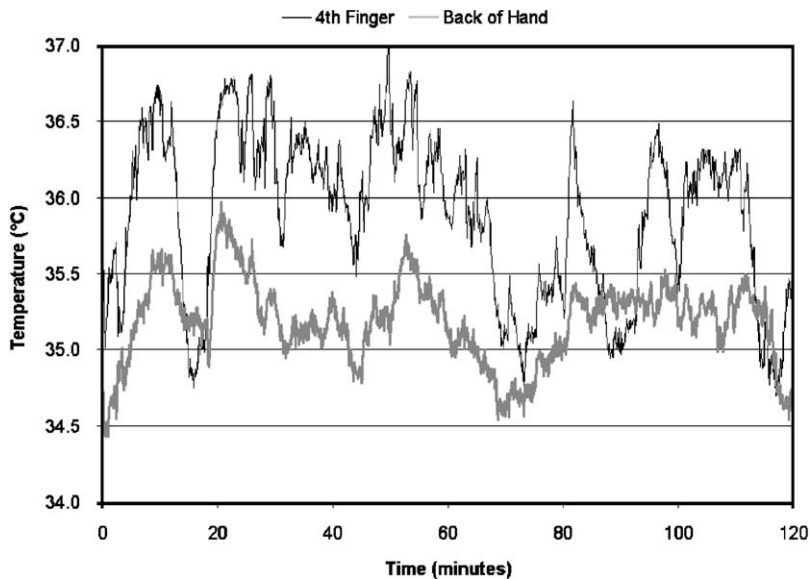

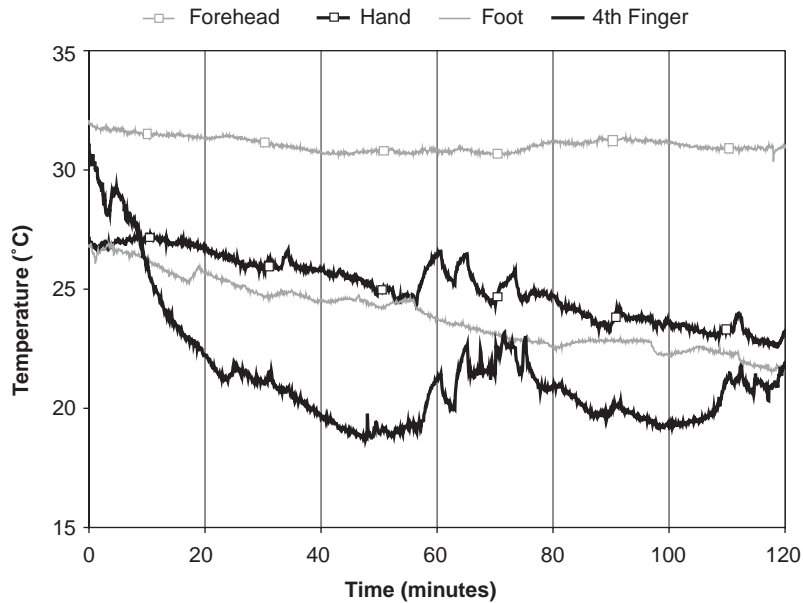Fig. 6. Hand and finger skin temperatures under neutral condition.

Fig. 7. Skin temperatures of the cold test ($T_{air} = 15.6\,°C$).

Table 1
Effect of using a computer mouse on 4th finger temperature (°C) in cold, neutral, and warm environments. Skin temperatures were measured at the end of a 2 h test

	T_{air}: 15.6	T_{air}: 19	Neutral	T_{air}: 30
Left	21.1	21.1	35.4	36.4
Right (using mouse)	17.8	19.3	34.7	36.2

the back of the hand. Cold air (12 °C) was applied at a high velocity (3 m/s) to both hands. After 30 min, while the hand skin temperatures were still dropping, the subject began slowly opening and closing the left hand over a 2 s cycle. The hand movement was very gentle, and the closed position of the hand was very loose so that nothing was touching the thermocouple on the palm of the moving hand. Twenty minutes later, the subject stopped moving the left hand and began the same slow movement with the right hand, continuing for 20 min and then stopping. The subject then repeated the same motion with the left hand for 10 min until the end of the test.

During the entire test, the back-of-hand and palm temperatures decreased steadily. When the left hand started its motion, the left finger temperatures became steady while the right fingers continued to cool. At the end of left hand motion, the difference between the left and the right fingers was 1.1 °C. During right hand motion, right finger temperatures started to increase while the now immobile left finger temperatures resumed decreasing. After about 5 min of right hand motion, the right finger temperatures peaked and resumed decreas-

ing, so that at the end of the right hand motion period, there was no difference between the fingers. In the final period, when left hand began motion again, its finger temperatures showed a similar temporary rise. The fact that the temperature increases were temporary may have resulted from the relatively high convective cooling rates in this test such that the skin temperatures eventually dropped all the way to the temperature of the cooling air. There may be a temporary relaxation of vasoconstriction due to muscular motion, similar to AVA action. For the more typical indoor temperatures and air movements seen in the computer mouse example, the temperature effects of finger motion versus immobility were much greater.

In addition to the thermocouple temperature measurements, we used an infrared video camera to record skin temperature distribution during many of the tests. Fig. 9 shows a comparison of hand temperature distribution at the end of warm and cold tests. When the body is warm (Fig. 9a and b), the hands are well dilated to increase heat loss and the fingers tips are the warmest part of the hand. When the body is cold (Fig. 9c), the hands constrict and the fingers become much colder than the rest of the hand. We measured variations as large as 12 °C between the fingertips and the palm during cold conditions.

3.2. Core temperature response to local cooling and heating

We performed many tests where we applied local transient heating and or cooling to one or more body parts. In a warm environment, when we applied local
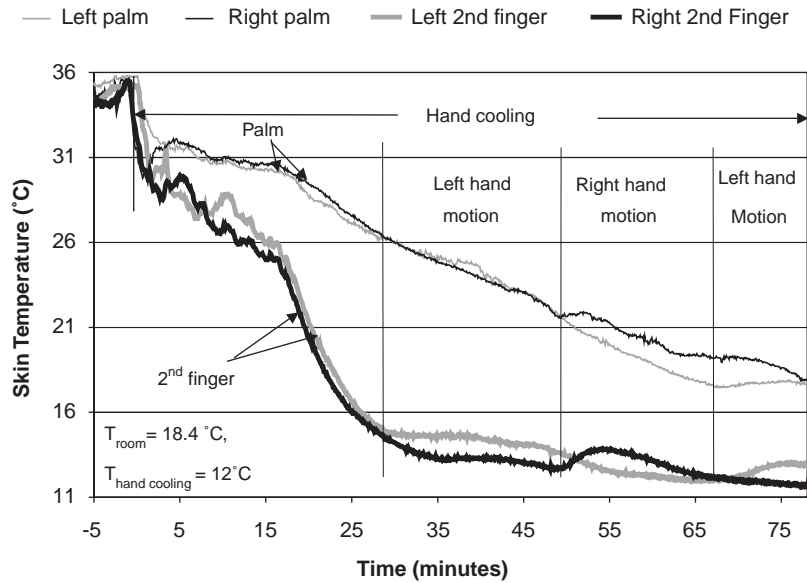
Fig. 8. Impact of hand motion on skin temperatures of hands and fingers during hand cooling.
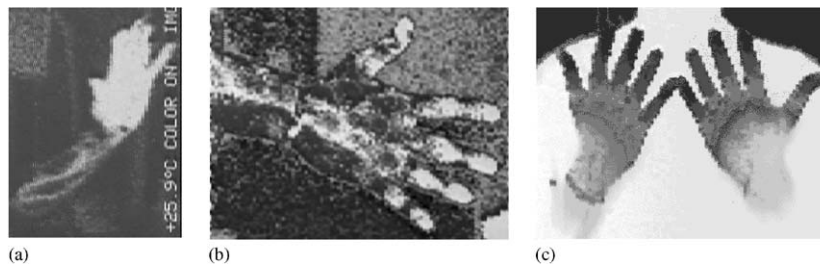

Fig. 9. Infrared images (darker shades represent cooler temperatures) of the hand skin temperature in warm (a,b) and cold (c) environments. Note that in the warm environment, the palm and fingertips are much warmer than the arm and back of the hand. In the cold environment, we saw as much as a 12 °C difference between the wrist and the fingertip temperature.

cooling to a single body part, we consistently observed a small but measurable increase in core temperature. When cooling the torso body parts, the increase is immediate. There is a delay for more distant parts like the hand or even the head. Fig. 10 shows core and skin temperature response when cold air (14 °C) was applied consecutively to the head, hand, and pelvis. During the head and hand cooling, the core temperature increase was observed about 3 min after applying the local cooling. When the pelvis was cooled, the core temperature increase was more rapid. When the local cooling was removed from the head and the hand, the core temperature started to drop after 3 and 4 min, respectively. The pelvis showed a 6 min delay. As in the stable tests, the overall decreasing trend of the core temperature is a result of the core temperature rise from the exertion of putting on the skin temperature harness and leotard before the testing started.

In a cold environment, when the skin of a single body part was warmed, we observed a decrease in core temperature. Fig. 11 shows that after a 1 h exposure to a cool environment (17.5 °C), supplying warm air (38 °C) to the face induced an immediate core temperature decrease. Warming the chest made the core temperature decrease after a 7 min delay, but warming the back did not produce a clear opposite response. There was a small increase 3 min after the chest warming was removed, but none when the face- and back warming was removed.

This less-clear response to local warming than to cooling might be expected, in that the human body is more protective against cold than heat. This might also explain why the *trunk* (pelvis and chest in these examples) in each case responds more quickly to cooling (applying cooling or removing warming) and more slowly to heating (applying heating or removing cooling) than does the head, hand, and face.
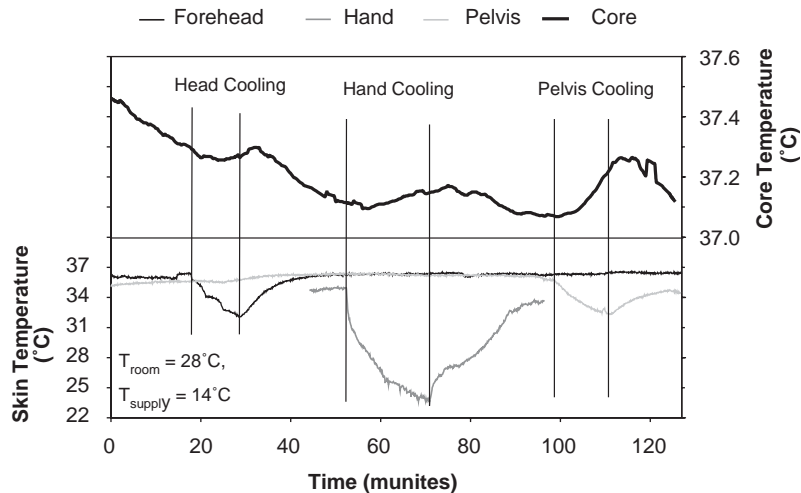
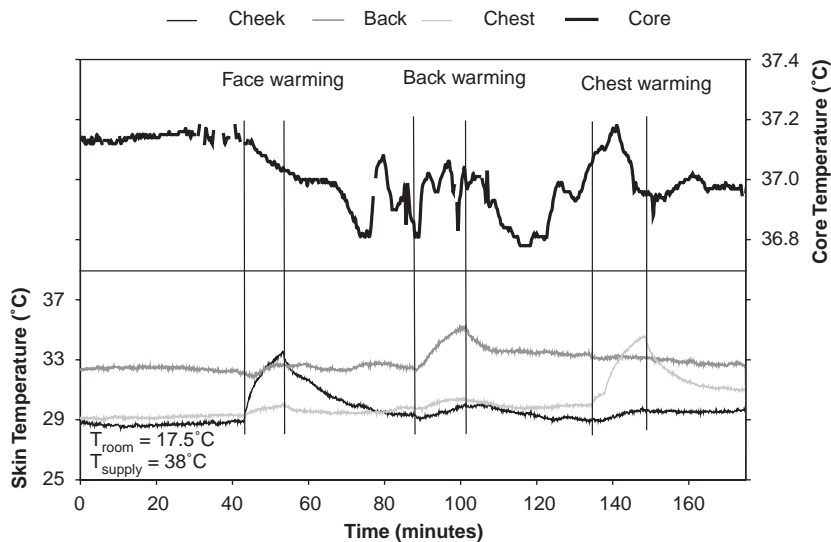Fig. 10. Core and local skin temperatures during local cooling applied to a warm body.

Fig. 11. Core and local skin temperatures during local warming applied to a cold body.

When we applied cooling to two body parts and warming to a third part, the warming had no appreciable effect on core temperature. Fig. 12 shows the core temperature increase when cooling the chest and face (14 °C), while warming the arm or leg (38 °C). This response could be due the fact that more surface area was cooled or because the thermoregulatory system is more responsive to cooling than warming.

3.3. Core temperature response to whole-body cooling and heating

In the local heating and cooling tests, we used fairly strong rates of cooling and warming. We also performed whole-body step change tests with more moderate levels

of heating and cooling and observed qualitatively similar responses of core temperature. Fig. 13 shows the core and skin temperature response to a warm/cool/warm step change sequence. In the first hour in the warm environment (31 °C), the back skin temperature reached a stable value of 35 °C, while the core temperature underwent a steady decrease. Immediately upon entering the cool environment (22 °C), the core temperature stopped decreasing and started increasing slightly for several minutes before resuming a slightly decreasing trend. Upon subsequently reentering the warm environment, the core temperature dropped immediately. We cannot determine from these tests if there is a minimum cooling rate which causes the core temperature to respond in the opposite direction. The
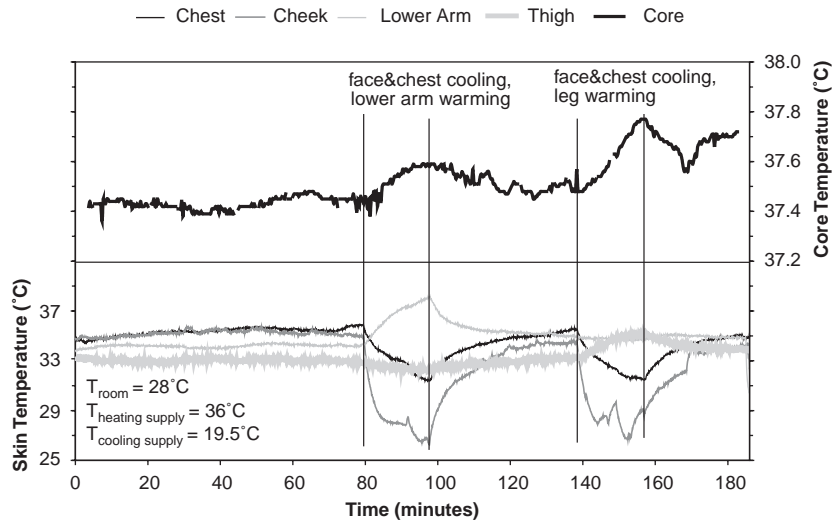
Fig. 12. Core and local skin temperatures during multiple body parts cooling/heating applications.

various non-uniform tests done above suggest that the threshold for each body part varies, possibly based on distance from the trunk and the amount of surface area being cooled.

3.4. Hand skin temperature recovery rate after cooling

The whole-body thermal state affects the rate at which hand skin temperature recovers after exposure to local cooling. If the body is warm, the hand quickly vasodilates and the hand skin temperature recovers quickly. When the body is neutral or cool, after hand cooling is removed, there is no need to pump the blood to the hand to release heat, so the hand skin temperature recovers very slowly.

Fig. 14 shows the skin temperature response of hand and forehead (in a normalized form) before, during and after local cooling was applied. When the body was warm, it took only 5 min for the hand to recover to near its original skin temperature. The recovery rate is similar to the recovery rate of the forehead. However, when the body was slightly cool, the hand skin temperature did not recover to its original pre-cooling skin temperature even after 30 min. It is interesting to note that in similar tests with the foot, skin temperature did not recover to its original temperature within 30 min even when the body was warm.

4. Conclusion

In steady-state, uniform thermal environments, the core temperature was very stable. It responded vigorously to the cooling and warming of local body parts, always responding in the opposite direction of the skin temperature (except when applying local cooling when the whole body was already cold). The responses were observed to be more pronounced for local cooling than for local warming, supporting the concept that human body is more protective against cold than heat. These opposite-directional responses also appeared in whole-body step-change tests where the temperature differences were smaller (between 31 and 22 °C), though we cannot suggest a threshold from the data in this experiment.

Hand and finger skin temperatures were observed to fluctuate in neutral conditions implying that near the neutral zone these temperatures do not reflect whole body thermal state. In cold environments (around 16 and 19 °C), muscular activity (such as by the unconstrained left hand fingers during computer work) can create a temperature difference from the right fingers (constrained while holding the mouse) as much as 3 °C. The health impact of the cold hand and fingers in long term on the mouse-holding hand of office people is worth further study. The impact from muscular activity may partially explain the cooler feeling in legs than in arms often reported for sedentary workers, because their arms may be more active than their legs.

When the whole body was warm, removal of a cooling stimulus to the hand was followed by rapid vasodilation in the hand and a corresponding increase in heat flux to the environment. This may have implications on task-ambient cooling systems in office buildings, or air-conditioning in automobiles. For example, the rapid recovery of the hands might make intermittent, local cooling an effective way to increase heat loss from the body in warm environments.
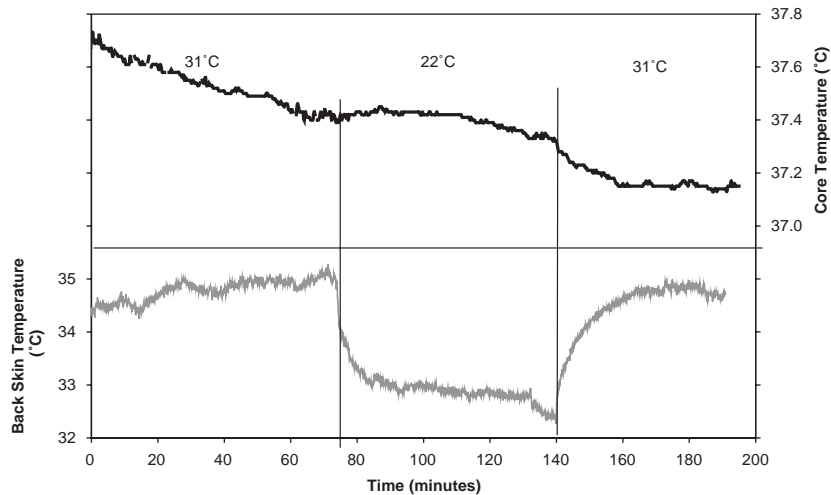
Fig. 13. Core and back skin temperatures during a step-change test.
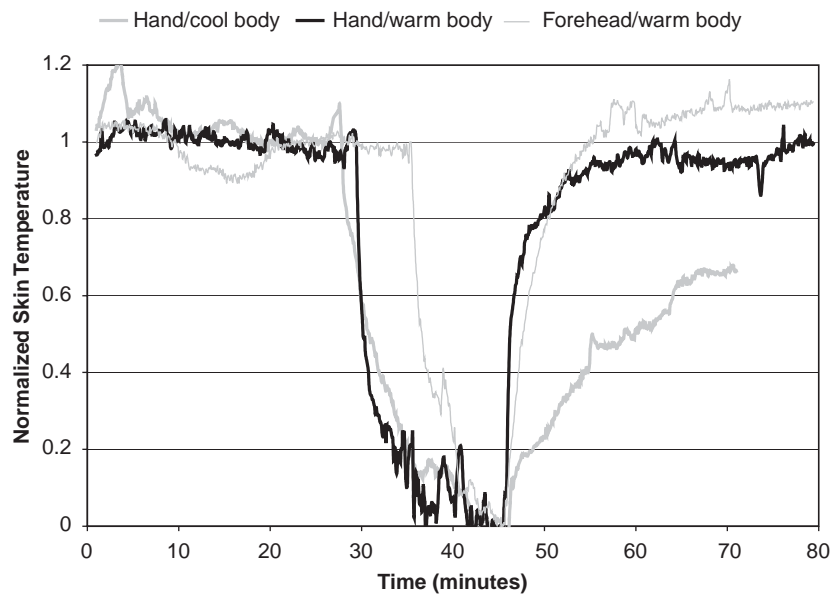

Fig. 14. Skin temperature recovery after local cooling. When the body is warm, the hand recovers much more quickly than when the body is cool. The foot recovers quite slowly even when the body is warm.

Acknowledgments

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