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Observations of upper-extremity skin temperature and corresponding overall-body thermal sensations and comfort

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Abstract

This paper explores how upper extremity skin temperatures correlate with overall-body thermal sensation. Skin temperature measurements of the finger, hand, and forearm might be useful in monitoring and predicting people's thermal state. Subjective perceptions of overall thermal sensation and comfort were collected by repeated surveys, for subjects in a range of test chamber temperatures. A positive temperature gradient (finger warmer than the forearm) of as much as 2 K was seen when subjects felt warm and hot, while a negative temperature gradient (finger colder than the forearm) as much as 8.5 K was seen for cool and cold subjects. A useful warm/cold boundary of 30 °C was found in finger temperature, for both steady state and transient conditions. When finger temperature was *above* 30 °C, or finger-forearm skin temperature gradient above 0 K, there was no cool discomfort. When finger temperature was *below* 30 °C, or the finger-forearm skin temperature gradient less than 0 K, cool discomfort was a possibility. Finger temperature and finger-forearm temperature gradient are very similar in their correlation to overall sensation. We also examine how overall sensation is affected by actively manipulating the hand's temperature.

Keywords: Thermal sensation; Thermal comfort; Skin temperature; Temperature gradient; Finger; Hand; Forearm; Comfort threshold; Occupant survey

1. Introduction

It is known that human extremities play an important role in human thermal regulation. Vasoconstriction and vasodilatation vary blood flow to hands and other extremities to control the heat loss from the skin to environment. As a result, cold hands indicate that the body is acting to retain heat; warm hands indicate the body is acting to lose heat. The hand temperature is probably the body's most sensitive indicator of thermal state. Glabrous skin, which includes the nail bed, finger, hand, and arm, has many arteriovenous anastomoses (AVAs), valves that control vasoconstriction and vasodilatation [1–3]. The number of AVAs in the hand and fingers is much greater than in the rest of the body surface, and their opening and closing varies the hand temperature across a wide range. They are primarily controlled by signals from the hypothalamus, and so their actions represent overall body thermal state.

Humphreys et al. [4] proposed that the skin temperature of the hands might be used instead of, or together with, the temperature of the surroundings in predicting the thermal comfort of people in buildings. He measured 2000 fingertip temperatures and overall thermal sensation votes from 200 office workers during the course of 1 year in the UK. He found a bimodal finger temperature distribution occurring in moderate thermal environments, with a large peak at 35 °C and a weaker peak at 26 °C. He compared the correlation of these sensation votes with globe temperature (a combination of air and radiant temperatures which represents human exposure to the thermal environment), and the correlation of sensation votes with globe temperature plus fingertip temperature. By adding finger

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temperature to globe temperature in fitting thermal sensation vote, he significantly improved the correlation coefficient from 0.31 to 0.43. He concluded that adding finger temperature to the temperature of the surroundings could be useful in explaining some of the variation in sensation votes that one sees in building occupant surveys.

In addition to surveys, one might imagine novel ways to monitor and predict an occupant's thermal state in real time, for example, by monitoring their finger and environmental temperatures with small sensors mounted in a ring, watch, steering wheel, computer mouse, keyboard, etc. How well might such concepts work? Although Humphreys' finger temperatures correlate with thermal sensation, they still vary substantially among people expressing the same thermal sensation, exceeding 10 °C among people feeling neutral or cooler than neutral. This variability might limit the accuracy of any method that uses fingertip temperature as a predictor of thermal sensation or comfort.

In this paper, we use data acquired in a laboratory study to explore Humphreys' hypothesis: that the finger temperature, or a combination of air and finger temperatures, might predict thermal sensation. It has been shown that the temperature difference between forearm and fingertip can indicate the onset of vasoconstriction [5]. We speculate that the extent of the vasoconstriction leads to a conscious sensation of cold in our tests. We therefore examine whether the *gradient* of skin temperatures, from finger to hand to forearm, might improve the predictive ability over using finger temperature alone. Much of this examination is done under steady conditions under which the subject has reached thermal sensation equilibrium. The gradient down the extremity will be seen to be the opposite in warm conditions as it is in cold conditions. We also look at gradients between forehead temperature and the extremity temperatures, since the forehead is, like the hand, a skin surface that is exposed to the environment and potentially subject to being remotely sensed. In automobile environment, the forehead skin temperature has been shown to be correlated with overall thermal sensation [6].

Since we are also interested in real-time prediction of future comfort, we also look at thermal behavior during thermal transients, during which the hand is cooling or warming. Here the cross-over point in thermal gradient is of interest. In addition, we observe a finger temperature fluctuation pattern that occurs in many subjects when they are near thermal neutrality; there may be some predictive utility in this.

The skin temperature thresholds corresponding to the edge of the thermal sensation neutral zone, and to the onset of discomfort, can be determined from the data. This requires us to quantify the relationships between thermal sensation and comfort; the data also allow us to examine this.

Finally, the extremity temperatures might be manipulated to provide overall comfort in a quickly acting and/or energy-efficient manner. 'Task-ambient air conditioning systems' essentially do this by warming or cooling specific local body parts to affect the body's overall sensation.

2. Methods

Thermal physiology tests were carried out in the Controlled Environmental Chamber at UC Berkeley from January to August 2002, in which 19 body segments, singly and in combination, were heated and cooled to determine local- and overall comfort relationships. The physiological responses (skin and core temperatures) during these tests are described in [7] and subjective responses in [8,9]. We focus here on two types of tests during which additional temperatures were taken on the upper extremities in order to examine the relationships between arm, hand, and finger skin temperatures and whole-body thermal comfort: (1) tests in *uniform, steady-state* thermal conditions controlled to produce overall sensations ranging from *cold* to *hot*, and (2) *local segment* tests in which the subject's left hand was cooled or heated for a period of 20 min, followed by a recovery period after the stimulus was removed.

A total of 23 of these tests were performed, in which 17 subjects participated. Subjects sat performing voluntarily selected work at a computer (Fig. 1) in a range of temperatures from cold through neutral to hot. Upper-extremity (finger, hand, and forearm) temperatures were measured at three locations: the dorsal side of the 4th finger of the left hand, dorsal side of the left hand, and dorsal side of the left forearm (Fig. 2). The forehead and other head temperatures were also measured. In the local segment tests, heated or cooled air was supplied to the hand through an air sleeve covering the hand segment (Fig. 3).

Tests were done one subject at a time. Upon their arrival, subjects swallowed a core-temperature-measuring radio pill, spent 15 min in a bath preconditioned to the temperature of that day's test, and then put on the thermocouple harness measuring 28 body locations. Aside from those at the hand and head locations, the thermocouples were covered by a thin elastic long-sleeved leotard and socks (clothing insulation value was 0.32 clo based on manikin measurement). Skin temperatures were measured with fine 36 gauge thermocouples every 5 s (accuracy level ± 0.1 °C). Core temperature was measured at 20-s intervals (accuracy level ± 0.1 °C). Subjective perception of overall thermal sensation and comfort was surveyed via the computer screen at 1–3 min intervals. The surveys used 9-point analog scales (Fig. 4). For sensation, the scale ranged from -4 "very cold" to 4 "very hot"; for comfort, it ranged from $+0.1$ "just comfortable" to 4 "very comfortable", and -0.1 "just uncomfortable" to -4 "very uncomfortable". The comfort screen is split in the middle to force a judgment. The movement of the left hand was not restricted.