DYNAMICS OF HUMAN SKIN TEMPERATURES IN INTERACTION WITH DIFFERENT INDOOR CONDITIONS

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Abstract

Human skin temperature represents an essential physiological variable in the evaluation of the human thermal sensation and comfort. The dynamics of local skin temperatures reflect the human thermoregulatory responses subject to environmental conditions. The variability in human responses challenges the research efforts for precise modelling of thermoregulation mechanisms; therefore, measured data always reveal useful inputs in this field. This paper reports on a laboratory-based measurement of local skin temperatures in different indoor conditions and exposure durations. The measurements aimed at investigating the human body response due to a step change and checking the variability in different duration tests with the same subjects as well as maintaining a physiological steady state at the different conditions. Eleven human subjects (males) participated in a total of 46 tests, in a controlled environment, including 33 tests in 1-hour duration, 12 tests in 2-hours duration and 1 test in 4-hours duration. The age of the subjects ranged from 27 to 40 years old and body weight from 62 to 105 kg. They wore normal office clothing (0.6clo, clo=0.155m²°C/W) and had normal sedentary office activities with own portable computers. The measurements of local skin temperatures and heart beat rate of subjects along with online measurements of the indoor conditions were carried out and recorded at short time intervals. The paper shows, in results, the variations of local skin temperatures in transients of different exposures and discusses the observations from the measurements. Main findings were related to the variability in response at body segments in different exposures and the skin temperatures at the physiological steady state conditions.

Keywords: local skin temperatures, thermal comfort, indoor thermal conditions

1 Introduction

The measurement of human local skin temperatures has become of great interest since the development of multi-segmental models of human thermoregulation started by Stolwijk and Hardy research work (1966). At first, the local skin temperatures were mainly employed to estimate the mean skin temperature of the human body (e.g. the 7-site averaged temperature developed by Hardy and DuBois 1938). The measured data in the literature is few and was mostly obtained during 1960-1980's. The human subjects in these measurements wore only shorts or uniform ensembles and were seated or reclining at rest.

In this study, measurements of local skin temperature were carried out in a controlled environment under three different indoor conditions and different exposure durations. The experiments aimed at investigating the local response due to a step change and the variability of the body temperatures for the different conditions and exposures as well as the physiological steady state temperatures. That was used by the authors to develop and verify a multi-segmental model of human thermoregulation (Foda and Sirén 2010). The experiments were conducted in 5 weeks period during February and March 2010. They were planned for office work activity with the participation of a diverse sample of male human subjects who wore normal office clothes and carried out their normal office duties during the measurements.

2 Methods

2.1 Experimental setup

The experiments were conducted in two adjacent test rooms at the HVAC laboratory at Aalto University. The test rooms are part of a two-storey single family house that has a large climate chamber equipped with all controls to simulate outdoor conditions and to control the air temperature and humidity over wide ranges. The main test room "Room 1" was conditioned by the climate chamber system while the pre-conditioning room "Room 2" was connected on the general ventilation system of the laboratory and was additionally equipped with an infrared heater. Room 1 was furnished with a workstation that consists of a height-adjustable table and an adjustable work chair with a small backrest. An additional workstation was placed in Room 2 during the step change tests. In these tests, the subjects remained at Room 2 for the pre-conditioning period and thereafter, they walked normally from Room 2 to Room 1. The researchers monitored the measurements procedure and the development of the skin temperatures on a screen in an adjacent room. Figure 1 shows the experimental setup and the rooms' layout.

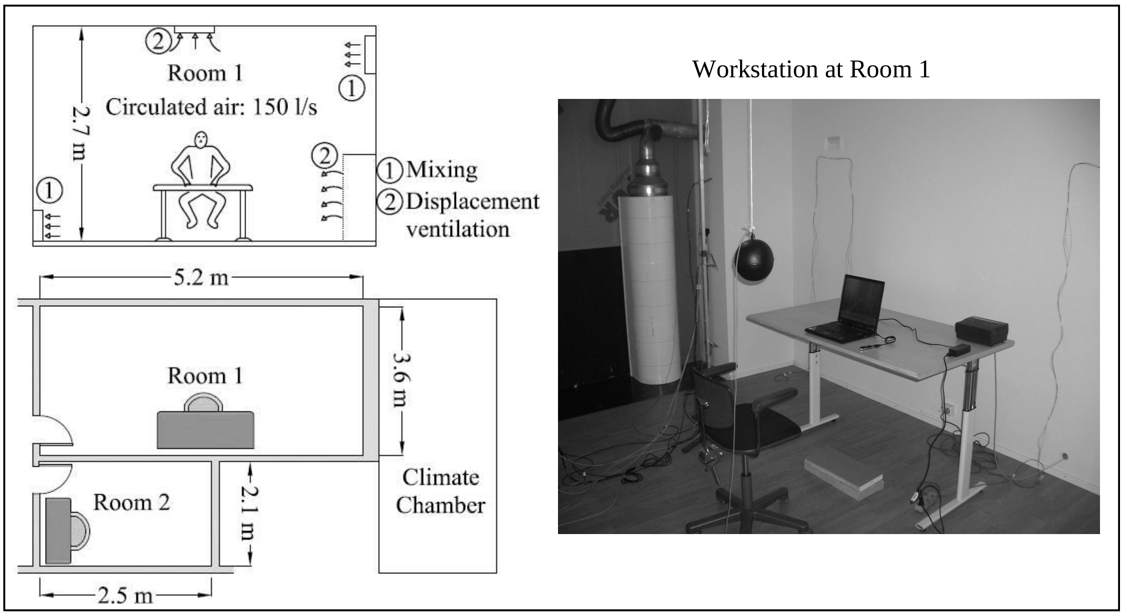

Figure 1. *Experimental setup and rooms' layout*

2.2 Indoor conditions

Three indoor conditions were planned based on the clothing thermal insulation value and office work activity (according to ISO 8996:2004). The 3 cases were initially determined to nearly create uniform neutral, warm and cold conditions by calculating the operative temperatures (T_o) at 0, +2 and -3 *PMV* (predicted mean vote) values respectively. The air mixing system was used in the neutral (Case 1) and cold (Case 3) conditions while a displacement ventilation system was the supply method in the warm condition (Case 2). Both systems used a constant air volume/variable air temperature (CAVVAT) control scheme. The relative humidity (*RH%*) was kept in a range from 40-60% over the 3 cases. The conditions at the main test room, for each case, were maintained and checked one day in advance before the experiments' time schedule.

2.3 Human subjects

Eleven male human subjects voluntarily participated in the experiments. The age of the participants ranged from 27 to 40 years old, their body mass index (BMI=Weight/Height²) from 19.6 to 30.7 kg/m² and their body fat percentage (calculated using Hodgdon and Beckett 1984) from 18.5 to 29.5%. They all participated in the three different conditions at least in the 1-h duration tests. The subjects wore normal office clothes that consist of: under-shirt, shorts, denim trousers, long-sleeve shirt and calf-length cotton socks. A thick wooden board was placed under their feet during the tests. The clothing intrinsic thermal insulation value was estimated beforehand (0.6clo, clo=0.155m²˚C/W) using the thermal manikin 'Therminator' (according to ISO 9920:2007) in a sitting posture at the same test room.

2.4 Measurements and test procedure

The experiments comprised 33 tests in 1-h duration, 12 tests in 2-h duration and 1 test (cold condition) in 4-h duration. The local skin temperatures at 24 body sites (Forehead, Neck, upper arms, lower arms, hands, thighs, legs, ankles, feet and the right and left sides of the: chest, abdomen, upper back, lower back) were measured using flexible thermocouples 0.127 mm thick (type K, accuracy ± 0.3°C) that was soldered to copper plates (Φ8 mm, 0.2 mm thickness). All were calibrated, using a liquid bath temperature calibrator, and connected to a data acquisition unit in groups based on the different body segments. The temperatures were recorded at 2s time interval. The human subjects heart beat rate was measured using a good quality heart rate watch with a chest strap transmitter. The subjects were asked to record their own heart rate every 10 minutes during the tests. The air velocities and temperatures were measured in the occupied zone at four different levels using Omni-directional transducers (accuracy 10% at its lower range) and type U thermistors (accuracy ± 0.2°C). These measurements were recorded at 10s time interval. The operative temperature (T_o) for each case was measured using a globe thermometer, at the trunk level of the sitting subjects, at the centre of the room. The temperatures of the room surfaces were measured using an infrared thermometer for each case and were used to calculate the radiant temperature (according to ISO 7726:1985) at different levels in the occupied zone. Table 1 shows the temperatures and air velocities for the 3 cases at the four different levels.

Table 1: *Indoor conditions measured at four levels in the occupied zone*

Level	Case 1 (neutral) T_o =24.8°C, RH =48% , PMV≈ 0			Case 2 (warm) T_o =30.2°C, RH =43%, PMV≈ +2			Case 3 (cold) T_o =15.3°C, RH =55%, PMV≈ -3		
	Air Temp., T_a (°C)	Radiant Temp., T_r (°C)	Relative air velocity, v (m/s)	Air Temp., T_a (°C)	Radiant Temp., T_r (°C)	Relative air velocity, v (m/s)	Air Temp., T_a (°C)	Radiant Temp., T_r (°C)	Relative air velocity, v (m/s)
0.1 m	24.38	24.82	< 0.05	29.34	29.85	< 0.05	15.51	15.03	0.30
0.6 m	24.57	24.89	< 0.05	29.91	29.99	< 0.05	15.44	15.03	0.14
1.1 m	24.65	24.98	< 0.05	30.45	30.18	< 0.05	15.52	15.01	0.10
1.6 m	24.83	25.03	< 0.05	30.65	30.26	< 0.05	15.67	14.99	0.08

The human subjects were asked to refrain from eating 2-3 h and to remain indoors at least for 1-h before the pre-conditioning period of the experiments. The measurements of their body weight, height and oral temperatures were carried out upon their arrival to the test place; thereafter changing clothes, putting on the chest strap transmitter, attaching the thermocouples using surgical tape and wearing the full clothing ensemble. The subjects had normal office work with their own portable computers during the test period. At the end of each test, they gave their thermal sensation votes on the cases using ASHRAE 7-point scale (-3 cold, -2 cool, -1 slightly cool, 0 neutral, +1 slightly warm, +2 warm, +3 hot).

Results and discussion

The variations of the local skin temperatures in time for the 3 cases are shown in **Figures 2-7**. The shared data are at 1 min time step to improve the figures' visibility. In general, the lower measured temperature was always at the ankles (≈2°C less than the feet). The neck temperatures were nearly similar to the forehead with slight increase when far from neutral. The lower arm had higher temperatures than the upper arm, in the office work posture, which is in agreement with Zhang (2003).

In Case 1 (neutral), the subjects reached a physiological steady state in less than 1 h. The variability in temperatures was high especially for the extremities (e.g. SD=1.34 for the feet). The averaged temperatures, for different body parts, (n=11) were nearly in agreement with earlier measured data from the literature (e.g. Olesen and Fanger 1973, Zhang 2003) except for the thigh and abdomen segments which had lower (≈2°C) values in our measurements.

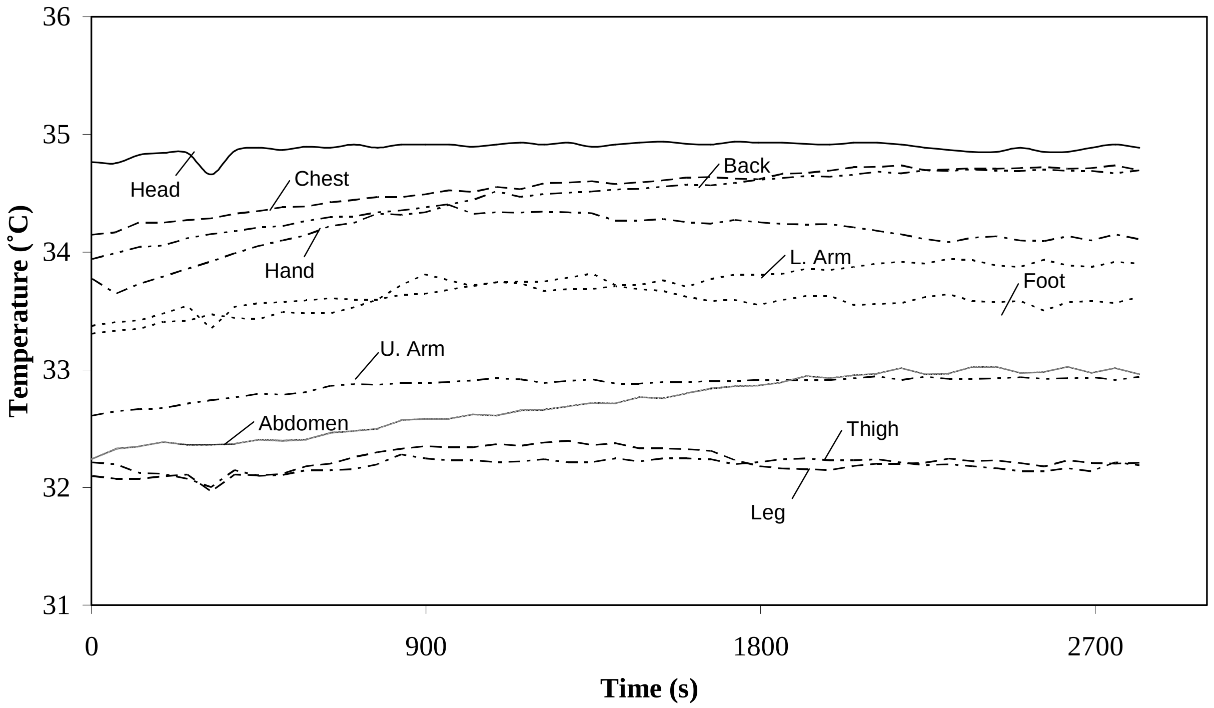

Figure 2. *The development of the local skin temperatures in time, Case 1 (neutral)*

In Case 2 (warm), a clear physiological steady state was not reached during the 1-h tests (n=11) for all body parts. The 2-h tests (n=6) showed a clear steady state for all body parts. The subjects at the pre-conditioning stage in Room 2 (T_o =23°C, vertical temperature gradient 0.6°C/m) reached the steady state with nearly similar level of the local temperatures for the two exposure durations (i.e. 1-h and 2-h tests).

In Case 3 (cold), the physiological steady state was not attained for most of body parts in the 1-h tests (n=11) and was not (clearly) attained as well for some of the body parts in the 2-h tests (n=6). The 4-h test (n=1) aimed at clarifying the physiological steady state for those body parts. The measurements results were compared with the subject’s results from the 2-h tests. The comparison showed nearly similar response for all body parts. Therefore, the averaged data from the 2-h tests could be treated to estimate the physiological steady state averaged temperatures for those body parts. The results from the cold tests show that the body thermoregulation system has a priority in preserving the temperatures of the head and trunk segments and maintains a quasi steady state condition in time (this coincides with Raven and Horvath 1970) that was observed clearly in the 4-h test. In that test, the forehead temperature attained a physiological steady state after 1.5 h duration and remained nearly constant for more than 1 hour. Thereafter, it started to decline and stabilized once again in the last 30 minutes of the test. The pre-conditioning stage at Room 2 (T_o =22°C, vertical temperature gradient 1.4°C/m) showed slight variations in the averaged body temperatures between the different exposure durations. This is mainly by the difference in the number of subjects for the different exposure tests and the higher variability observed in the cold condition. Table 2 shows the steady state temperatures for the different body parts as well as the standard deviation to indicate the variability.

Table 2: *The steady state local skin temperatures for the three cases (in °C) and the standard deviation* [(a)]

	Head	Back	Chest	U. arm	L. arm	Hand	Thigh	Leg	Foot	Abdomen
Case 1 (neutral)	34.88 (0.35)	34.72 (1.15)	34.74 (0.65)	32.93 (0.59)	33.95 (0.66)	34.05 (0.69)	32.16 (0.49)	32.17 (0.91)	33.54 (1.34)	33.00 (0.77)
Case 2 (warm)	35.76 (0.28)	35.85 (0.47)	35.68 (0.44)	34.70 (0.23)	35.68 (0.2)	35.32 (0.45)	33.57 (0.36)	33.24 (0.52)	34.63 (0.35)	34.48 (0.94)
Case 3 (cold)	31.60 (1.21)	32.97 (1.12)	32.01 (0.93)	29.50 (1.12)	29.84 (0.95)	23.25 (0.74)	26.35 (0.69)	27.50 (0.78)	23.40 (1.9)	31.81 (0.86)

[(a)] Values in brackets refer to the standard deviation

The average subjects' vote on ASHRAE 7-point scale at each case was 0.4, 2.0 and -2.1 for the cases 1-3 respectively. The average was consistent with the planned condition for Case 2 (warm) and nearly consistent for Case 1 (neutral) while in Case3 (cold), it indicated a slightly warmer perception than the planned condition. This may be related to the effect of the outdoor cold winter conditions, during the period of the experiments, on the thermal sensation of the subjects. The average outdoor temperature during the experiments' period was -6.4°C. The average heart beat rates was 76, 81 and 70 for the 3 cases respectively. This falls in the very light activity category defined by ASHRAE (ASHRAE Handbook—Fundamentals 1993).

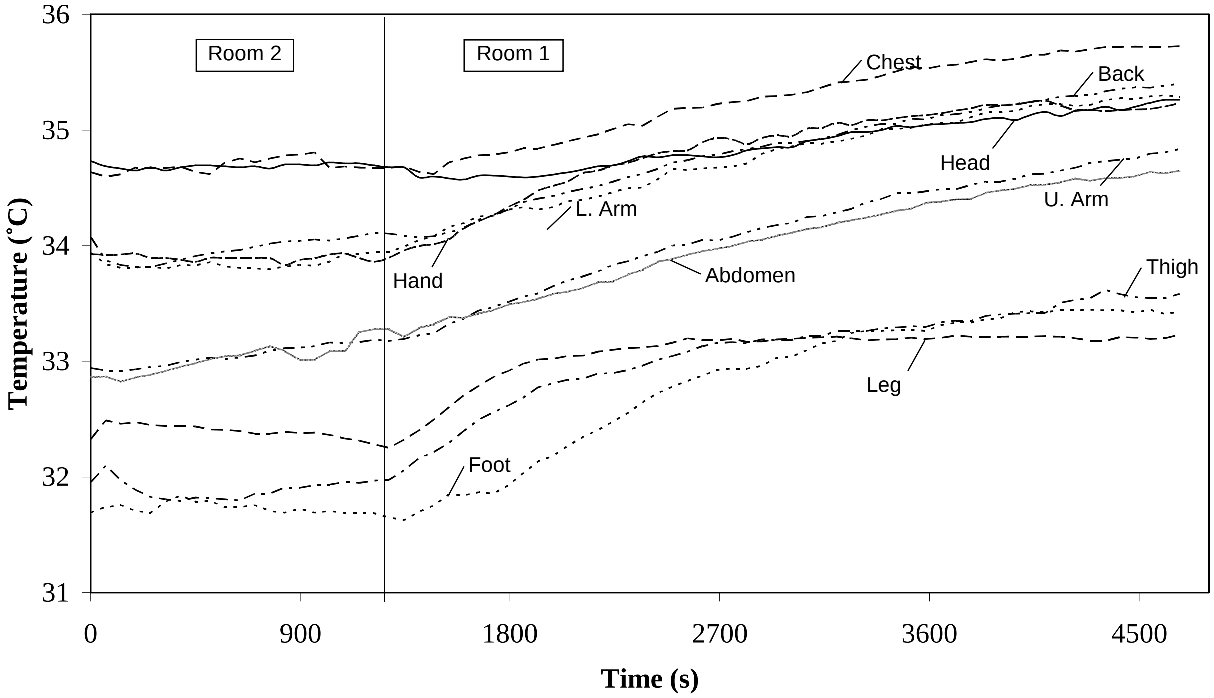

Figure 3. *The development of the local skin temperatures in time, Case 2 (warm) 1h test*

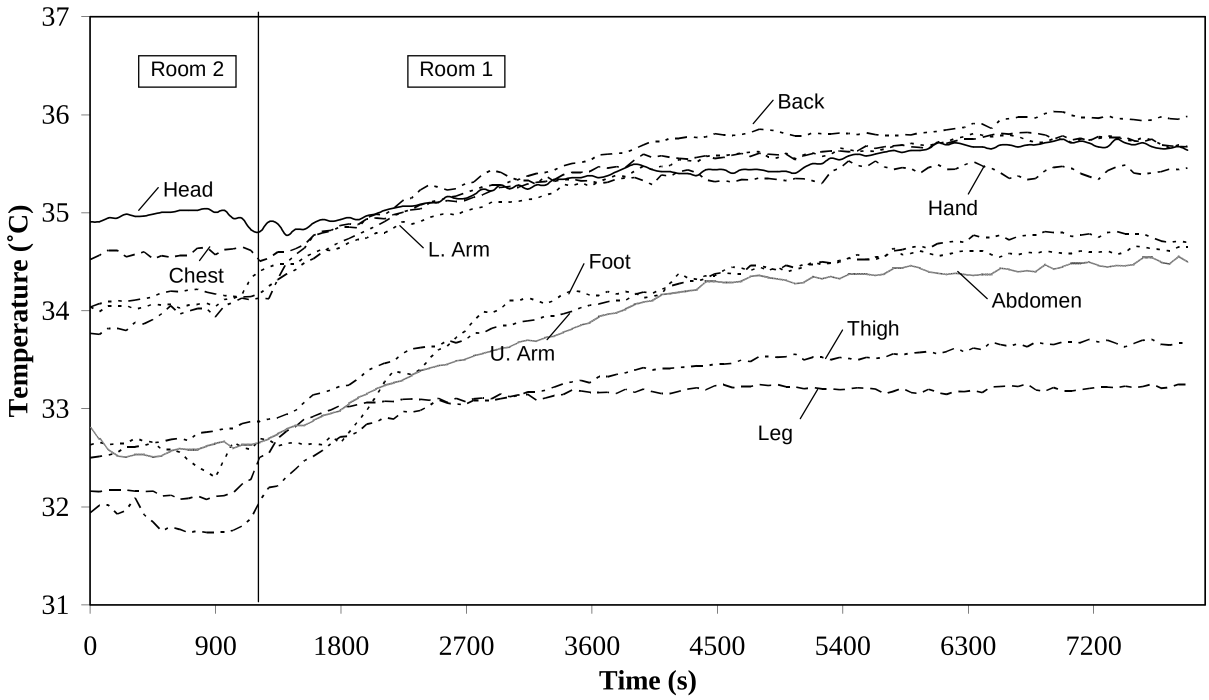

Figure 4. *The development of the local skin temperatures in time, Case 2 (warm) 2h test*

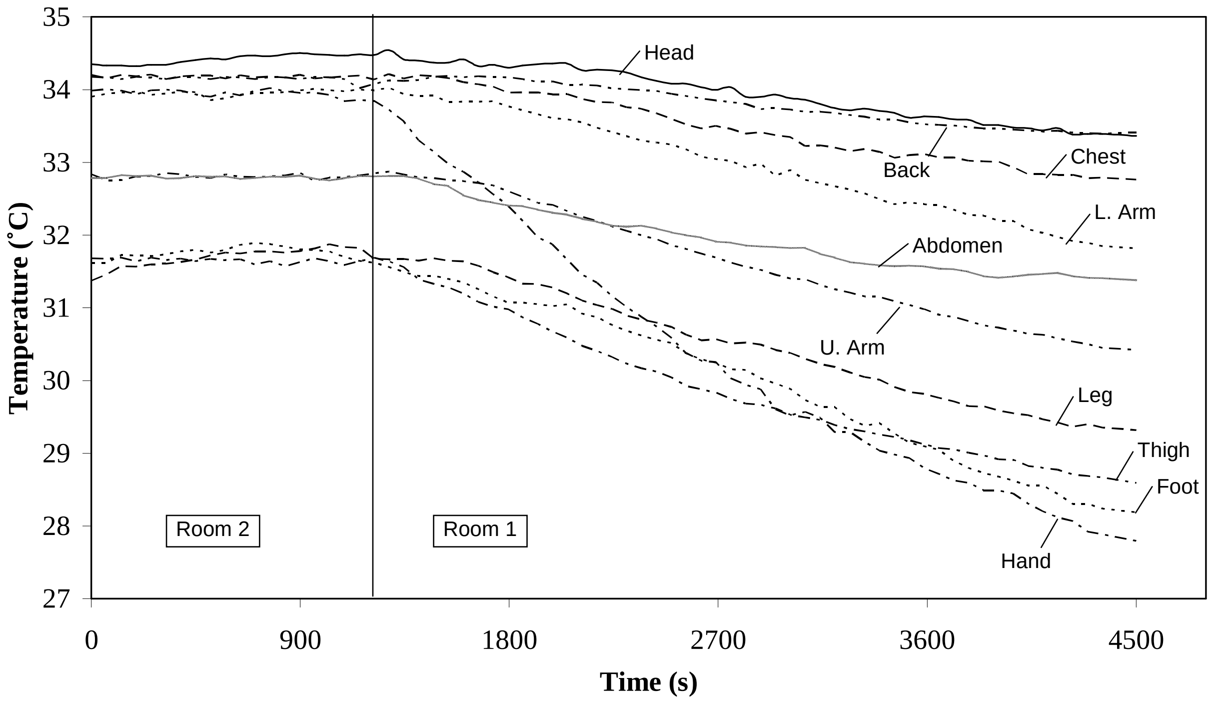

Figure 5. *The development of the local skin temperatures in time, Case3 (cold) 1h test*

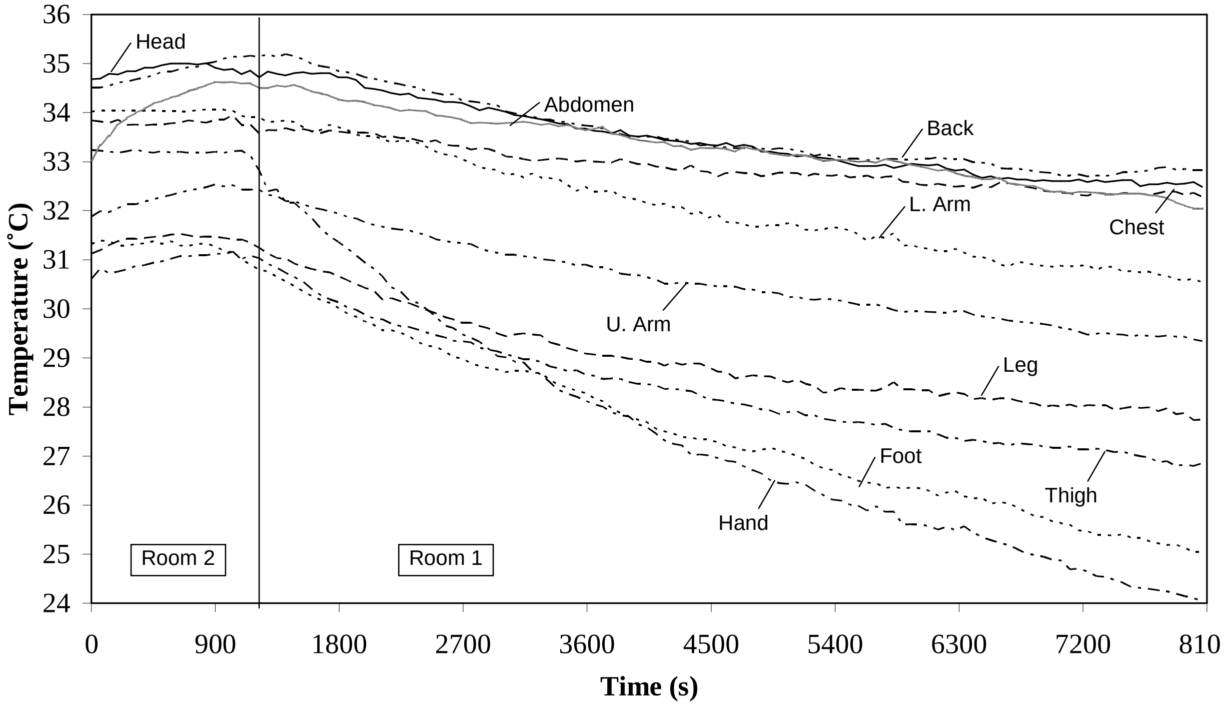

Figure 6. *The development of the local skin temperatures in time, Case 3 (cold) 2h test*

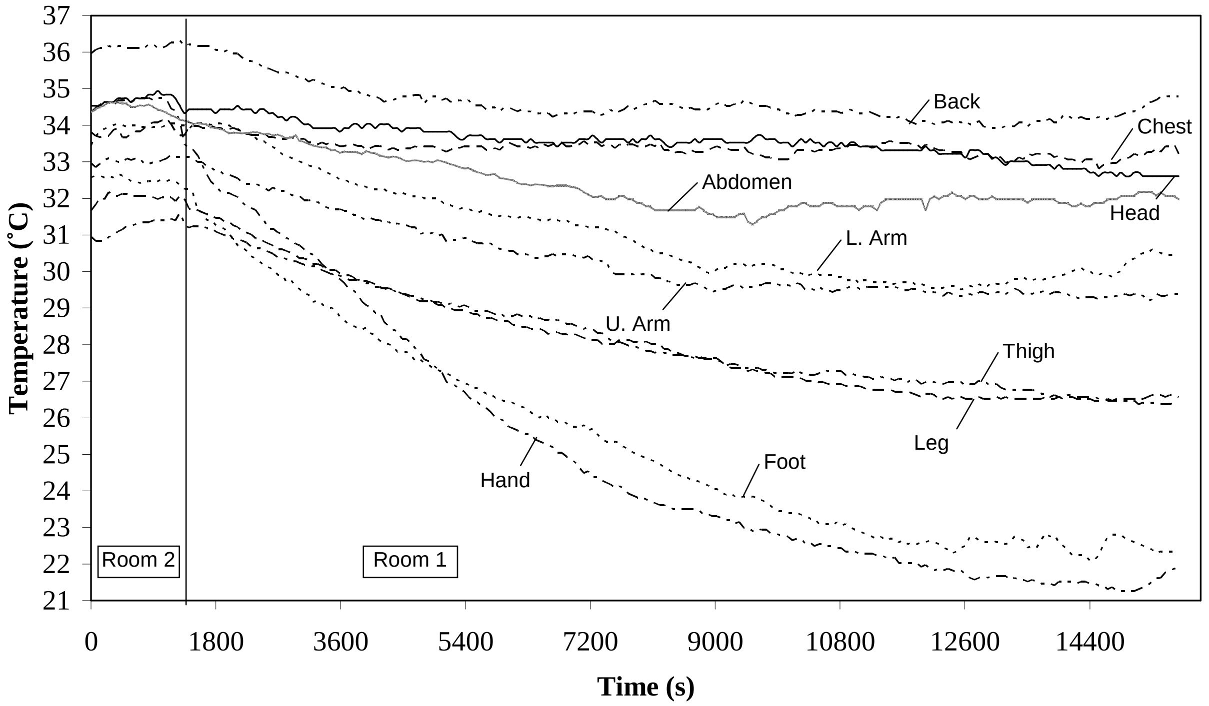

Figure 7. *The development of the local skin temperatures in time, Case 3 (cold) 4h test*

4 Conclusion

In this study, measurements of local skin temperature were carried out under three different indoor conditions using a diverse sample of human subjects who wore normal office clothes. The measurements focused on the office work activity and investigated the variability in local responses and the local skin temperatures at the physiological steady state condition. In general, the variability in the local temperatures was high for the extremities in the neutral condition and it increased for all body parts in the cold condition while in the warm condition it decreased for all body parts. The differences in the variability for the different exposures, in the warm and the cold conditions, was minor for the trunk and head while in the longer exposures for the extremities it decreased based on the same test subjects. The steady state temperatures under the neutral condition are comparable and nearly in agreement with measured data from the literature. The distribution of the body temperatures was in a narrow range (<2.5°C) in the warm condition. In cold conditions, the body thermoregulation mainly preserves the temperatures of the body's vital organs in the head and trunk segments; hence these segments had lower cooling rate in the cold tests. In these tests, the difference between the local temperatures increased and was up to 10-14°C. The body extremities needed longer exposure (>2 hours) to reach the physiological steady state under the cold condition.

5 Acknowledgement

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