Evaluating the thermal comfort performance of heating systems using a thermal manikin with human thermoregulatory control

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Abstract

The evaluation of the local thermal comfort and application of thermal manikins can further assist the design and selection of heating systems. This study aimed at evaluating the thermal comfort performance of different heating systems using a newly developed thermal manikin with an enhanced thermal control. The heating systems for a workstation, included a conventional radiator (convector) mounted under the window, heated floor in the occupied zone and an infrared heater mounted to the ceiling. The experiments were conducted in a test room with a façade attached to a climate chamber to simulate outdoor winter conditions. In these experiments, the supplied power for the different systems was kept constant to independently quantify the differences in their thermal comfort performance at same energy consumption. The thermal manikin was deployed in the occupied zone to evaluate the local and overall thermal comfort under each system using the equivalent temperature (Teq) approach. The thermoregulatory control used in the manikin operation is based on a model of human thermoregulation that interacts accurately with the surrounding environment through real-time measurements. The results showed that at the same energy consumption of the different systems, the variations in local thermal comfort levels were up to 1 on the comfort scale.

Keywords *Thermal comfort, Thermal manikin, Heating systems, Human thermoregulation, Equivalent temperature*

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1. Introduction

Sedentary workers represent the vast majority of the labour market worldwide. They spend most of their time indoors and expect to have conditions that satisfy thermal comfort requirements. These conditions are created by the effectiveness of the building envelope and the use of heating, ventilation and air-conditioning (HVAC) systems. The thermal comfort performance of different HVAC systems is commonly evaluated using the predicted mean vote (PMV) model[1] and guidelines given in the international standards [2–4]. Thermal comfort research over the last 10 years has undergone an extensively new wave of development of methods and concepts[5–12] that is mainly linked to the concept of the local (segmental) thermal comfort. The local thermal comfort underlies the evaluation for the whole body and represents the current state of art for the evaluation of thermal comfort. The evaluation of thermal comfort based on local (segmental) basis weighs local effects from all body segments and accounts for local discomfort. In non-uniform thermal environments, as is mostly the case in buildings, the body segments may experience a wide range of relevant environmental parameters (i.e. air temperature, radiant temperature and air velocity). Therefore, the evaluation methods that are based on mean physiological variables and whole-body heat balance with its surroundings, such as the PMV model, may not be adequate. Then, the evaluation of the local (segmental) thermal comfort under these conditions becomes necessary. Subjective tests are time consuming, susceptible to errors and require great organizational efforts, especially for dealing with ethical guidelines. On the other hand, relying only on measurements of room physical parameters may be at the expense of accuracy. Then, a more optimal evaluation of local comfort can be carried out using thermal manikins. Multi-segmental thermal manikins provide a realistic three-dimensional measurement of body heat loss (conductive, convective and radiant) from different body segments that is accounting accurately for room conditions, clothing, body posture and interaction with room objects. The history of the development of thermal manikins is presented, in detail, in a study by Holmer[13]. Different sorts of thermal manikins were used in several studies to evaluate: clothing thermal insulation[14,15]; influence of thermal environments on segmental heat transfer[16–18]; and thermal comfort using the equivalent temperature (Teq) approach[19–21]. Although a thermal manikin that has the shape of a human body provides the realism of the human physical presence, the traditional control modes of thermal manikins (i.e. constant skin temperature (CST) mode, constant heat flux (CHF) mode and comfort equation (CE) mode) cannot simulate accurately the human thermal presence. The CST is the most common mode that uses feedback control to regulate skin surface temperatures (normally at 34°C) with a short response time. The CST mode relies on pre-assumed value of skin surface temperature that is not applicable under all different conditions. The CHF mode uses the same value of heat flux with no need of feedback control. The skin temperature then depends on the environmental conditions and clothing that usually results in unrealistic temperatures. The CE mode uses the CE, derived from Fanger[1] which is setting the skin surface temperature according to neutrality using a linear correlation with the sensible heat loss. This control mode uses an iterative procedure for processing with a long response time, and in reality it only represents a neutral condition. The disadvantages of each of the existing control modes have been overcome in earlier studies using additionally human subjects tests[22,23]. However, using human subjects for all cases of measurement with thermal manikins is not an efficient procedure. The authors, in an earlier study[24], pointed out the disadvantages of the common control modes and introduced a new control mode that is based on a multi-segmental model of human thermoregulation (i.e. multi-segmental pierce (MSP) mode). In that study, the new control mode was implemented onto the control system of the thermal manikin 'Therminator' and was validated for the estimation of the Teq[25]. The evaluation of the local thermal comfort and application of thermal manikins may further assist the design and selection of HVAC systems. From this perspective, the thermal manikin 'Therminator' with the MSP control mode was used in this study to evaluate the local and overall thermal comfort under three different heating systems. The systems included a conventional system (i.e. under-window mounted radiator) and two localized (personalized) systems. The results were compared to demonstrate the differences related to the localized or conventional heating system used.

2. Methods

2.1. Thermal Manikin

The thermal manikin 'Therminator' is a Scandinavian male size 50 (European sizes) that can stand, sit, move his arms and breathe. It consists of 24 body segments that can be individually heated and set at a target value. The manikin thermoregulatory control is based on the MSP model of human thermoregulation developed by the authors[26]. The model's predictability of skin temperature was verified for steady state and dynamic conditions using measured data at uniform neutral, cold and warm as well as different asymmetric thermal conditions and had the average absolute deviation in a range of 0.3–0.8 K[27]. The thermoregulatory control was implemented onto the manikin's system using LabVIEW platform[24] and was validated for the estimation of the local (segmental) thermal comfort using the Teq approach. Figure 1 shows a flow chart of the manikin's system with LabVIEW. The manikin control works with the MSP mode through on-off control (time step =50ms, deviation <0.05 K). Measurements of the indoor condition such as air temperatures, velocities and globe temperatures were connected through LabVIEW and used with the MSP control at 1 min step. The feedback measurements and control signal in connection with the manikin's program on LabVIEW were handled through NI interface (NI USB-6225, National instruments). The interface was connected to the manikin's power supply unit and power distribution control cards, as well as the measurement cards that correspond to the manikin's embedded resistance temperature detectors (accuracy±0.1 K). The system front panel, on LabVIEW, shows the development of the segmental temperatures and heat losses during the measurements. The segmental skin temperatures and heat losses were recorded at 1 min time interval.

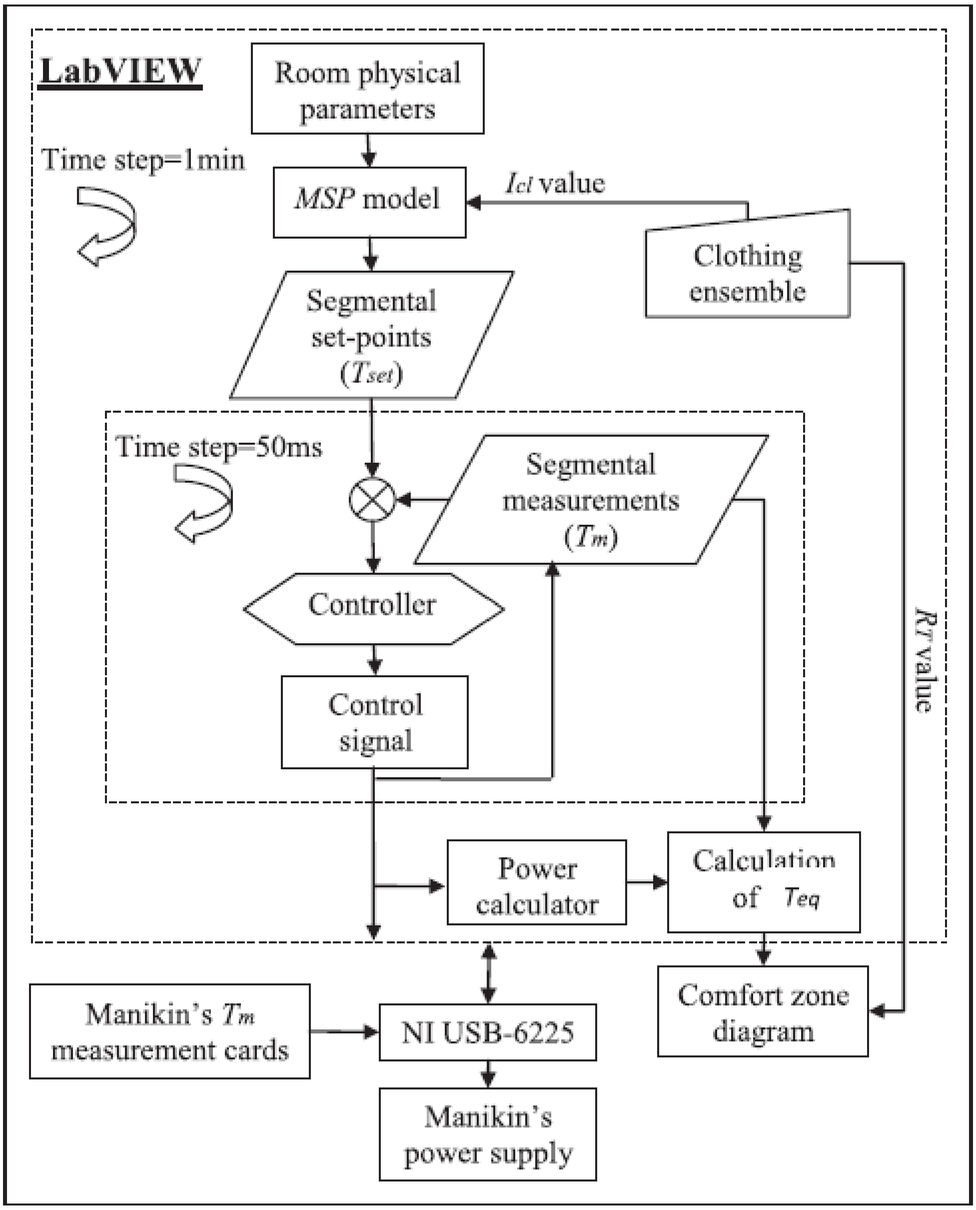

Figure 1 Flow chart of the manikin's system with LabVIEW

2.2. The equivalent temperature (T_{eq}) approach

The Teq approach was first introduced by Wyon et al.[25] for assessing the vehicle climate using a thermal manikin. Wyon and Sandberg[28] used the same approach in evaluating local thermal discomfort due to vertical temperature gradients in buildings and it was then used in several studies evaluating buildings [19–21]. The Teq approach is a feasible method for laboratory and field measurements evaluating thermal comfort of sedentary people. The segmental and overall Teq are calculated, from thermal manikin experiments, using equation (1)[25]:

$$T_{eq} = T_{sk} - \frac{Q_s}{h_{cal}}, \ (°C) \qquad (1)$$

where

T_{sk} is the manikin skin temperature (°C)

Q_s is the manikin sensible (dry) heat loss (W/m²)

h_{cal} is the heat transfer coefficient from calibrations under uniform and calm conditions (W/m²K)

Wyon et al.[25] presented the Teq on a diagram that shows the so-called ideal profile (neutral) and acceptable ranges (mean vote = 0.8 corresponds to 20% dissatisfied) for the different body segments. A new diagram, called comfort zone diagram, with wider acceptable ranges (mean vote=1.5) was later obtained by Nilsson[29] to deal with variability and repeatability due to different human subjects panels and manikins used, respectively. That was developed using subjective votes from 600 tests under 30 sets of climatic conditions. The Teq at these conditions was estimated using two thermal manikins (with the constant surface temperature CST control mode at 34 °C) and correlated with the mean votes from the subjective tests. The following correlation, equation (2), was then introduced for each body segment and for whole body to construct the comfort zones[29]:

$$T_{eq} = T_{sk} - R_T * (a + b * MTV), \ (°C) \qquad (2)$$

where

R_T is the clothing total thermal resistance (m²K/W)

a and *b* are the linear regression coefficients given in [29]

MTV is the mean thermal comfort vote.

In this study, the comfort zones were obtained by substituting the segmental R_T, a, b and the MTV border values as well as the T_{sk} (equals 34°C) in Eq. 2. Table 1 shows the suggested MTV ranges of the comfort zones and its correspondent sensations.

Table 1 Mean vote ranges of the comfort zones and correspondent sensations [(a)]

Mean vote range	Thermal sensation
+1.5 : +3.0	Too hot
+0.5 : +1.5	Hot but comfortable
-0.5 : +0.5	Comfort
-1.5 : -0.5	Cold but comfortable
-3.0 : -1.5	Too cold

[(a)] Given by Nilsson [29]

2.3. Heating systems

In this study, Therminator was sitting at a workstation to investigate the thermal comfort performance of three different heating systems accompanied with a mechanical ventilation system. The systems were a radiator (convector) mounted under the window which is commonly applied in buildings, a heated floor in the occupied zone (20% of total floor area) and a household infrared (IR) heater focused on the occupied zone (ceiling mounted). The choice of these systems aimed at testing the performance of a conventional system (i.e. under-window mounted radiator), with two localized (personalized) systems based on the local comfort concept. Localized or personalized term here means that the energy use is focused on a local position that is occupied by a person. Thus, it needs not to be confused with typical existing systems using these terms. The radiator used was an electric oil-filled radiator (E612, WARMOS). The radiator placement under the window (i.e. typically the coldest surface in the room) is a common practice to prevent downdraft and air movements in general over the space. The heated floor (1.8m x 2.0 m) was constructed in the occupied zone using two electrical heating elements (TEVAL 90-235-315, ENSTO) covered with a 2mm aluminium sheet that was also painted using a mat brown colour to overcome the low emissivity of the shiny metal surface. The IR heater (BH Smart 2000, BURDA) was mounted to the ceiling which was meant to be a safer and advantageous placement to focus the energy use on the occupant's body. It should be noted that applying direct or indirect IR heating in buildings needs to conform to precautions concerning its recommended control, placement and exposure durations. The use of electrical heating in this study was mainly to simplify the experimental setup and easily control the energy supply at a fixed value. However, the heating method could preferably be based on a hydronic system, in the case of floor heater or radiator, to eliminate dependency on certain means of energy production.

2.4. Experimental setup and procedure

The experiments were conducted in a test room at the HVAC laboratory at Aalto University. The test room is part of a two-storey single family house that has large climate chamber equipped with all controls to simulate outdoor conditions and to control the air temperature and humidity over wide ranges. The experimental setup and room layout are shown in Figure 2. The air temperature in the climate chamber (behind the window) was adjusted to set the inner surface temperature of the room window at 12.5°C (±0.2 K). That window's temperature corresponds to the Finnish extreme outdoor winter conditions together with the use of a Finnish standard window type. The ventilation air (~50 l/s, i.e. 2.5 l/s.m^2) was mechanically supplied to the room at 18°C (±0.5 K). The surrounding rooms were at 21°C (±0.5 K) and the room's operative temperature in steady state with no heating (only ventilation) was around 18.4°C (±0.2 K). The inner surface temperatures of the partition walls and floor were at 19.2°C and 18.5°C (±0.5 K), respectively. It should be noted that the test case is simulating a room condition with heating failure during winter. Then under the different heating systems, the electrical power supplied to the systems was kept constant to independently quantify the differences in their thermal comfort performance. The constant power was 400W supplied through a voltage controller (MAL9-230, Intelecsa). The power supply value was decided in pilot tests to have slightly cool discomfort condition (as a case of undersized system with no influence of controls), corresponding to a maximum floor temperature of 29°C based on ISO 7730:2005[2]. The manikin calibrations, to estimate the segmental heat transfer coefficients, were carried out at the same test room under uniform room temperature (at 18°C, 21°C, 24°C, 27°C and 30°C) and still air conditions (v<0.05 m/s). In all procedures, the manikin wore a clothing ensemble that consists of under-shirt, shorts, denim trousers, long-sleeve shirt, and calf-length cotton socks. A thick wooden board 0.5m x 0.2m x 0.1m (W x L x H) was placed under the manikin's feet during the tests. The clothing intrinsic thermal insulation value was measured (0.6 clo, where clo = 0.155m2°C/W) according to ISO 9920:200730 regulations using the manikin in a sitting posture, also at the same test room. The clothing was selected among other parameters in pilot tests to create a slightly cool condition. This aimed to compare the heating systems at the cold side of the symmetrical comfort scale. Online measurements of the indoor conditions were carried out during the whole experimental procedure. The air velocity was measured, at three different levels in the occupied zone, using transducers (8465/75, TSI Inc., accuracy±5%). The air and operative temperature, at same levels, were measured in the occupied zone using thermistors and globe thermometers (type U, Grant Instruments, accuracy±0.2 K). This was used to calculate the radiant temperature, for the MSP control mode, at the same three levels according to ISO 7726:1998 (equation 7)[31]. Under the three different heating systems, the relative humidity (RH%) was around 30% that was measured at the room centre using a humidity indicator (HM141, Vaisala, accuracy±0.1%). All room measurements were connected through a data acquisition unit (SQ2040 Squirrel, Grant Instruments) and were recorded at 10 s time interval. The online measurements (at 1 min time interval) were used with the thermal manikin regulation as real-time input parameters to the MSP control mode.

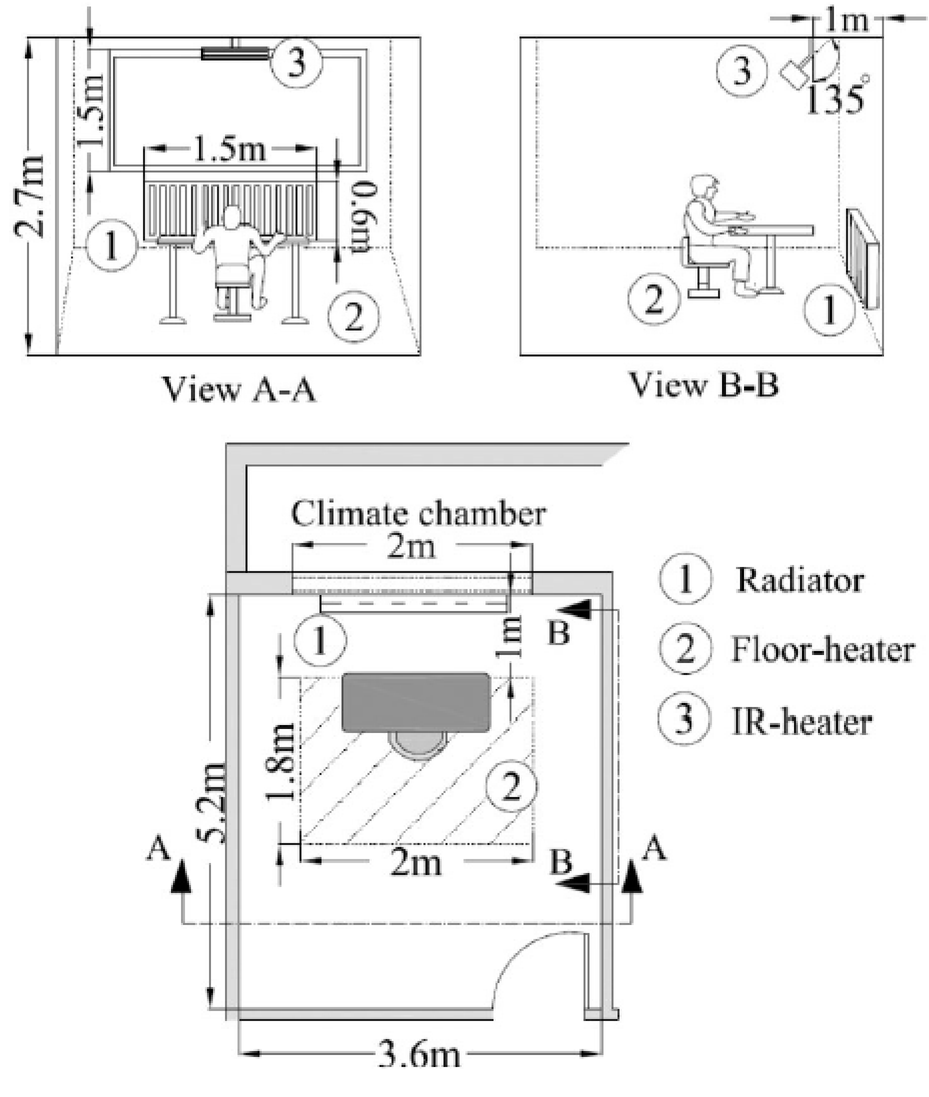

Figure 2 The different heating systems and layout of the test room

3. Results and discussion

3.1. Room physical parameters

The room physical parameters (i.e. air, globe temperatures and air velocity) were measured at the occupied zone. Figure 3 shows the measured data at three different heights (0.1, 0.6 and

1.1 m) under the conditions by the different heating system (uncertainties were added as error bars). The air temperatures at the three different heights (Figure 3(a)) varied for the three different systems. The differences were around 1–1.5K with the greatest difference at 0.1m height. The standard deviation (SD) of the air temperature at 0.6 and 1.1m heights and under the three systems was less than 0.05 K, while it was around 0.1K at 0.1m height under the floor and IR heaters and 0.05K with the radiator. The differences in the measured globe temperatures, at the three heights (Figure 3(b)) in the occupied zone, for the three different systems were in a range of 1–1.8 K. The SD was less than 0.05 K at the three heights under the radiator and IR heater systems, while it was up to 0.1K at 0.1m height under the floor heater. Figure 3(c) shows the calculated radiant temperatures according to ISO 7726:1998 (equation 7)[31] using the measured air and globe temperatures. As can be seen, the difference in the radiant temperature between the different systems was up to 2 K. The air velocities (shown in Figure 3(d)) were in a range from 0.04 to 0.16 m/s under the three systems. The greatest difference in the air velocities was at 0.1m height between the radiator and floor heater systems. The difference decreased much at 1.1m height and was less than 0.02 m/s. The SD was around 0.02 m/s at the three different heights. These measured temperatures and air velocities reflected known characteristics of the used systems. For example, the radiator system showed the least temperature gradient and air velocities as expected. The IR heater resulted in the greatest temperature gradient and nearly constant air velocities (around 0.1 m/s) at the three heights. The localized floor heater system showed a slight gradient (i.e. <1 K/m) in the operative temperature but resulted in the highest air velocity (i.e. 0.16 m/s) at the 0.1m height. The radiator system under the window indeed prevented the downdrafts near to floor level. However, at that fixed power supply (i.e. 400 W) and with the implemented ventilation rate (i.e. ~2.5 l/s/m2) it could not influence the room temperature in the occupied zone compared to the room temperature with no heating (i.e. 18.4°C). Furthermore, the highest temperature gradient with the IR heater may be related to the positioning of the heater and interaction with the room objects. As the IR heater was focused on the manikin and the used furniture (desk and chair), the electromagnetic waves from the heater heated up these objects and they consequently resulted in heating the surrounding air upwardly through convection. In addition, the used desk has probably blocked the IR heater effect towards the floor level.

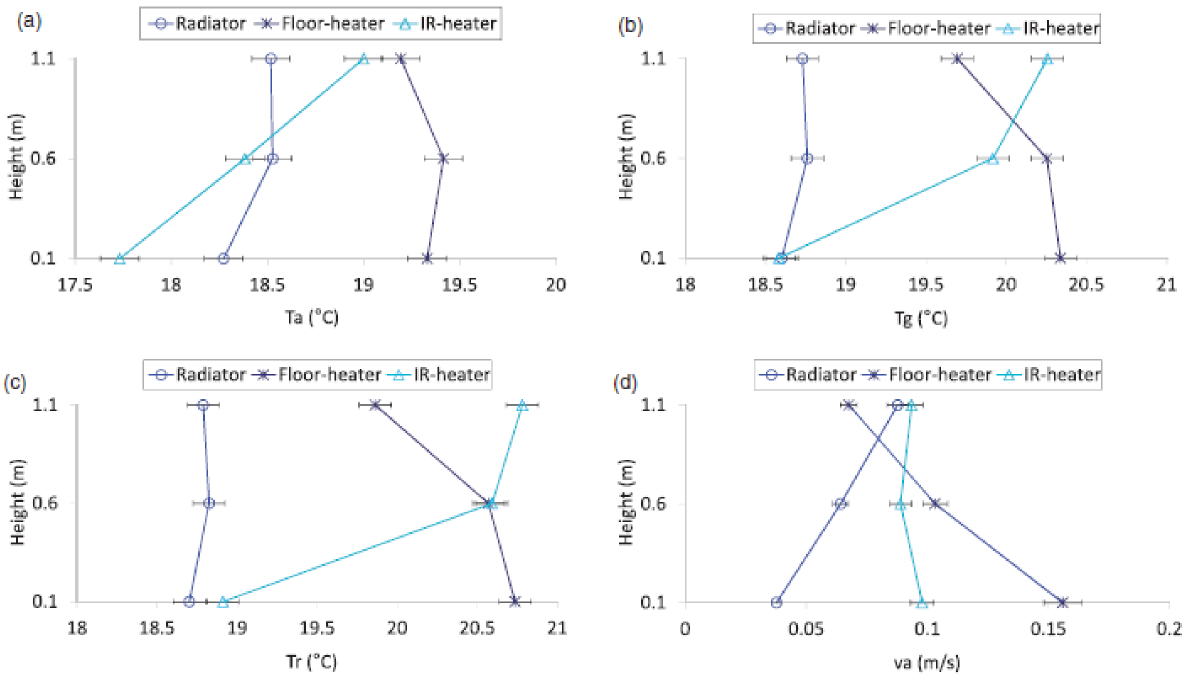

Figure 3 Measured physical parameters at the occupied zone and calculated radiant temperatures

3.2. Thermal comfort performance

The manikin calibrations were carried out and repeated twice under five different uniform indoor temperatures (from 18°C to 30°C). Figure 4 shows the obtained hcal at the different temperature levels for the clothed whole body. The obtained values for whole body using the MSP mode were nearly constant at the different temperature levels. Figure 5 shows the segmental hcal obtained under the different calibration levels. For most body segments, the hcal was nearly constant under the different calibration conditions. The hcal of some segments varied for the calibration's lower and upper limits with a maximum value of 1 W/m^2K. The obtained hcal are specific to the manikin 'Therminator' with the used clothing ensemble. The accuracy of the obtained hcal may be influenced by uncertainties of measuring instruments, slight changes in the manikin posture and the clothing thermal insulation impact on the convective air flow under the different room temperatures. The repeatability of the manikin measurements was found ±5%, i.e. inclusive of sensors errors (these are shown on figures as error bars). The obtained hcal are comparable to data from literature[4]. However, they primarily correspond to the manikin segmental geometry, physical condition and the used clothing insulation as well as the used measurement devices under these experimental conditions. In the experiments, the measurements at the occupied zone were connected with the manikin's system to interact with the surrounding environment at 1 min time step, which was chosen to allow the control system enough time to respond. However, under that controlled environment the fluctuations based on that 1 min averaging in the room physical parameters were minor and the manikin's skin temperature remained nearly constant during these tests. Then, based on the heat loss over the 1 min step, the equivalent temperature (Teq) was instantaneously calculated using equation (1). The results were then presented on the comfort zone diagram that was constructed using equation (2).

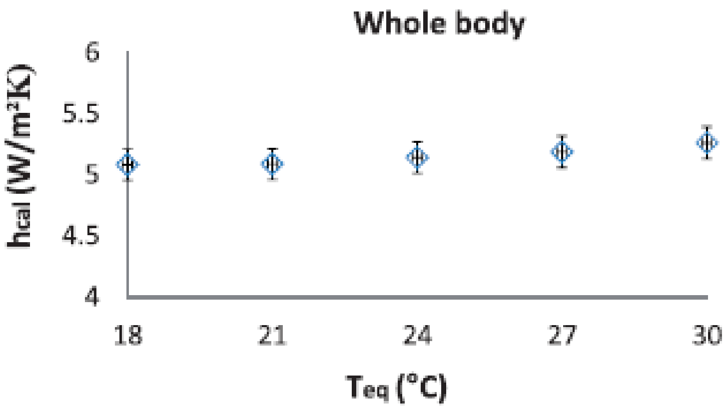

Figure 4 Heat transfer coefficients at the different temperature for the clothed whole body.

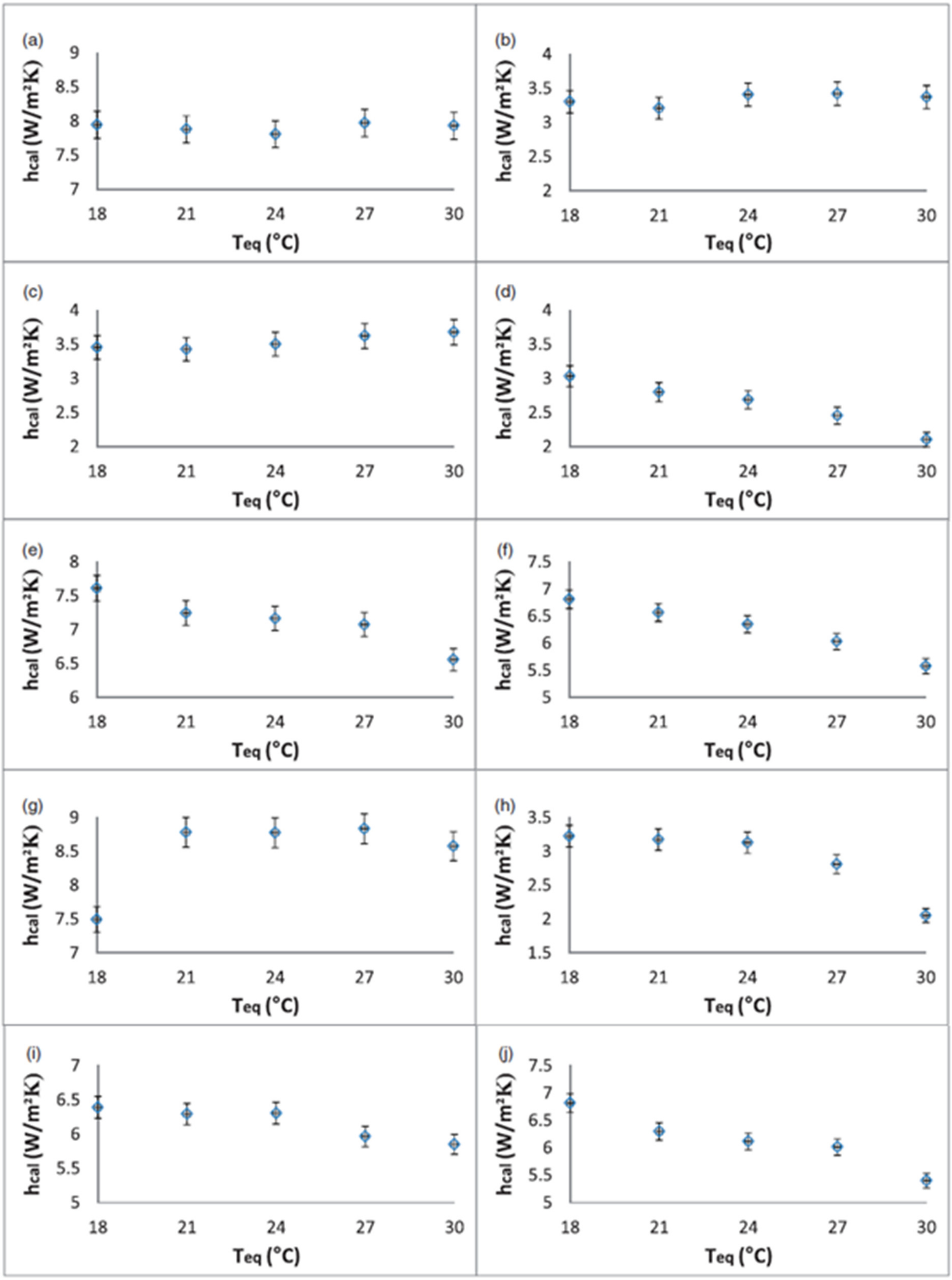

Figure 5 Segmental heat transfer coefficients at the different temperature levels. (a) Head, (b) Chest, (c) Back, (d) Pelvis, (e) U arm (f) L arm, (g) Hand, (h) Thigh, (i) Leg and (j) Foot.

Table 2 presents the parameters used with equation (2) and the segmental skin temperatures (mean, min and max) of the manikin during the experiments. Figure 6 shows the results of the segmental and overall Teq under the three systems (uncertainties of ±5% are shown as error bars). Additionally, the numeric values for better visibility of the results are presented in Table 3. As can be seen, the difference in the segmental Teq was in the range from 0.7 to 3.4 K. The greatest difference was at the chest segments between the IR heater and radiator systems while the smallest was at the hand segments, that is related in the chest case to the focused heat from the IR heater on the manikin's body while in the hand's case to their positioning stretched over the desk away from the effect of the different systems. The segmental Teq at the lower limbs' segments were somehow improved with the floor heater system. However, the effect of the floor heater on the limbs' segments was not significant due to: (1) the relatively higher air velocity near to the floor level; (2) and the feet's positioning on a wooden thick board not in contact with the floor. The difference in the segmental Teq, compared with the other systems, was in a range from 1 to 1.8 K. The IR heater clearly resulted in better comfort levels at the upper body segments based on the measured Teq. As mentioned earlier, the maximum difference in the segmental Teq was at the chest while it was around 1.5 for the other upper body segments. Based on the Teq approach and the defined comfort zones, most body segments were cold but comfortable while the lower limbs were below that limit especially with the radiator and IR heater systems. Only few body segments such as the head and pelvis were in comfort zone (±0.5 on comfort scale). The difference in the overall Teq between the different systems was nearly 1K in favour of the localized floor and IR heaters. These two systems nearly fulfilled the limit of the cold but comfortable sensation while the comfort level of the radiator was below that limit. Furthermore, the overall comfort levels under the three systems were estimated using the PMV model. Figure 7 shows the overall thermal comfort measured by the manikin under the three different systems and calculated values using the PMV model. The PMV calculations were based on: the room physical parameters at 0.6m height as specified for a seated person, the overall intrinsic clothing thermal insulation (i.e. 0.6 clo) and the office work activity. The uncertainty of that calculation was estimated ±5% based on full uncertainties of physical measurements, i.e. same as the manikin repeatability; these are shown in Figure 7 as error bars. As can be seen, the variation in the estimated comfort levels between the two methods was <0.5 on the comfort scale for the three cases. However, the predictions by the PMV model relied on the room physical parameters at a specified height for a seated person (i.e. 0.6 m) and could not account for the non-uniformity as it was most clear with the IR heater. Conversely, the evaluation of thermal comfort using the manikin reflected the local comfort levels and weighed those local effects from all body segments in the overall comfort evaluation. Therefore, it can be stated that PMV model and overall comfort evaluation alone may mislead the design or selection of HVAC systems.

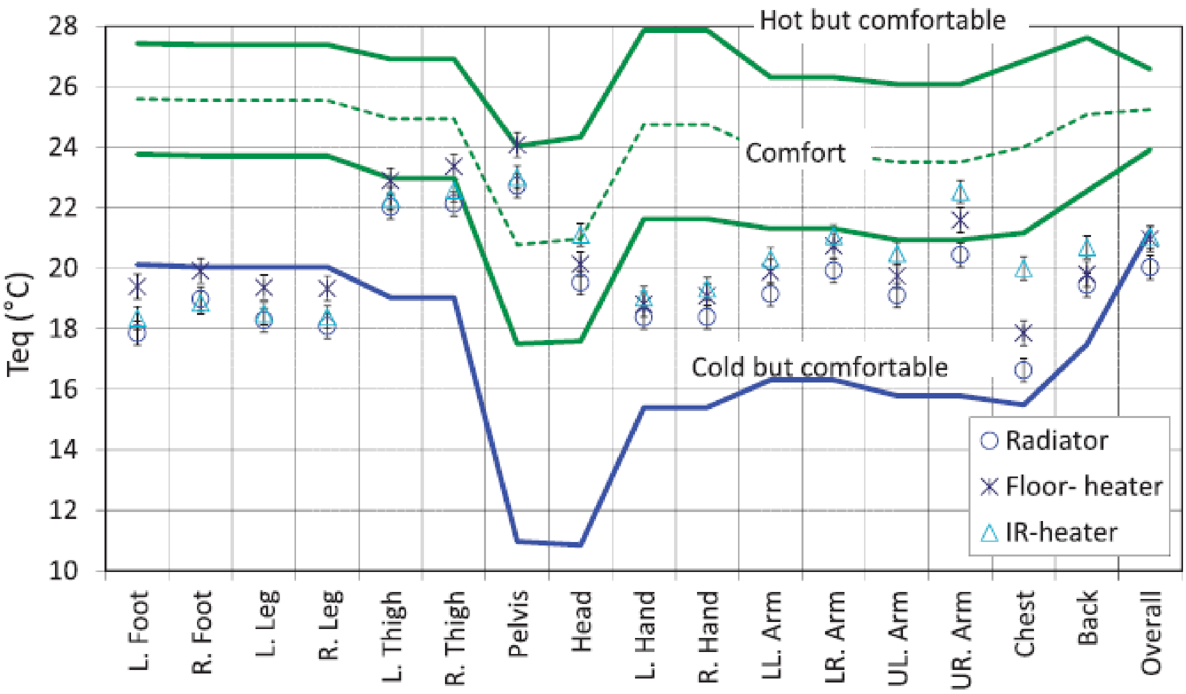

Figure 6 Measured Teq under the different heating systems on the comfort zone diagram.

Table 2 Parameters used in Eq. (2) and manikin's skin temperature distribution in the experiments

	Parameters used in equation (2)			Manikin's skin temperature (°C)			
Segment	RT (m^2K/W)	a^a	b^a	Mean	Min	Max	SD
Head	0.20	65.5	−33.9	33.6	33.5	33.8	0.2
UR Back	0.25	36.1	−20.5	34.7	34.4	35.0	0.3
UL Back	0.25	36.1	−20.5	34.7	34.4	35.0	0.3
R Chest	0.28	36.1	−20.5	33.7	33.6	33.8	0.1
UR Arm	0.24	43.0	−21.1	31.9	31.7	32.1	0.2
LR Arm	0.24	43.0	−21.1	32.5	32.2	32. 9	0.2
R Hand	0.11	84.9	−57.2	26.2	25.8	26.9	0.6
L Chest	0.28	36.1	−20.5	33.6	33.6	33.8	0.1
UL Arm	0.24	43.0	−21.1	31.9	31.7	32.1	0.2
LL Arm	0.24	43.0	−21.1	32.5	32.2	32.9	0.4
L Hand	0.11	84.9	−57.2	26.2	25.8	26.9	0.6
R Thigh	0.19	46.7	−20.3	29.3	29.0	29.7	0.4
R Leg	0.18	46.7	−20.3	29.7	29.3	30.1	0.4
R Foot	0.22	46.7	−20.3	29.8	29.4	30.4	0.5
L Thigh	0.19	46.7	−20.3	29.3	29.0	29.7	0.4
L Leg	0.18	46.7	−20.3	29.7	29.3	30.1	0.4
L Foot	0.22	46.7	−20.3	29.8	29.4	30.4	0.5
LR Back	0.25	36.1	−20.5	33.3	33.1	33.4	0.2
LL Back	0.25	36.1	−20.5	33.3	33.1	33.4	0.2
Pelvis	0.34	39.5	−19.5	32.7	32.6	32.8	0.1
Overall	0.21	43.8	−13.3				

L: left; LL: lower left; LR: lower right; R: right; UL: upper left; UR: upper right.
[a]Values are obtained from Nilsson[6]

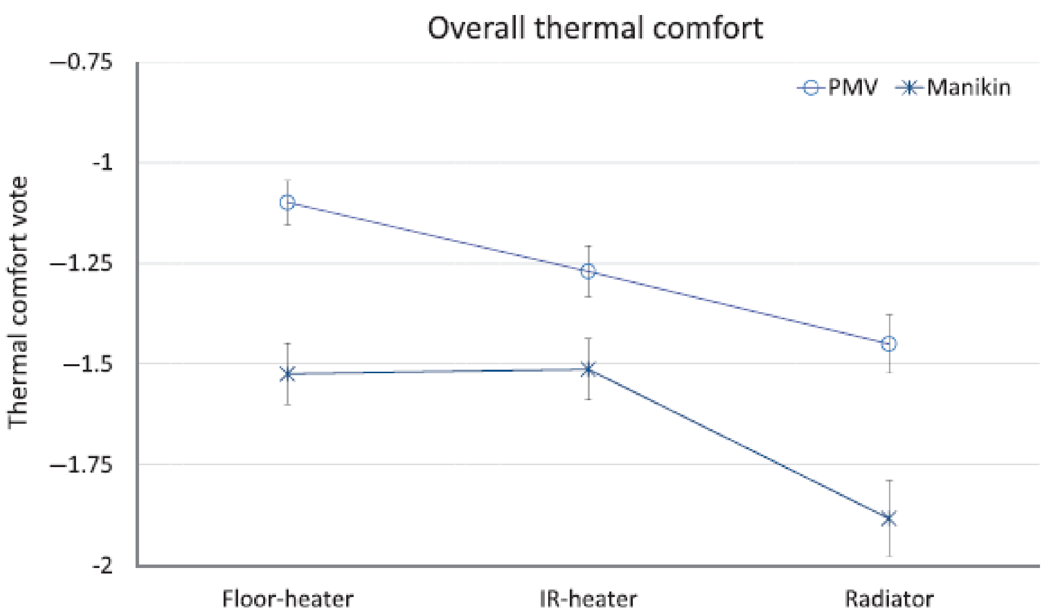

Figure 7 Overall thermal comfort measured by the manikin and calculated PMV values

Table 3 The measured Teq (°C) under the three different systems.

Segment	Floor heater	IR heater	Radiator
L. Foot	19.4	18.4	17.9
R. Foot	19.9	18.9	19.0
L. Leg	19.4	18.5	18.3
R. Leg	19.3	18.4	18.1
L. Thigh	22.9	22.3	22.0
R. Thigh	23.4	22.6	22.1
Pelvis	24.1	23.0	22.7
Head	20.1	21.1	19.5
L. Hand	18.8	19.0	18.4
R. Hand	19.1	19.3	18.4
LL Arm	19.9	20.3	19.1
LR Arm	20.7	21.1	19.9
UL Arm	19.7	20.5	19.1
UR Arm	21.6	22.5	20.4
Chest	17.9	20.0	16.6
Back	19.8	20.7	19.4
Overall	21.0	21.0	20.0

L: left; LL: lower left; LR: lower right; R: right; UL: upper left; UR: upper right.

3.3. Selection of a heating system

The selection of a heating system or method is mainly targeting: thermal comfort, energy and cost efficiencies plus the common engineering targets such as controllability, maintainability and reliability. This study investigated the thermal comfort performance at a fixed energy supply for three different systems that represented conventional or localized methodology. The newly developed manikin was successful in showing the characteristics of these systems. The difference between localized or conventional systems was shown from the results in favour of the localized systems. For both systems, that is with average ΔTeq of 0.3–1.2K at lower body limbs, 0.7–1.2K at upper limbs and 0.9–1.6K at torso and head. At the used energy supply rate, the localized floor heater was the closest to fulfil (Max deviation<0.5K at left foot) the comfort limits according to the comfort zones suggested by Nilsson[29]. That localized floor heater with workstations can be a good option towards energy efficiency and thermal comfort. The performance of the IR heater system, in general, was within the comfort limits except at the lower body limbs. The positioning of the IR heater needs to be carefully studied especially in interaction with office furniture. Furthermore, the safe use of electrical IR heater system with on-site renewable electricity production may represent a good possibility to consider in the selection process. The conventional under-window mounted radiator system is still a good option to reduce air drafts; however, in office buildings this should be thought differently when dealing with energy efficiency. Finally, it should be noted that the cost efficiency and the engineering targets (i.e. controllability, maintainability and reliability) were not in the scope of this work and may not be in agreement with this view.

Conclusions

In this study, the local and overall thermal comfort performance of three different heating systems were evaluated using a thermal manikin with a new thermoregulatory control. The heating systems (conventional radiator, localized heated floor, and IR heater) were supplied with the same constant power. At that constant power input, the localized systems (i.e. floor heater, IR heater) showed a better performance than the conventional radiator system mounted under the window. The difference in the segmental comfort levels, estimated using the equivalent temperature (Teq) approach, was in a range from 0.7 to 3.4K (i.e. up to 1 on comfort scale). The difference in the overall Teq was nearly 1K in favour of the localized systems. This evaluation using the manikin clarified the characteristics of the different systems and impact on different body segments. A comparison of the overall comfort results with predicted values by the PMV model showed variations <0.5 on the scale under the three systems. However, as the PMV model does not weigh segmental sensations or account for the thermal non-uniformity; therefore, it cannot be applied especially with localized or personalized systems. The localized floor heater system nearly fulfilled the comfort limits (±1.5 on the scale) for all body segments under the planned conditions. The IR heater showed a better performance at the upper body segments while it could not influence the lower limbs due to its positioning and interaction with the workstation furniture. The safe application of IR heater systems in buildings needs further investigations before it can be utilized, perhaps with on-site renewable electricity generation. Future work will include further development of a design strategy for maximizing the energy and cost efficiencies subject to general comfort criteria.

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