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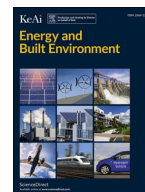
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Thermal comfort of Frail People under dynamic and non-uniform thermal environments using a thermal manikin with thermoregulatory control: An experimental study

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ABSTRACT

The thermal comfort of frail people has to be considered carefully, mainly because of the high thermal sensitivity of this population and the negative influences that unsatisfactory thermal conditions have on their health. Most existing thermal comfort works have been conducted under steady-state, uniform thermal environments, with far fewer being performed in dynamic and non-uniform thermal environments, and even less for frail people. This study aimed at assessing the thermal responses of frail people under transient and non-uniform thermal environments, using a thermal manikin and a climatic test cell. Thermal responses were investigated and discussed in both genders. The analysis of variance showed a significant difference in thermal comfort and thermal sensation between females and males over time, under hot exposure. Under cold exposure, results showed a significant difference in thermal sensation between females and males over time, but no significant difference was observed in term of thermal comfort. Analysis revealed also significant differences in the dynamic thermal sensation between the sexes under cold exposure, while results confirmed that there is no significant difference in the dynamic thermal sensation between sexes under hot exposure.

1. Introduction

Global climate changes do affect human indoor thermal comfort since people spend most of their time in a building. Therefore, an acceptable indoor thermal environment in buildings is an important criterion for the performance of a building, not only by making it comfortable to live in, but also by reducing its energy consumption through the optimization of HVAC control systems. Thermal comfort is defined as “that condition of mind which expresses satisfaction with the thermal environment” [1]. Generally, thermal perception researches are related to healthy groups of occupants, with few works exploring the thermal comfort of frail people (see for instance [2–4]) due to a lack of knowledge in this field [5]. It also seems that published standards on this issue are still missing the concept of thermal comfort for frail people under a non-uniform thermal environment, e.g. ASHRAE Standard 55–2020 [6], as well as ISO/TS 14,415 [7]. Therefore, studies that investigate the thermal responses of frail people for non-uniform environments are required.

Improving thermal perception, in non-uniform and dynamic thermal environments, attracts the attention of researchers. Current standards do consider non-uniformities such as radiant asymmetry and thermal stratification. With the need to reduce energy consumption, in recent years non-uniform thermal environments under different energetic systems have been developed. Therefore, to assess the performance of these systems, it is helpful to know the occupant’s thermal interactions with the non-uniform thermal conditions.

Although most studies have been interested in uniform conditions, a few works have examined non-uniform environments. Wang et al. [8] indicate that the non-uniformity of indoor thermal conditions, e.g. temperature distributions around human body, is a good indicator to understand the local interaction between the body and the environment. Yuemei et al. [9] experimentally investigated the thermal sensation and thermal comfort in the thermally non-uniform environments, results indicated that the thermal non-uniformity increased the percentage of dissatisfaction. Jin et al. [10] predicted overall thermal sensation via two levels, a local thermal sensation model based on skin temperature and an overall thermal sensation model using weighting factor method. Zhang et al. [11] proposed an overall thermal sensation model for sedentary

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activities, which combines the weighted local thermal sensations on the body segments for different environmental conditions. They also developed an overall thermal comfort model whether thermal conditions are dynamic or steady-state. Zhang et al. [12] studied the interaction between thermal sensation and thermal comfort experimentally under uniform and non-uniform, steady and dynamic environments. Results indicate that under dynamic conditions, thermal sensation changes with time significantly affect thermal comfort. In the same way, Zhang et al. [13] investigated the interaction between whole body thermal sensation, comfort and acceptability under uniform and non-uniform conditions and highlighted the fact that the non-uniformity of thermal sensation significantly influences thermal comfort in non-uniform environments. Song et al. [14] investigated the effects of air velocity on human thermal comfort under non-uniform thermal conditions and indicated that increasing air velocity can improve people's thermal performance and reduce thermal discomfort caused by the difference between radiant temperature and air temperature. Cao et al. [15] highlighted that the use of different airflow in operating rooms may contribute to ensure the required indoor air quality. Tadepalli et al. [16] studied the influence of ceiling fan induced non uniform conditions on thermal comfort. They found that higher airflow from ceiling fans could provide a good thermal sensation in summer. Wang et al. [17] experimentally studied the effect of air temperature and radiant temperature on human thermal comfort in a non-uniform thermal environment, and they proposed thermal dissatisfied percentage models for the different conditions. Fanger's model, is one of the best indices used worldwide to assess thermal comfort, but it is not applicable to non-uniform thermal environments [18]. Lai et al. [19] proposed a 12-segment model for dynamic and non-uniform environment on the basis of Fiala's work, by considering two-dimensional heat transfer in each part of a human body. Lai's model also takes into account the arterial blood temperature and the estimated clothing insulation at local segments. Nagano et al. [20] proposed a new thermal index for outdoor and non-uniform environments with heat conduction. The index allowed an understanding of the effect of environmental parameters on human thermal comfort in outdoor and non-uniform environmental conditions. Deng et al. [21] investigated thermal comfort

Nomenclature

T_{core}	Core temperature [°C]
T_{skin}	Zone average skin temperature [°C]
T_{hy}	Hypothalamus temperature [°C]
$T_{skin, local}$	Local skin temperature [°C]
$T_{skin, local, set}$	Local skin set point temperature [°C]
$\bar{T}_{skin, set}$	Mean whole-body skin set point temperature. [°C]
\bar{T}_{skin}	Mean whole-body skin temperature. [°C]
S_{local}	Local sensation [-]
$S_{overall}$	Overall sensation [-]
w_i	Weighting factor for segment i [-]
C_1	Body-part specific regression coefficients [-]
C_2	Body-part specific regression coefficients [-]
C_3	Body-part specific regression coefficients [-]
K_1	Body-part specific regression coefficients [-]
TS	Thermal sensation [-]
TC	Thermal comfort [-]
DTS	Dynamic thermal sensation [-]

and sensation in a non-uniform environment with personalized heating. Results showed that personalized heating improves thermal sensation and comfort, and provides warmer sensations and better comfort in cool environments. The results also confirmed that thermal comfort and sensation in whole body is affected by local effects. L. Schellen et al. [22] experimentally investigated the thermal comfort and productivity in response to thermal non-uniform environments. Results showed that the females are more uncomfortable compared to the males. They also indicated that the local sensations and skin temperatures of the extremities have a significant influence on overall thermal sensation. Sun et al. [23] investigated a temperature range for thermal comfort in non uniform conditions. They found that local ventilation could improve thermal comfort while reducing energy consumption.



Fig. 1. Thermal manikin: Newton®.

Thermal manikins are the most realistic devices suitable for the evaluation of thermal responses under dynamic and non-uniform conditions. Good assessment of thermal responses is only possible if local effects are considered. To achieve this aim, in this study, the local thermal responses were studied using a "Newton thermal manikin". These local responses were then transformed into overall thermal responses. The use of manikins began more than 70 years ago. The thermal manikin is usually employed in two research areas: the assessment of clothing's thermal properties, or the evaluation of the effects of the thermal environment on the thermal responses [24].

Despite the importance of these findings on thermal comfort and sensation in scientific works previously mentioned, the occupant's thermal responses in some specific conditions, such as frail people under dynamic and non-uniform environments, requires further study, and many unaddressed topics should be considered, such as: (i) the effect of sex on thermal comfort and sensation in frail people; (ii) the analysis of the thermal comfort of frail people under dynamic and non-uniform environments; (iii) the analysis of thermal sensation and dynamic thermal sensation of frail people under dynamic and non-uniform conditions.

The findings presented in this paper aim to provide some responses to these unaddressed topics. To achieve this goal, thermal comfort, thermal sensation and dynamic thermal sensation of frail people under dynamic and non-uniform thermal environments were investigated. Simulations using an adaptive thermal manikin in an experimental test cell were carried out and coupled with the ANOVA statistical model (the analysis of variance in combination with Fisher's statistical test ($p_{value} < 0.05$) were used to test the significance effect).

2. Research methods

2.1. Thermal manikin

The thermal manikin "34-zone Newton®" is a 50th percentile Western male (corresponding to the average North American male) that can sit, stand and move (see Fig. 1). It consists of 34 separate body parts designed to spread heat through the garments (see Fig. 2). The manikin contains modular heaters (each body part can be individually heated) and different sensors to simulate metabolic heat generation. The thermal manikin experiments are compliant to the ISO, EN and ASTM standards. The manikin thermoregulation system is based on the Fiala human body model [25,26].

2.2. Experimental facilities

This study was carried out using a thermal manikin in an experimental test cell as shown in Figs. 2a,2b and 3 at the EPF Graduate School of Engineering in the city of Troyes, France. The test cell comprises two climatic chambers, each having an area of 5.5 m², with an internal height of 2.1 m. These are known as inside and outside zones, in which we can create both indoor and outdoor thermal conditions, respectively. The main purpose of the inside zone is to ensure an indoor environment heated by means of several heating systems (in our experiments, we only used a radiant heated floor). Whereas the outside zone is considered as an outdoor cool environment with controlled temperature and was equipped with a cooling system.

The chamber's envelope is a wooden structure and insulation made from hemp wool and wood fibers. The selection of these insulation materials is based upon their very poor conduction of heat (good thermal insulation properties), and considers French construction standards. Physical parameters were measured at a low height (0.60 m) according to ISO 7726 for seated persons [27] (see Table 1).

2.3. Experimental procedure

To evaluate the occupant's thermal responses in indoor and outdoor environments, the manikin was placed in the climatic chambers. The

Table 1
Environmental parameters.

Parameter	Accuracy	Operational Range
Temperature	+/- 0.2 °C	-20 to 50 °C
Relative Humidity	+/- 1.1%	0 to 100%
Air velocity	+/- 3.0%	0 to 2.5 m/s

indoor temperature was increased from 18 °C to 30 °C within the inside zone (hot exposure), and it was progressively decreased from 15 °C to 5 °C within the outside zone (cold exposure) as shown in Fig. 3. For each experimental test, the thermal manikin was put in the test chamber for two hours, to adapt to the indoor conditions before operating the control system.

The data acquisition was set to 30 s, and each test lasted between twelve hours to seventeen hours during hot exposure, and between seven hours to ten hours during cold exposure, following a repeated test protocol as shown in Fig. 4. When start-up the system control, the model monitors all the segments on the thermal manikin via the heat flux. Then, the total thermal resistance was determined during dry tests by measuring the heat flux through the clothing once steady-state conditions are achieved.

2.4. Thermal comfort indices

The following three indicators were investigated in this study (see Table 2):

- Thermal comfort index: it based on the human thermal comfort model developed by Zhang [28]. Zhang's indices predict thermal sensations and thermal comfort in dynamic and non-uniform thermal conditions. Overall sensation and thermal comfort are determined by means of the skin temperature and core temperatures as well as their change over time. As stated by Zhang, Thermal comfort is based on a scale of -4 to 4, to indicate whether a sensation makes the manikin feel "very uncomfortable" or "very comfortable" respectively. A value just above zero (+ 0) is "just comfortable", value just below zero (- 0) is "just uncomfortable". Thermal sensation: Sensation is independent of comfort, is based on a scale of -4 (very cold) to +4 (very hot). Positive values are warmer sensations, negative values are cooler sensations, where a value of zero means neutral sensation as indicated in Table 4. local thermal sensation is defined as a function of local skin temperature, while overall thermal sensation is represented as the weighted average of local sensations (refer to Eq. (1) and 2).

$$S_{local} = 4 \left(\frac{2}{1 + e^{-C_1(\bar{T}_{skin, local} - \bar{T}_{skin, local, set}) - K_1[(\bar{T}_{skin, local} - \bar{T}_{skin, local, set}) - (\bar{T}_{skin, local} - \bar{T}_{skin, local, set})]} - 1} \right) + C_{2i} \frac{dT_{skin, local}}{dt} + C_{3i} \frac{dT_{core}}{dt} \tag{1}$$

$$S_{overall} = \frac{\sum_i (w_i S_{local, i})}{\sum_i w_i} \tag{2}$$

Dynamic Thermal Sensation: The Dynamic Thermal Simulation is based on the FPC Fiala model. In the FPC model an equation is included to predict the thermal sensation under dynamic conditions, it's called Dynamic Thermal Sensation (DTS), based on the mean skin temperature and the simulated core temperature with the dynamic variable dT_{skin}/dt (refer to Eq. (3)). This index runs from -3 (cold) to +3 (hot) and is for many cases comparable with the ASHRAE seven-point scale [29].

$$DTS = 3 \tanh \left[a (\bar{T}_{skin} - \bar{T}_{skin, set}) + g + (0.11 \frac{dT_{skin}^{(-)}}{dt} + 1.91 \left(\frac{dT_{skin}^{(+)}}{dt} \right)_{max} \right] e^{-0.681 \Delta t} \tag{3}$$

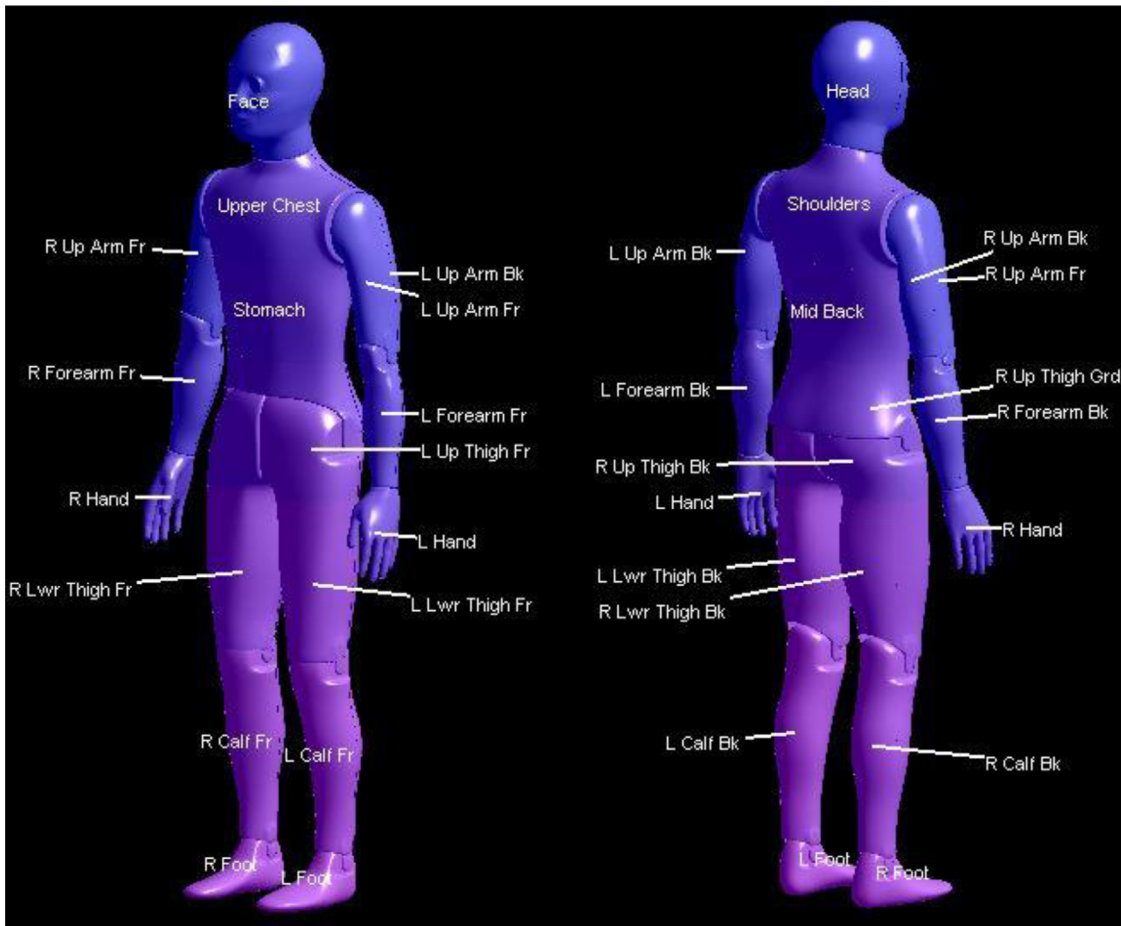


Fig. 2. a.Segments of the manikin
b.Layout of the test cell.

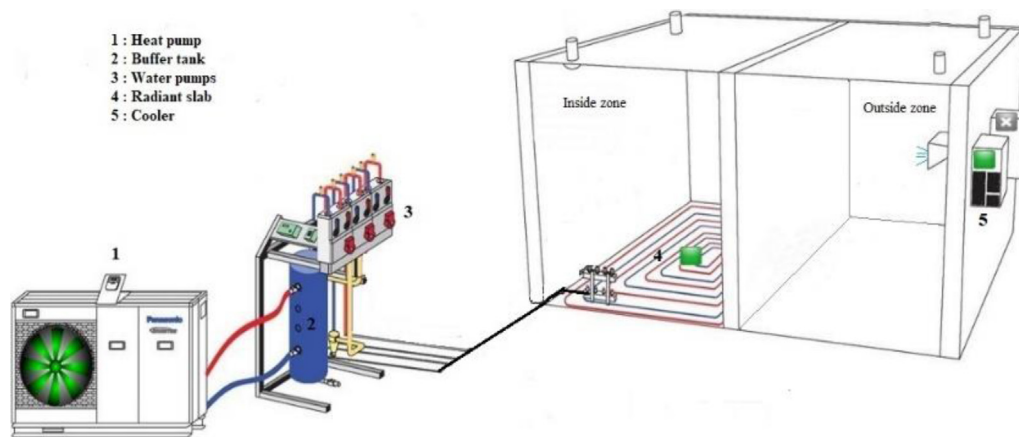


Fig. 2. Continued

Where:

$$g = 7.94 e^{\left(\frac{-0.902}{(T_{hy} - T_{hy,set})^{+0.4}} - \frac{7.612}{(T_{skin} - T_{skin,set})^{-4}} \right)} \quad (4)$$

where a is 0 and 1.08 for mean skin temperature above and below its set point respectively, and:

$$\begin{cases} \frac{dT_{skin}^{(-)}}{dt} = 0 \text{ for } \frac{dT_{skin}}{dt} < 0 \\ \frac{dT_{skin}^{(+)}}{dt} = 0 \text{ for } \frac{dT_{skin}}{dt} > 0 \end{cases} \quad (5)$$

3. Results and discussion

3.1. Indoor environment: skin and body core temperatures

Changes in average skin temperatures, rectal temperatures, and average body core temperatures are illustrated in Figs. 5 and 6, for both males and females. During the first minutes of exposure (72 min and 57 min for males and females, respectively), the average skin temperature decreased significantly for both genders,



Fig. 3. Experimental facilities.

Table 2
Thermal model scales.

Scale	Thermal Sensation	Dynamic Thermal Sensation	Scale	Thermal comfort
-4	Very Cold	-	-4	Very uncomfortable
-3	Cold	Cold	-2	Uncomfortable
-2	Cool	Cool	-0	Just uncomfortable
-1	Slightly Cool	Slightly Cool	+0	Just comfortable
0	Neutral	Neutral	+2	Comfortable
+1	Slightly Warm	Slightly Warm	+4	Very comfortable
+2	Warm	Warm	-	-
+3	Hot	Hot	-	-
+4	Very hot	-	-	-

and at the end of first minutes of exposure, it was 3.04 °C and 3.29 °C less than the initial temperature for males and females, respectively.

For the remaining thermal exposure time, the difference between air temperatures and the mean skin temperature decrease as the air temperature increased, while it generally remained the same for both sexes ($p_{value} = 0.58$). However, this comparison is limited to frail people under sedentary activities.

Concerning the mean body core temperature, over the first 164 min of the thermal exposure, it decreased (0.37 °C lower than the initial temperature) for both genders. It then increased and showed small changes throughout the duration of the test, which indicating good body heat storage.

These decreases in skin temperature and core temperature, during the first period are explained by the fact that these experiments were done directly after thermo-neutral test (this will import skin temperatures that were previously recorded by the manufacturer. These skin temperatures are typical of a human in a thermos-neutral state).

3.2. Indoor environment: thermal sensation (TS)

The transient air temperature in both sexes influences thermal sensation. In Fig. 7, the average body sensation increased from -1.2 (slightly

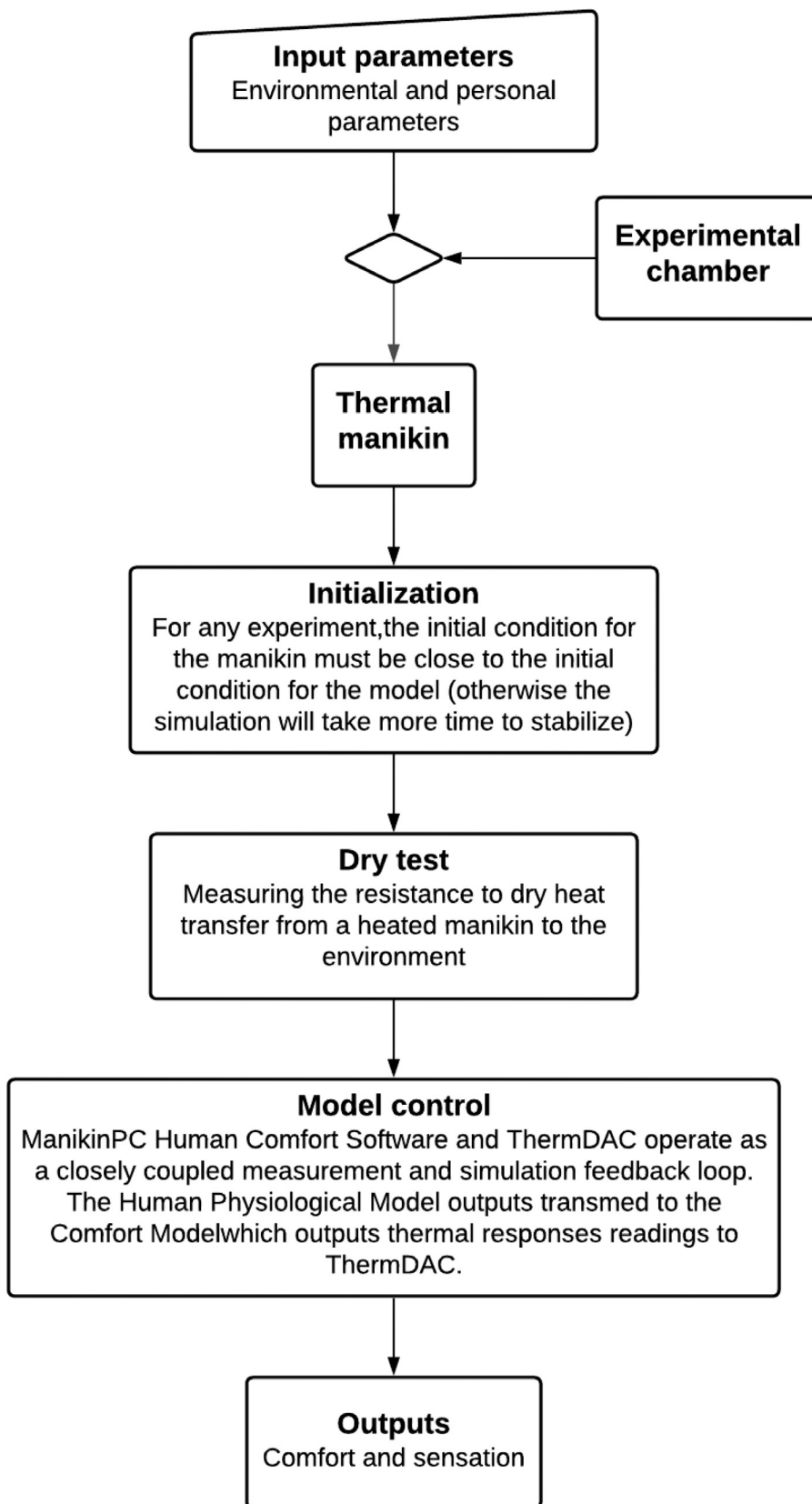
cool) to 0.3, with the temperature raised from 18 °C to 30 °C. For the assessment of TS, there was a significant difference ($p_{value} = 0.0054$) between genders over time, and under the same conditions. This means that the change of thermal sensation under dynamic conditions is a decisive parameter to evaluate appropriately the thermal responses of each gender.

The TS changed gradually from -1.2 to 0 for the first period (315 min). During the last 385 min of the exposure, the TS change from 0 “neutral sensation” to 0.3, the air temperature change from 26.9 °C to 30 °C, and the maximum variation in skin temperature was around 0.6 °C. This can be explained by the fact that investigated temperatures are inside the neutral temperature range of the thermoregulatory mechanism of the manikin, which occurs only minimal thermoregulatory reaction from the active system. The neutral TS temperature occurs at 26.9 °C for males and at 27.0 °C for females.

3.3. Indoor environment: thermal comfort (TC)

A significant difference in TC ($p_{value} = 0.01$) was found between the females and males in the temperature range from 18 °C to 30 °C. Fig. 8 shows the TC time-evolution for each gender. TC was less than 0 (uncomfortable side of the scale) immediately after the start of the experiment. Increases in the air temperature from 18 °C to 24.72 °C and from

Fig. 4. Experimental protocol.



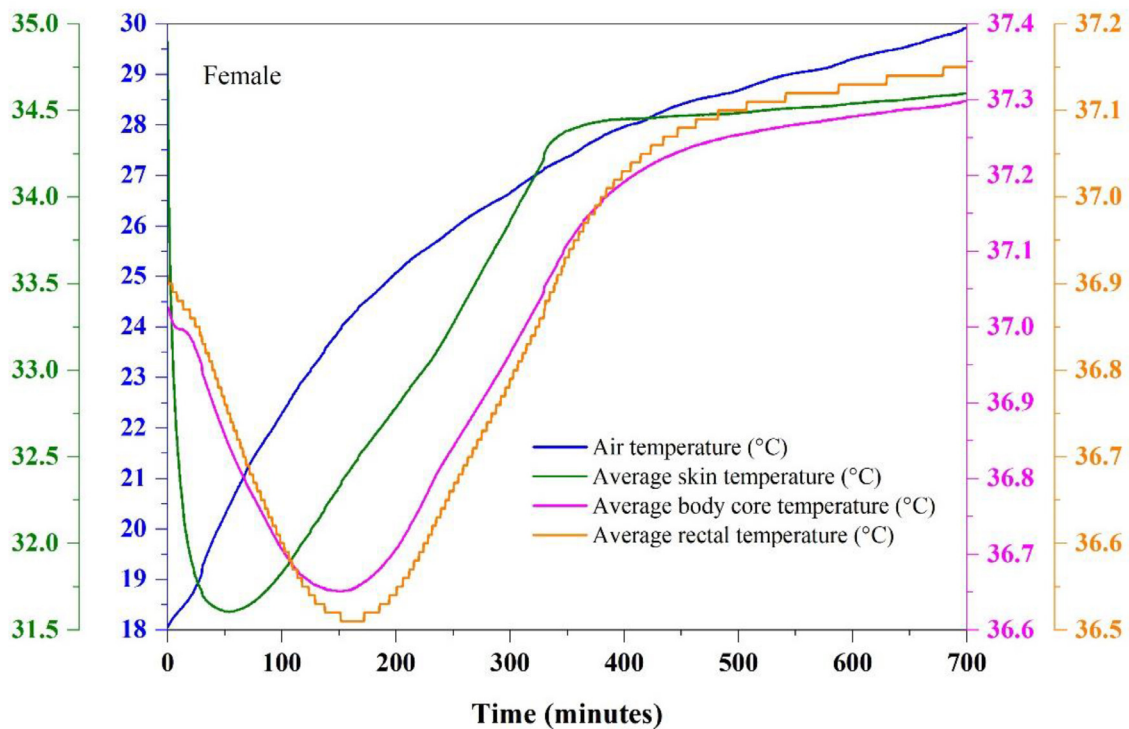


Fig. 5. Evolution of the average skin and average body core temperatures in females (hot exposure).

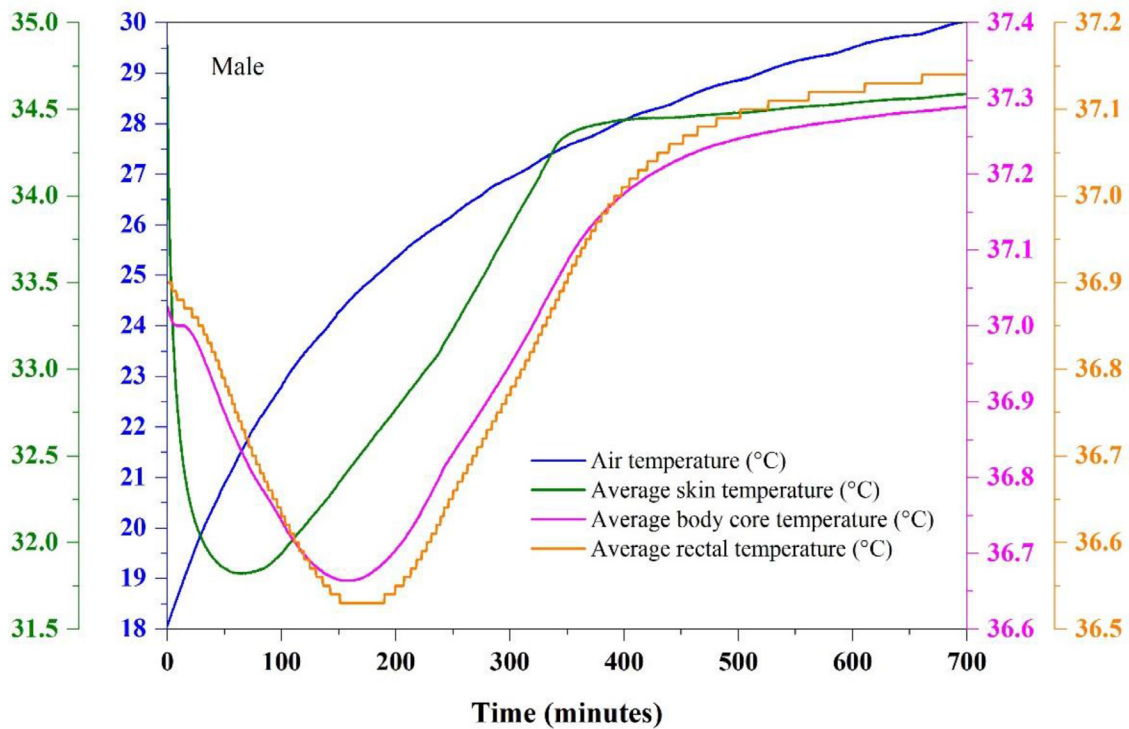


Fig. 6. Evolution of the average skin and average body core temperatures in males (hot exposure).

18 °C to 25.02 °C for males and females respectively, caused the TC to increase by about 1.2 scale units, from -0 (just uncomfortable) to 0. TC then increased significantly and was on the “just comfortable” side of the scale (+0) after 176 min for males (at 24.72 °C), and after 197 min for females (at 25.02 °C) .

In comparison to neutral TS, frail people in seated position were able to achieve partial TC more rapidly in non-uniform and dynamic environments. The range of temperatures within frail people feel "partially comfortable" is between 24.72 °C - 28.2 °C and between 25.02 °C - 28.03 °C for males and females respectively.

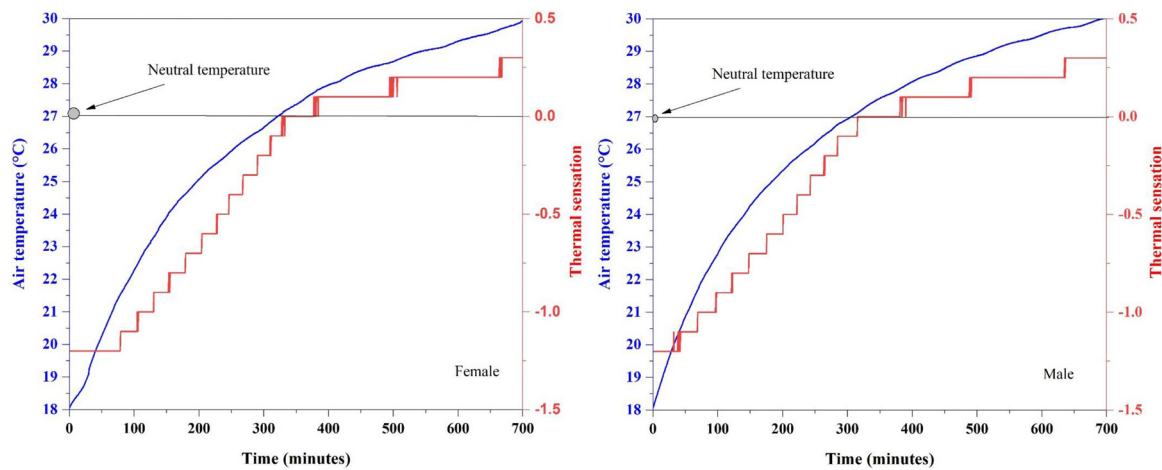


Fig. 7. Time-evolution of thermal sensation in males and females (hot exposure).

3.4. Indoor environment: dynamic thermal sensation (DTS)

Fig. 9 shows the DTS time-evolution for males and females. Analysis of variance showed no significant difference in DTS between genders over time ($p_{\text{value}} = 0.40$). DTS increases well over time with the air temperature. In comparison with neutral TS, frail people were able to achieve the neutral DTS in the same time phase in non-uniform and dynamic conditions.

DTS increases from a scale-value between cool and cold to a scale-value between slightly warm and warm when the air temperature change from 18 °C to 30 °C. The neutral DTS temperature occurs at 26.83 °C for males and 26.67 °C for females under sedentary activities in the seated position.

3.5. Outdoor environment: skin and body core temperatures

Changes in average skin, average body core and rectal temperatures are shown in Figs. 10 and 11 for both genders. During the exposure time (300 min, from 15 °C to 5 °C), the average skin temperature decreased significantly for both genders, and at the end of this cold/cool exposure, it was 5.53 °C for males and 5.80 °C for females less than the initial temperature. The peripheral parts of the body (extremities) are particularly vulnerable to cold temperatures. The exposure to cold causes a peripheral vasoconstriction. This mechanism results in a significant decrease in surface temperature and skin blood circulation.

During the cool/cold exposure, the mean body core temperature decreased by 0.61 °C and 0.62 °C than the initial value, for both males and females respectively, which means that the thermoregulatory mechanisms respond well and maintain the core temperature as stable as possible.

When the air temperature decreases, the temperature differences between the skin and both the core, and the rectal temperatures increases. The skin temperature variations were more important in cold/cool conditions than the core temperature, which was due to several factors, such as body segment differences in metabolic heat production and heat dissipation, which means that skin temperature responses are more variable than those of core temperature.

3.6. Outdoor environment: thermal sensation (TS)

Fig. 12 shows the averaged whole-body thermal sensation for cool/cold conditions. TS is influenced by the air temperature variation in both genders. The change from 15 °C to 5 °C caused TS to decrease about 1.1 and 0.9 scale unit, for males and females respectively. Analysis of variance revealed a significant difference ($p_{\text{value}} = 0.0053$) between males and females over time and under the same temperature conditions

(from 15 °C to 5 °C), therefore, thermal sensation under dynamic conditions is a critical factor to evaluate the thermal perception appropriately for each gender.

TS variations with time in the present conditions were all below zero (below neutral sensation), when whole body is cool, TS change with time is negative, which means the change of thermal sensation with time makes the occupants more uncomfortable. The more the temperature decreases with time, the more discomfort the occupants perceive. When the air temperature ranged around 5 °C, the maximum TS was around -1.7 scale unit. A possible explanation for this might be that the shivering mechanism occurred, which means a reasonable body temperature and not very cold thermal sensation.

3.7. Outdoor environment: thermal comfort (TC)

Fig. 13 shows the averaged whole-body thermal comfort for cool/cold conditions. Analysis of variance revealed no significant differences in the thermal comfort ($p_{\text{value}} = 0.60$) between the sexes in the air temperature range from 15 °C to 5 °C. Thermal comfort was on the uncomfortable side of the scale (less than 0) under these conditions. The changes from 15 °C to 5 °C caused the thermal comfort to decrease by about 3.2 scale units for males and 3.1 scale units for females.

Compared to the TC under warmer conditions, TC variations with time in the present conditions (from 15 °C to 5 °C) were important. TC changes with time and space, however, TC is a good indicator of well-designed dynamic and non-uniform thermal environments for both comfort and energy conservation.

3.8. Outdoor environment: dynamic thermal sensation (DTS)

Fig. 14 shows the DTS evolution for males and females under cool and cold conditions. Unlike warm conditions, a significant difference in terms of DTS between males and females over time ($p_{\text{value}} = 0.002$) was found. The variation from 15 °C to 5 °C caused DTS to decrease about 0.58 and 1.21 scale unit, from a scale-value between slightly cool and cool to a value close to cold, and from a value between cool and cold to a value close to cold for females and males, respectively. Compared with the TS and TC, it implied that DTS decreased when the TS and TC levels decrease, and remains nearly stable, when TS and TC are stable.

4. Conclusion and work limitations

Thermal comfort and thermal sensation for frail people in dynamic and thermally non uniform environments were experimentally investigated. The significant findings of the current study are:

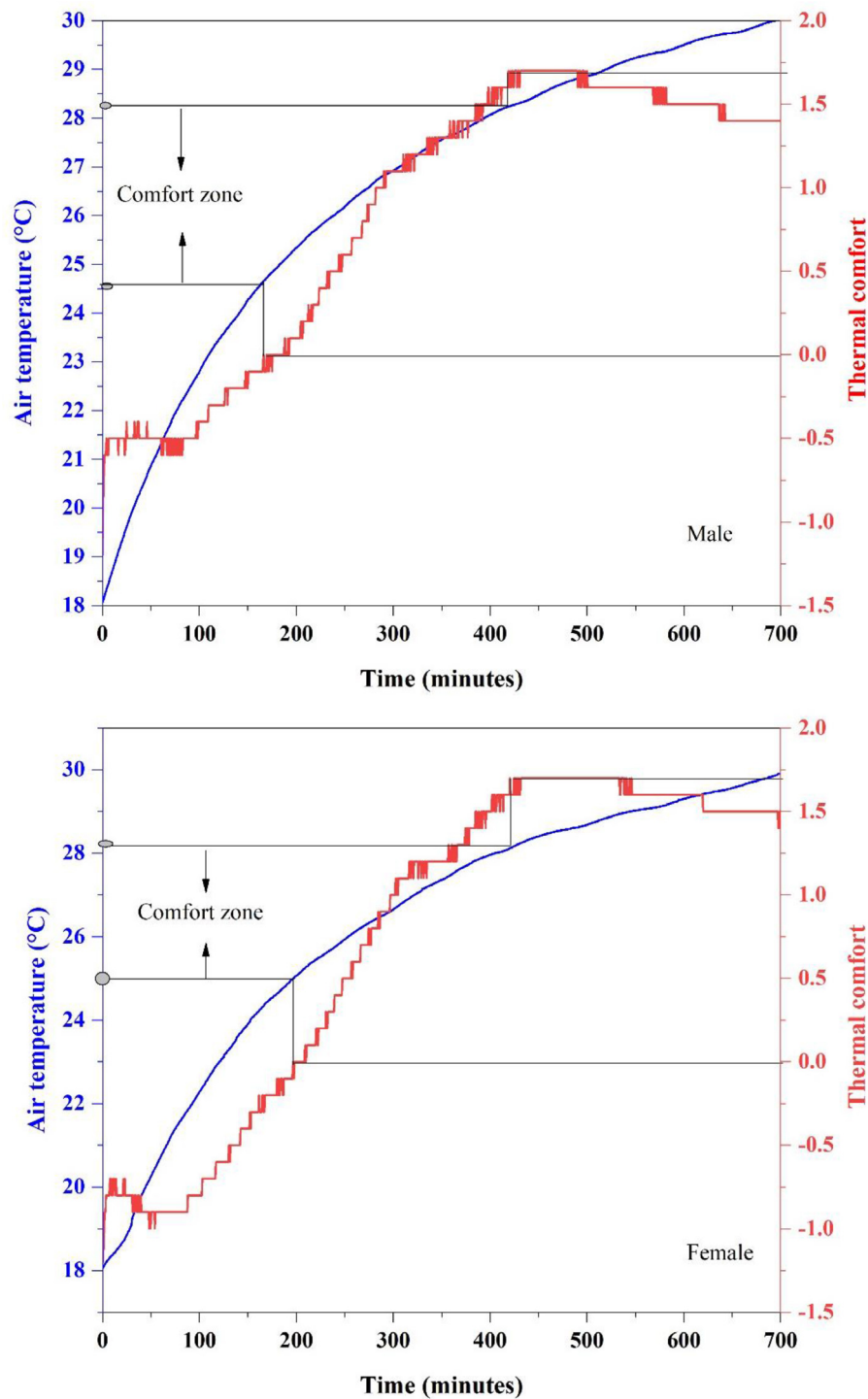
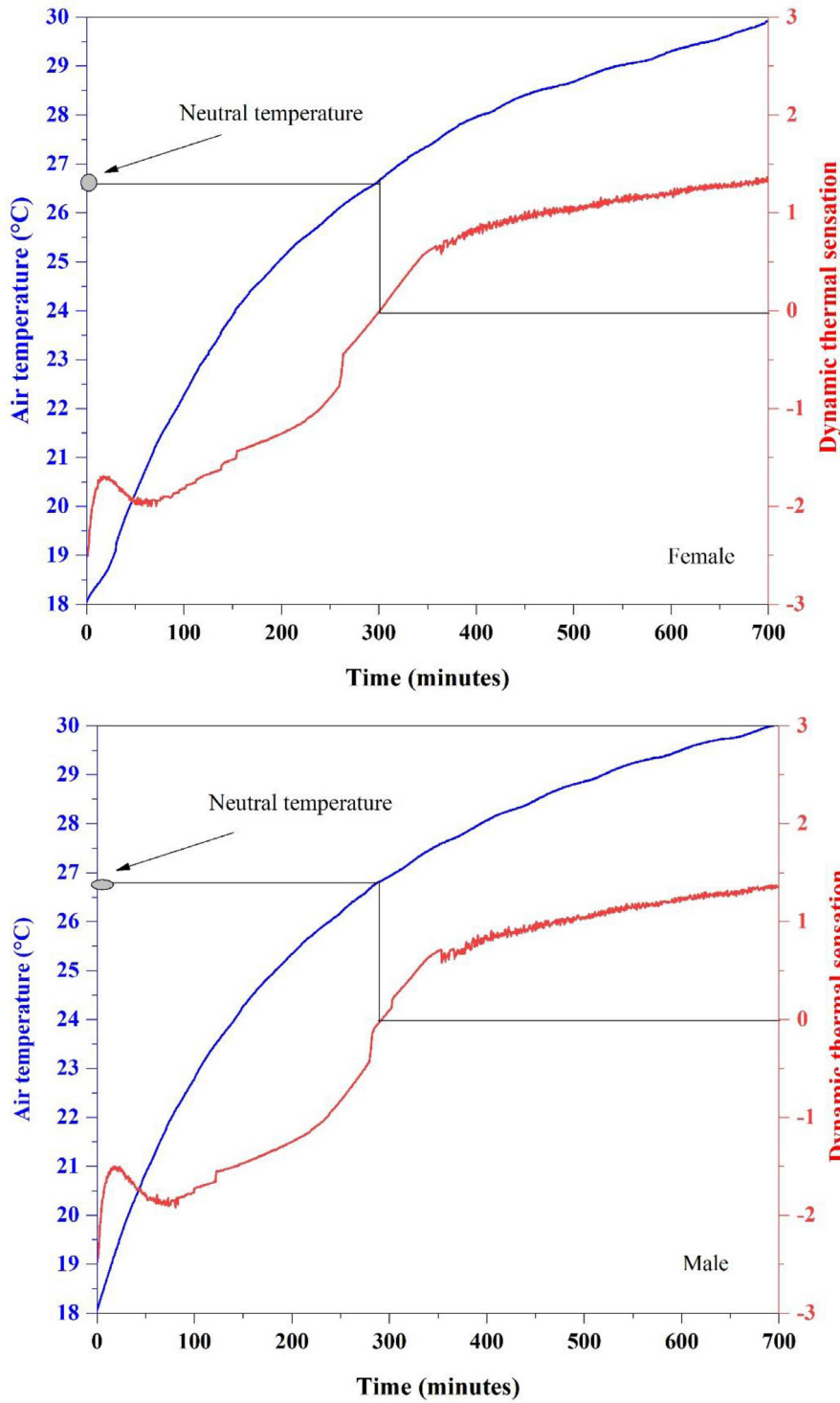


Fig. 8. Time-evolution of thermal comfort in males and females (hot exposure).

- i A significant difference in the TS and TC between the genders over time was found in the air temperature range from 18 °C to 30 °C.
- ii A significant difference in the TS between the genders was found in the air temperature range from 15 °C to 5 °C, over time. but the analyze of variance shows no significant in TC, under the same experimental conditions.
- iii A significant difference in the DTS between the genders was found in the air temperature range from 15 °C to 5 °C. However, the results confirmed that there is no significant difference in the DTS between sexes in the air temperature range from 18 °C to 30 °C, which means that the DTS is more sensitive to cooling exposure events than to heat exposure. Further studies are needed to understand to which input parameters the DTS is more sensitive.
- iv The neutral TS temperature occurs at 26.9 °C and 27.06 °C for males and females, respectively.
- v The range of temperatures in the environment within which frail people are partially comfortable is [24.72 °C; 28.2 °C] and [25.02 °C; 28.03 °C] for males and females, respectively.
- vi The neutral DTS temperature occurs at 26.83 °C and 26.67 °C respectively for males and females under sedentary activities and seated position.

Fig. 9. Time-evolution of dynamic thermal sensation in males and females (hot exposure).



vii TC, TS and DTS change with time, and space, and sex, therefore, these parameters are most suitable for good design of dynamic and non-uniform thermal environments, both for comfort and energy conservation.

Concerning work limitations, the present study is limited to frail persons carrying out sedentary activities, under dynamic and non-uniform thermal environments.

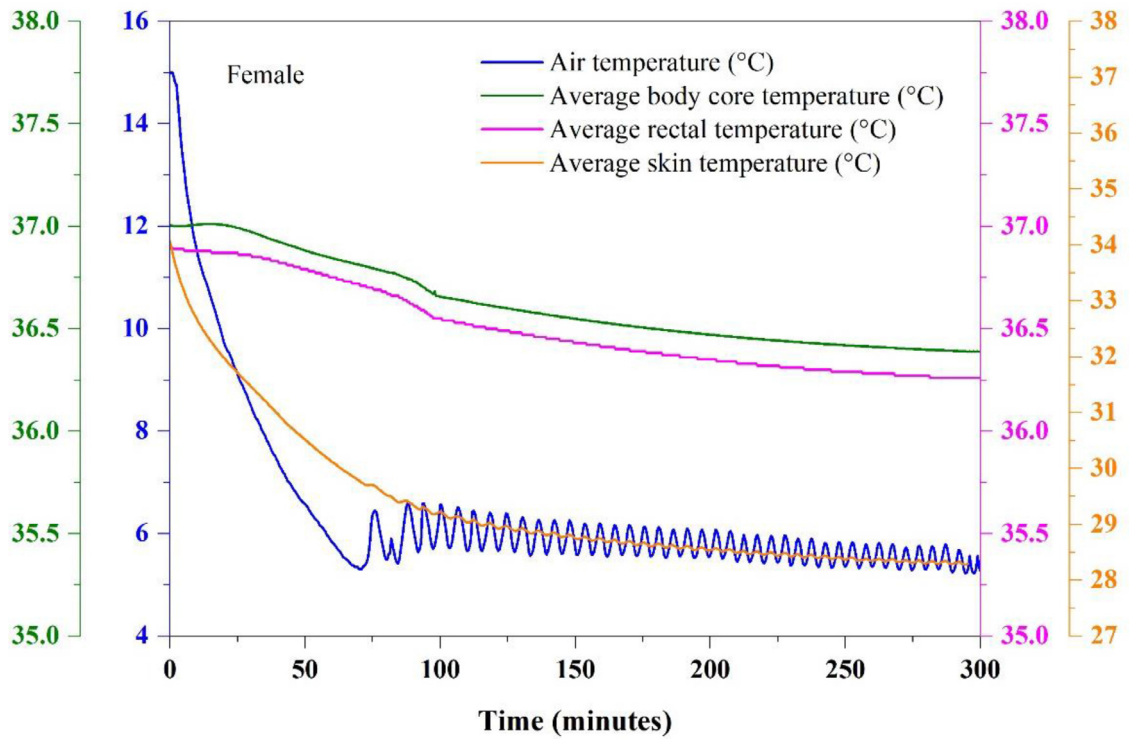


Fig. 10. Evolution of the average skin and average core temperatures in females (cold exposure).

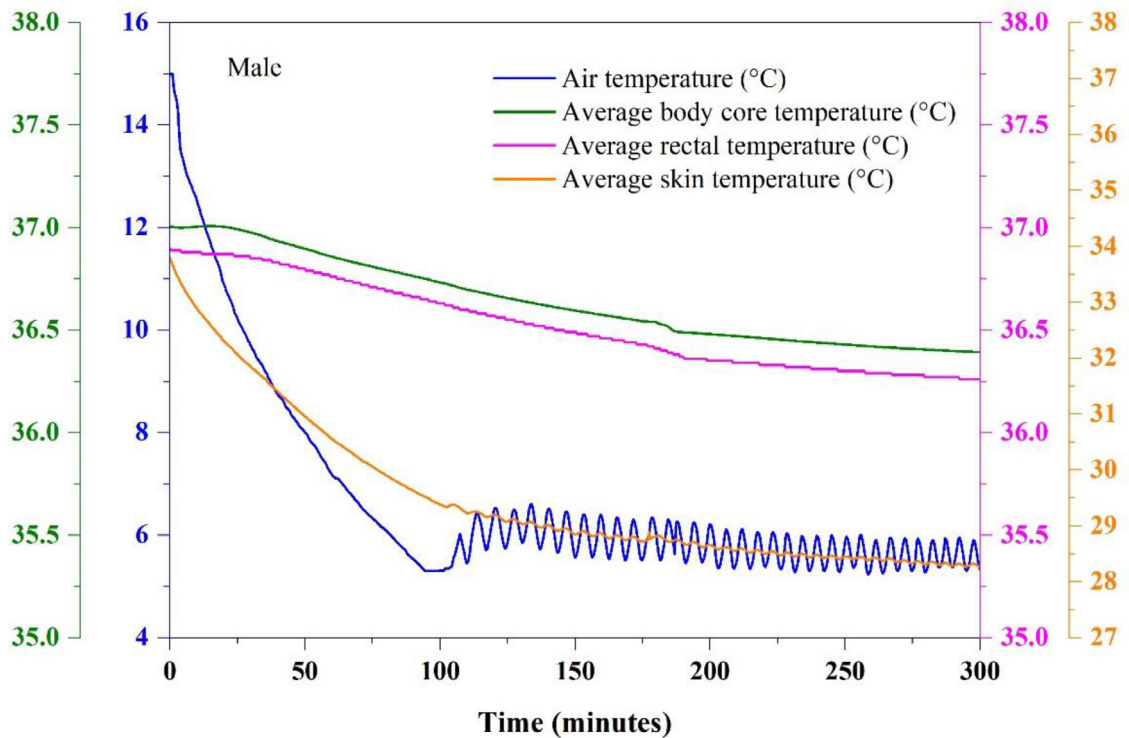


Fig. 11. Evolution of the average skin and average core temperatures in Males (cold exposure).

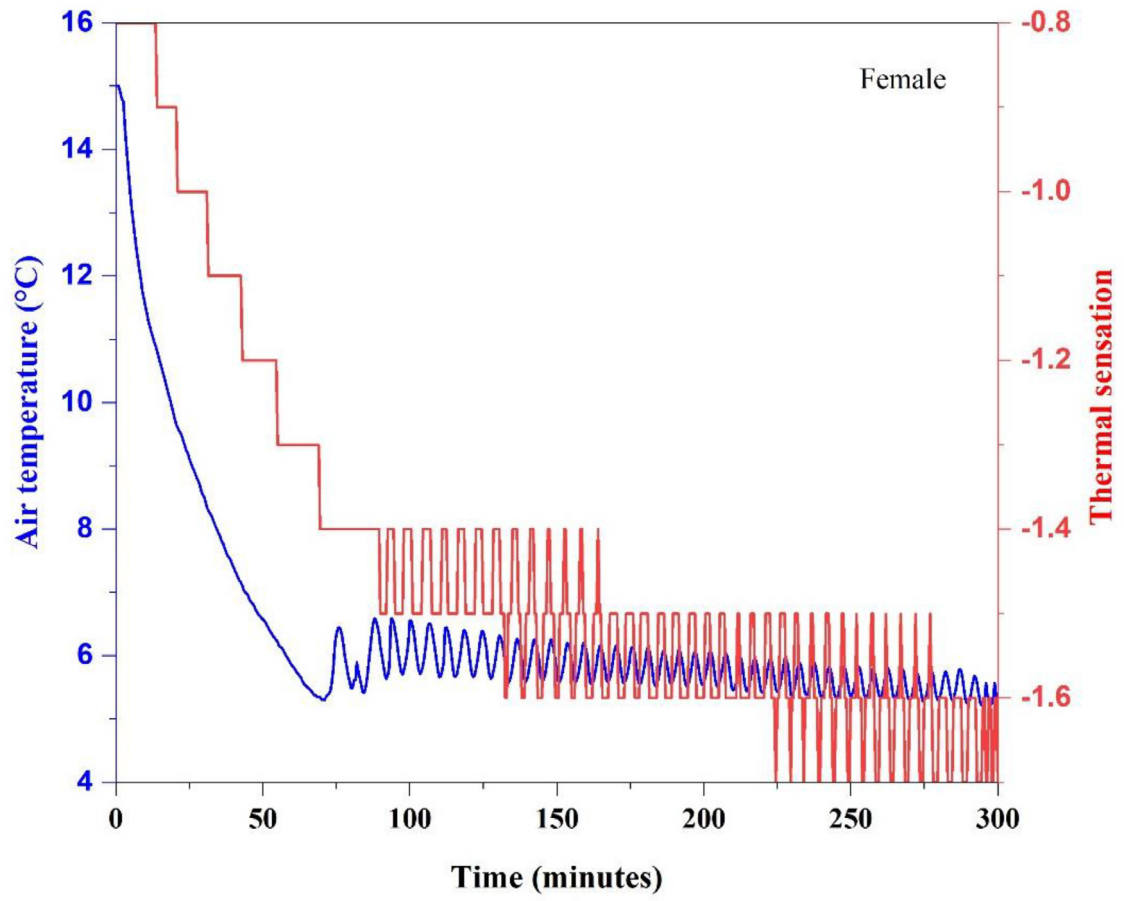


Fig. 12. Time evolution of thermal sensation in males and females (cold exposure).

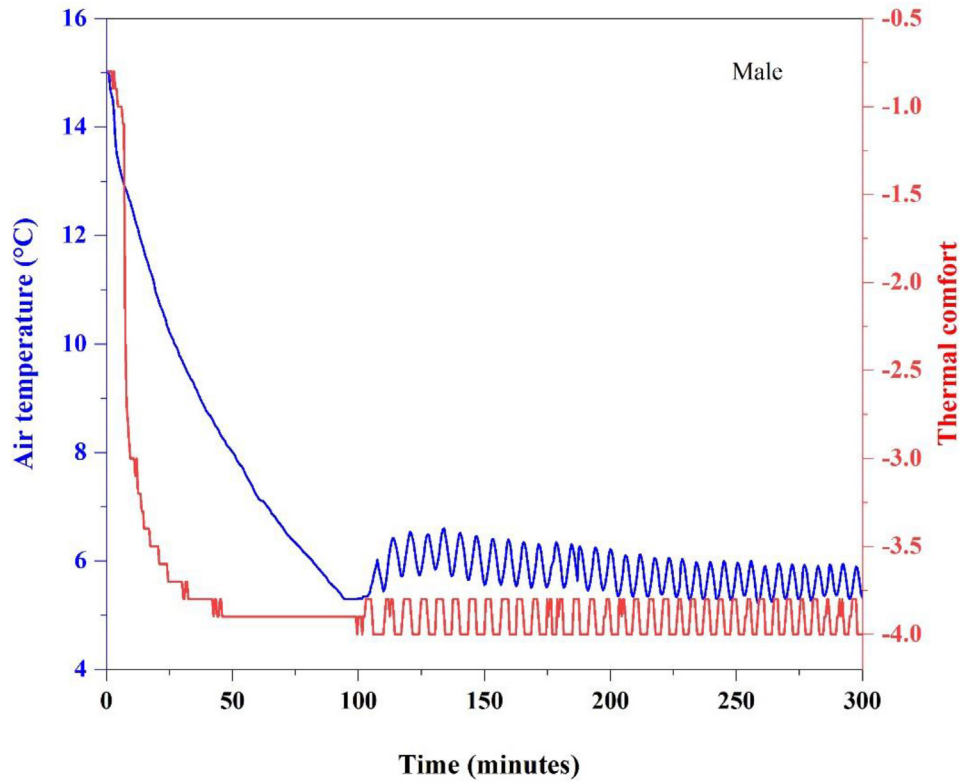
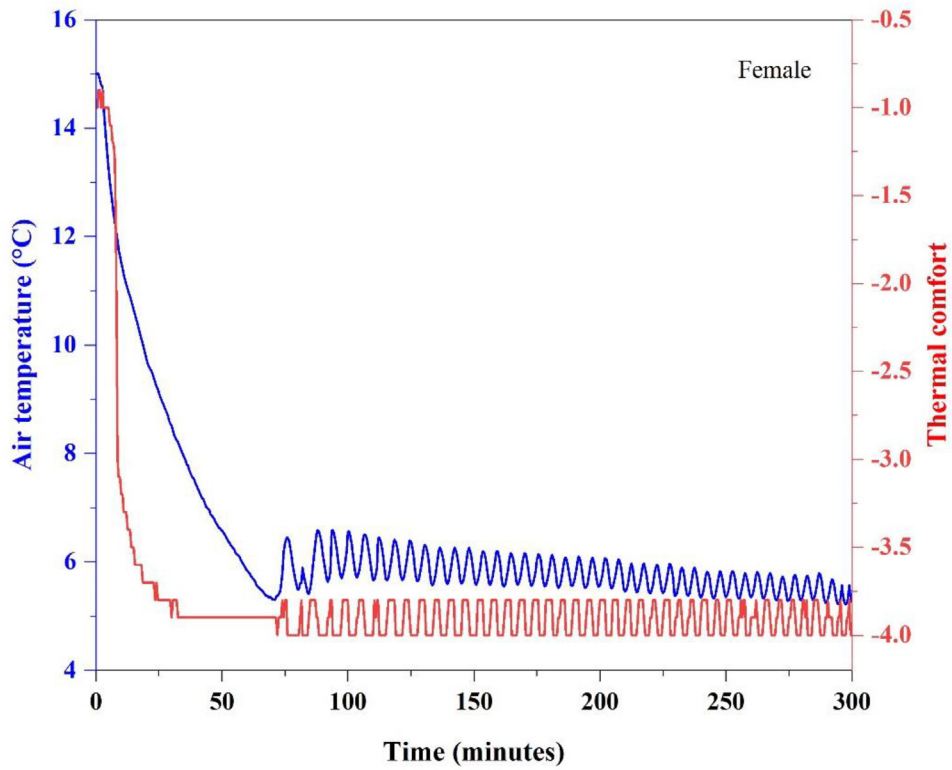


Fig. 13. Time evolution of thermal comfort in males and females (cold exposure).



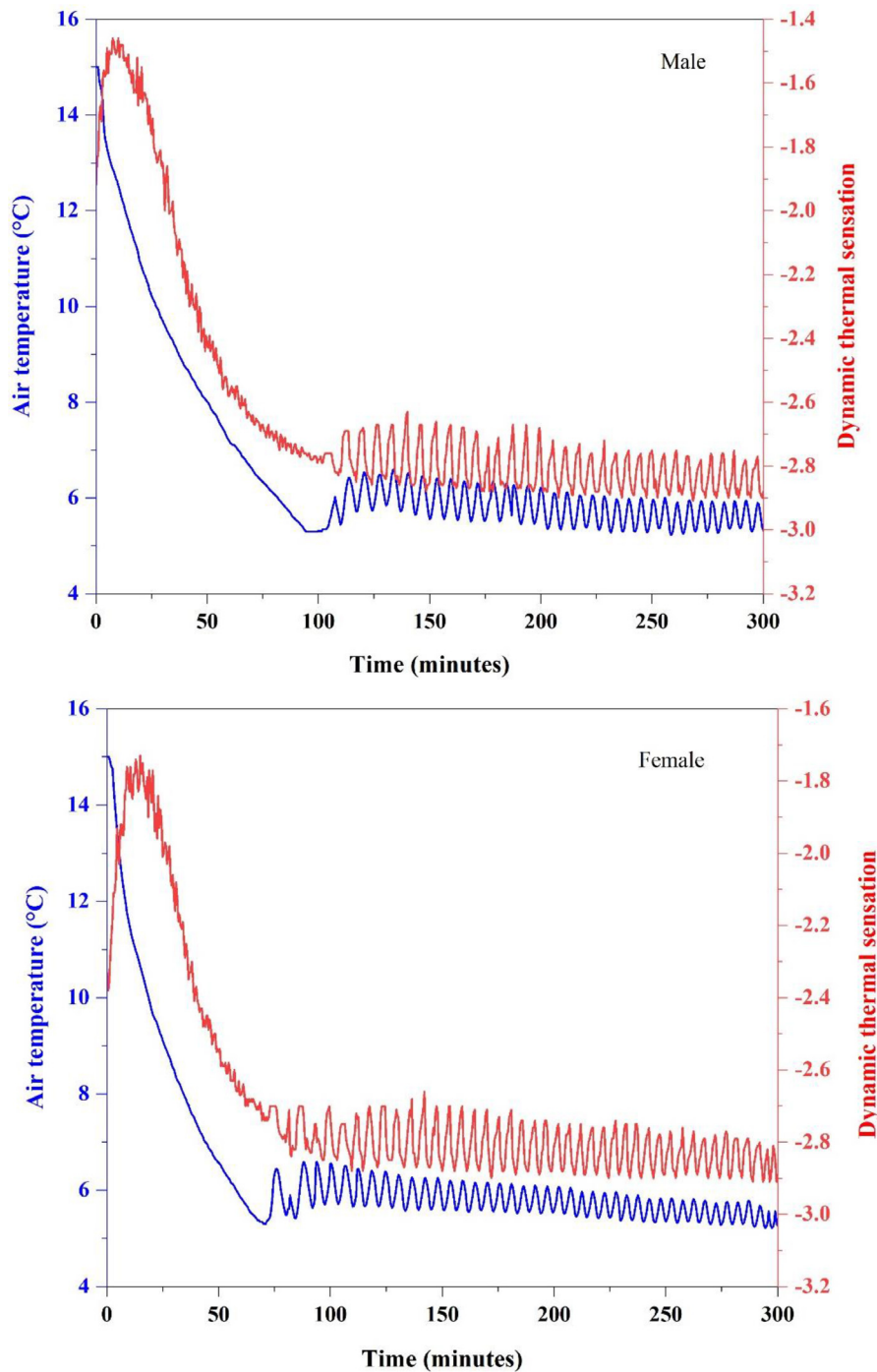


Fig. 14. Time evolution of dynamic thermal sensation in males and females (cold exposure).

Credit author statement

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.enbenv.2022.03.005.

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