Local heating and cooling effectiveness - an evaluation method based on calculated local and overall thermal state

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Abstract. The application of Personal Comfort Systems (PCS) in the buildings demonstrated their potential to improve thermal comfort and reduce energy use by the HVAC systems. With its personal controllability PCS is a practical solution to tackle the diversity in perceiving thermal comfort between occupants. The differences in thermal perception can be due to physiological and psychological factors, such as metabolic rate, acclimatization, body composition, gender, and age. In addition to the primary purpose of improving individual thermal comfort, it allows for a wider set point temperature of the HVAC system conditioning the space, which may lead to an extensive reduction in energy use.

Several PCS device options have already evolved, but incorporating these devices into building conditioning faces lots of restrictions. The PCSs are categorized between movable, portable, and fixed devices, and PCS devices can function with different means of heat exchange.

In this study, the capability of local heating and cooling to correct the individual's thermal state toward thermal neutrality when the rest of the body is exposed to cold or heat was evaluated. A detailed physiology model was applied to evaluate the impact of the nonuniform environment from PCS on local skin, heat flux, and thermal comfort. Different locations of the human body (head, hands, feet, legs, thighs, back, and pelvis) have been tested since the heat exchanged at local body parts differs in its effectiveness in improving the overall thermal state. Different operative temperature relaxations have been tested with a base cooling setpoint of 25°C and heating of 24°C. Multiple simulations have been conducted to account for multiple local environmental settings. We have evaluated the influence of local heating and cooling of different body parts on correcting the whole-body thermal state toward thermal neutrality. Results showed that the thigh could be a promising prominent body part for both cooling and heating, followed by the hands and feet, which are good responders to local heating. The percentage of correction toward thermal neutrality varies with background temperature and local heating or cooling power, and can range from 50–80% for hands and feet to 60–100% for the thigh.

Keywords. Personal comfort system, Local heating and cooling, Energy efficient system, Human thermo-physiology.
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1. Introduction

It is a fact that people spend the majority of their time indoors in urbanized areas, which makes indoor environmental quality (IEQ) accountable in new and existing buildings for assuring the well-being of the occupants [1]. IEQ is characterized by environmental categories such as thermal comfort, air quality, lighting, and acoustics. While each category is equally important for the comfort and well-being of occupants, thermal comfort has repeatedly been determined to be the primary factor in people's overall satisfaction with indoor environmental quality [2]. Studies have shown that good indoor thermal comfort plays an important role in determining people's well-being, health and productivity. Therefore, indoor temperatures are typically set in buildings with the aim of providing thermal comfort to occupants by keeping their thermal sensation around thermal neutrality (the state when a human body primarily maintains its core body temperature with minimal metabolic regulation) [3]. However, the practice of setting the indoor temperature at a narrow range is achieved by the use of heating, ventilation, and air conditioning systems. HVAC, on the other hand, has repeatedly been criticized for its excessive energy use that reaches almost 40% of operational energy use in buildings [4]. Furthermore, it has been found to be difficult to satisfy individual thermal comfort due to individual differences such as gender, age, body composition, and personal preference [5,6]. As a result, it is difficult to thermally satisfy all building occupants using the common practice of uniform indoor temperature created by an HVAC system [7]. Therefore, in the quest to improve the well-being of occupants and limit energy use in buildings, indoor energy-efficient personal comfort systems (PCSs) have been widely employed to increase occupant thermal comfort and acceptance under a variety of thermal circumstances.

A PCS delivers heating and cooling to local body parts rather than whole surroundings, allowing for specific heating and cooling to suit the real occupant's need [8,9]. As a result, the ambient temperature range can be broader beyond the temperature range specified by regulations, which potentially saves energy. When using the appropriate PCSs, a reduction of 4% to 60% of the energy used is expected [10,11,12]. Different PCS devices have already been presented and tested individually in the literature; each device can target one or more body areas. When it comes to PCS that directly target a body part, it's important to distinguish between a covered and uncovered body part with cloth. Furthermore, the format of heat transmission between the body surface and the heating/cooling device/surface varies.

Based on the literature, PCSs can be categorized as fixed and attached to the workplace (furniture) such as radiant heating and cooling desks, personal ventilation systems, movable such as heating and cooling chairs, portable heaters, and foot mattresses, and wearable such as wristbands, active clothes, shoe insoles, and gloves. In most of the studies reported in the literature, the effectiveness of the PCS is evaluated based on the subjective tests by evaluating the occupants' votes on thermal sensation, thermal comfort, and thermal acceptance. These methods require a large number of subjects to derive a statistically valid answer [13].

Different characteristics that influence the heat transfer from the skin of a body part to local heating or cooling devices. Starting from the skin surface area, to the body part (mass) or layer composition, to the different heat generation distribution. The skin blood flow plays the main role in transferring heat between the different layers and different body parts. For example, hands/ limbs skin temperature has always a bigger range of temperature fluctuation compared to the head and torso skin temperature. Therefore, the comparison of local thermal sensitivity becomes more challenging.

According to the literature review conducted by [14], in terms of local thermal perception, the head shows the largest heating-induced local thermal sensation response to a warm stimulus in a neutral environment, whereas the extremities appear to have the least. On the other hand, the local perception of a cold stimulus differs between research studies. Face cooling resulted in the greatest increase in whole-body comfort in a hot climate [15]. Abdomen cooling is the least recommended [15]. In a cold climate, face warming is regarded as less comfortable than heating on the chest, abdomen, and thighs, with abdominal warming providing the most comfort [15]. [16] In an experiment involving 24 subjects, they found that the legs, thighs, and back were the key body segments for local cooling in summer. In the winter, the primary segments for local heating were the leg, thigh, back, and upper arm. Due to the differences in evaluation between studies, as some tend to point to heat flow and others rely on the user's thermal perception, it is hard to draw a conclusion on the most influential body part. For example, [17] pointed out that the legs and thighs are the most influential body parts, when other studies claimed that the lower body parts are the least influential.

Most of the multi-node HTPMs are based on Stolwijk's model [18], and one of the latest models called JOS3 segments the human body into 17 parts [19]. The model is based on the energy balance between the environment and the human body; thus, it includes heat transfer between the skin layer and the environment through 3 modes of heat transfer in addition to conduction between the different layers and convection due to the blood circulation between layers and body parts. Using a detailed human thermo-physiology to project the changes and influences of local heating and cooling on the whole body could be a potential approach. This approach can help in addressing several questions in order to properly design, select and improve a PCS system.

In the extensive literature review of [14] they tried to answer the basic question of which body parts should be targeted. The literature showed a significant contradiction between the studies and for that the question has yet to be resolved. This research seeks to answer this issue by methodically examining the impact of local body parts heating and cooling on the entire body.

Luo et al. [14] defined the three different factors that affect the effectiveness of a personal comfort system as: 1) environmental factors, 2) user factors, and 3) system factors. In our simulation, we considered the effect of different background operative temperatures as an environmental factor, as well as the differences between a male and female and the different clothing insulation representing two seasons, winter and summer. Local heating and cooling were represented as an imaginary system that could provide an ideal operative temperature uniformly distributed around the targeted body part. The influence of power has been represented as a different local operative temperature. In addition, the influence of the body thermal state before activating the local cooling and heating has been considered in our study which can be added as an additional environmental factor to what has been reported in [14].

The model has been validated by a set of data from a pilot study. In the experiment, a temperature drift from 24°C to 16°C has been conducted in a climatic chamber during winter. The subjects were sitting relaxed, wearing winter clothing with a total insulation value of 0.8 clo. In the HTPM simulation, we specified all local environmental parameters from the detailed experimental measurements. In addition, we used dynamic EE data directly from the experiments rather than estimating metabolic rate.

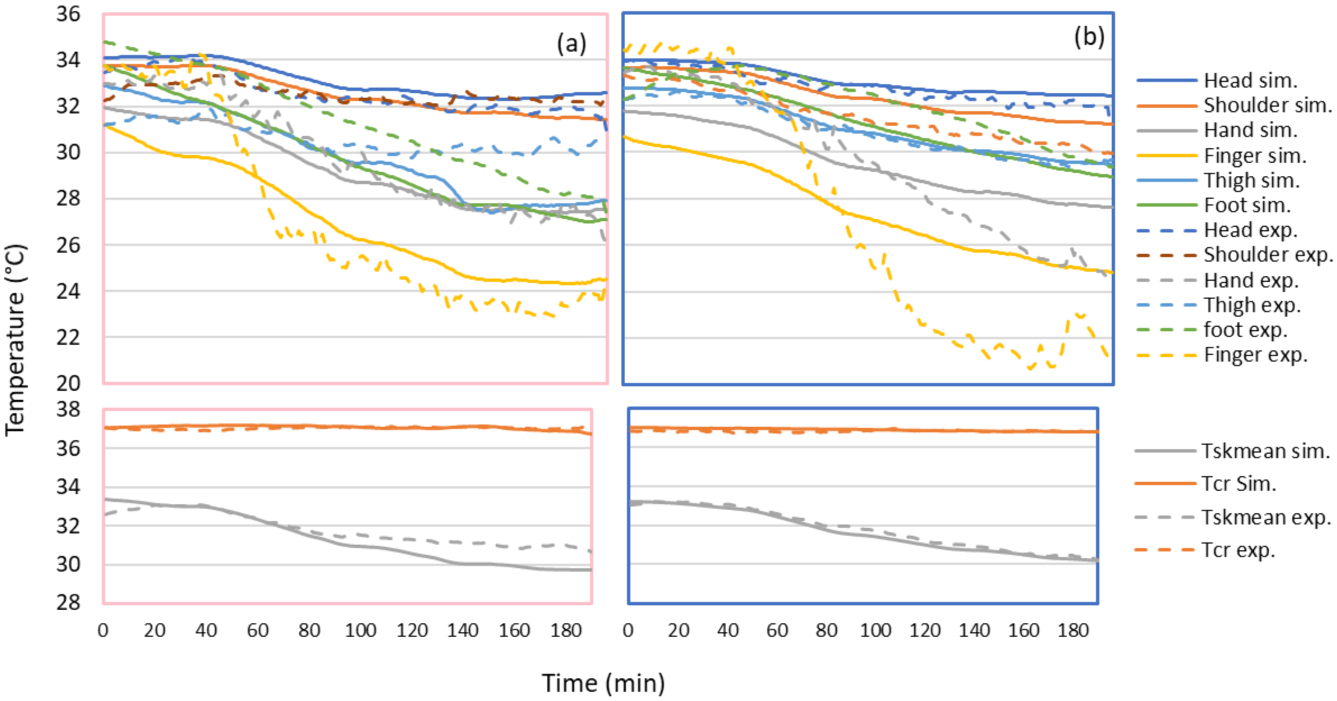

Fig. 1- Experimental results vs. HTPM Simulation in a drift environment from 24°C to 16°C.(a) are the results from a female and (b) for a male subject

2. Simulation

2.1 Thermo-Physiology model

In this study we have adopted the human thermo-physiology model JOS3 as an open source model developed by [19]. The model initially includes 17 body parts including the head, neck, chest, back, pelvis, right and left shoulders, arms, hands, thighs, legs, and feet. We have further improved the model to account for the 10 fingers.

The simulation has been conducted on two mid aged healthy subjects a male and female subject the body composition of each subject are presented in table 1

2.2 Model improvement

We have improved the model by including the fingers as separate body parts from the hands. We believe that hands including fingers are sensitive to the changes in the environment as most of the time bare skin body parts, and as extremities the skin temperature fluctuate the most in a wider range.

2.3 Model validation

Tab. 1- Subjects body composition

Sex	Age	Hight (m)	Weight (Kg)	Fat percent. %	Body surf. area (m2)
F	37	1.64	62	35.2	1.69
M	36	1.78	85	28.8	2.06

Figure 1 presents the results of the mean skin temperature, core temperature, as well as some local skin temperatures for 2 subjects, a female (a) and a male (b). We personalized inputs such as age, gender, fat percentage, height, and weight as mentioned in table 1. The local experimental results were compared with the simulation results from the HTPM for the head, shoulder, thigh, hand, and foot.

According to the results, both subjects showed an acceptable MSE for mean skin temperature, with a value of less than 0.5°C and a core temperature with an MSE of 0.1°C. Furthermore, the results showed that the skin temperature of the female subjects' hands and fingers correlated better with the simulation, with an MSE of less than 0.5 °C when compared to male subjects, which could be attributed to female participants' lower BMI. Contrarily, the results of the foot showed a slightly better agreement in the male subject compared to the female. The actual foot skin temperature was higher in both subjects than the predicted foot skin temperature. The head showed an acceptable result for both subjects, with an MSE of 0.5°C for the female and 0.2 for the male. Females had better agreement on the shoulder, with an MSE of 0.5 °C. The skin temperature of the thigh predicted from the HTPM simulation was compared with the averaged anterior and posterior thigh skin temperature from the experiment, where the results were in alignment with each other.

Although the results showed an acceptable agreement, there is still some deviation in the local skin temperature of the extremities, especially the feet. This highlights some limitations of the model in extreme environments. As the HTPM follows the changes in the environment correctly, we believe that using the model to study the effect of local heating and cooling on the thermal state of the whole body can be valid.

2.4 Mean skin temperature

Mean skin temperature is essential to represent the thermal state of the whole body. For example, during a cold exposure, vasoconstriction at the extremities occurs before a noticeable change in core temperature, giving the mean skin temperature an additional advantage as a better indicator of the whole-body thermal state [20].

In most of the research, the mean skin temperature is calculated based on a number of local skin temperatures from specific body parts. Some used measurements from only one side, either the left or right side of the body. For example, [21] calculated the mean skin temperature using seven body locations, whereas others used a fourteen-point method [20]. In this study, we intended to consider all body parts included in the model and the weight of each body part calculated by the weighted surface area. All local weights are presented in table 2. It is the purpose of having a consistent influence on the locals.

$$T_{mean} = \sum_{i=1}^{27}(f_{weight,i} \times T_{local,i})$$

Tab. 2- Body parts weighting factor

Body part	Weight factor
Head	0.059
Neck	0.015
Chest	0.094
Back	0.086
Pelvis	0.118
Shoulder x2	0.051
Arm x2	0.033
Hand x2	0.013
Finger x10	0.003
Thigh x2	0.112
Calf x2	0.06
Foot x2	0.03

3. Results

The results from the thermo-physiology model simulations represent an ideal situation as the ambient and local environments are considered uniform, thereby limiting the various influences on human thermoregulation to only influences from local heating or cooling.

The differences between the gender or, in another word, the effect of the different body composition has been considered. All simulations have been repeated for a male and a female subject considered, the body characteristics are reported in table 1. With a fixed metabolic rate of 1.2 met representing office work, and winter clothing of 0.8 clo and summer clothing of 0.6 clo.

3.1 Steady-state results

We have conducted several simulations that all started from the same initial conditions as reported in table 3. Simulations were grouped into two categories: one represents a cold exposure with local heating and the second is a hot exposure with local cooling. Three different ambient environments have been selected for each cold and hot exposure correspondingly, as follows: cold exposure at 16°C, 18°C, and 20°C; hot exposure at 28°C, 30°C, and 32°C.

Tab. 3- Neutral environmental conditions

Neutral environment	Winter	Summer
Operative temperature(°C)	24	25
Air velocity (m/s)	0.1	0.1
Relative humidity %	50	50

Four different powers of local heating and cooling have been tested, with the power represented by the local temperature. For local heating, we considered 34°C, 36°C, 38°C, and 40°C, and for cooling, we considered 16°C, 18°C, 20°C, and 22°C. Each body part was locally heated or cooled while the other body parts were exposed to either cold or hot temperatures. The difference of mean skin temperature resulted to the neutral case has been calculated. The mean skin temperature was taken after 60 min of exposure. Figure 2 shows the heat map results from the local heating and cooling of the hands, feet, head, chest, back, thigh, and pelvis in addition to some combinations of multiple body local

backgroud	24°C	16 [°C]					18 [°C]					20 [°C]				
Body part	Neutral	No Local H/C	$T_{op,local}$34°C	$T_{op,local}$36°C	$T_{op,local}$38°C	$T_{op,local}$40°C	No Local H/C	$T_{op,local}$34°C	$T_{op,local}$36°C	$T_{op,local}$38°C	$T_{op,local}$40°C	No Local H/C	$T_{op,local}$34°C	$T_{op,local}$36°C	$T_{op,local}$38°C	$T_{op,local}$40°C
Hands	33.5	-2.9	-2.2	-2.1	-2.0	-2.0	-2.2	-1.5	-1.5	-1.4	-1.3	-1.5	-0.9	-0.8	-0.7	-0.7
Feet	33.5	-2.9	-2.5	-2.4	-2.4	-2.4	-2.2	-1.8	-1.8	-1.8	-1.7	-1.5	-1.2	-1.1	-1.1	-1.1
Hand+Feet	33.5	-2.9	-1.8	-1.7	-1.6	-1.5	-2.2	-1.2	-1.1	-1.0	-0.9	-1.5	-0.6	-0.5	-0.4	-0.3
Head	33.5	-2.9	-2.5	-2.4	-2.4	-2.3	-2.2	-1.8	-1.8	-1.7	-1.6	-1.5	-1.1	-1.1	-1.0	-0.9
Chest	33.5	-2.9	-2.3	-2.3	-2.2	-2.1	-2.2	-1.7	-1.6	-1.6	-1.5	-1.5	-1.0	-1.0	-0.9	-0.9
Back	33.5	-2.9	-2.3	-2.3	-2.2	-2.2	-2.2	-1.7	-1.7	-1.6	-1.5	-1.5	-1.1	-1.0	-0.9	-0.9
Pelvis	33.5	-2.9	-2.4	-2.3	-2.3	-2.2	-2.2	-1.7	-1.7	-1.6	-1.5	-1.5	-1.1	-1.0	-0.9	-0.9
Pelvis+Back	33.5	-2.9	-1.8	-1.7	-1.6	-1.5	-2.2	-1.2	-1.1	-1.0	-0.9	-1.5	-0.6	-0.5	-0.4	-0.3
Thigh	33.5	-2.9	-1.5	-1.4	-1.2	-1.1	-2.2	-1.0	-0.8	-0.7	-0.5	-1.5	-0.4	-0.3	-0.1	0.1
Pelvis+Thigh	33.5	-2.9	-1.0	-0.8	-0.6	-0.4	-2.2	-0.5	-0.3	0.0	0.2	-1.5	0.1	0.3	0.6	1.0
Thigh+Back	33.5	-2.9	-1.0	-0.8	-0.6	-0.4	-2.2	-0.5	-0.3	0.0	0.2	-1.5	0.1	0.3	0.6	0.9
Thigh+Back+Pelvis	33.5	-2.9	-0.5	-0.2	0.2	0.5	-2.2	0.1	0.4	0.9	1.2	-1.5	0.7	1.1	1.4	1.6

backgroud	25°C	28 [°C]					30 [°C]					32 [°C]				
Body part	Neutral	No Local H/C	$T_{op,local}$16°C	$T_{op,local}$18°C	$T_{op,local}$20°C	$T_{op,local}$22°C	No Local H/C	$T_{op,local}$16°C	$T_{op,local}$18°C	$T_{op,local}$20°C	$T_{op,local}$22°C	No Local H/C	$T_{op,local}$16°C	$T_{op,local}$18°C	$T_{op,local}$20°C	$T_{op,local}$22°C
Hands	33.2	1.6	0.9	1.1	1.2	1.3	2.0	1.9	1.9	2.0	2.0	2.2	2.1	2.1	2.1	2.2
Feet	33.2	1.6	1.2	1.3	1.4	1.4	2.0	1.9	1.9	1.9	2.0	2.2	2.1	2.1	2.1	2.1
Hand+Feet	33.2	1.6	1.0	1.1	1.2	1.3	2.0	1.8	1.8	1.9	1.9	2.2	2.3	2.3	2.3	2.2
Head	33.2	1.6	1.0	1.1	1.2	1.3	2.0	1.8	1.9	1.9	2.0	2.2	2.1	2.1	2.1	2.1
Chest	33.2	1.6	1.0	1.1	1.2	1.3	2.0	1.8	1.9	1.9	2.0	2.2	2.1	2.1	2.1	2.1
Back	33.2	1.6	0.3	0.5	0.7	1.0	2.0	1.3	1.5	1.7	1.8	2.2	1.9	1.9	1.9	2.0
Pelvis	33.2	1.6	1.0	1.1	1.2	1.3	2.0	1.8	1.9	1.9	1.9	2.2	2.1	2.1	2.1	2.1
Pelvis+Back	33.2	1.6	0.4	0.6	0.8	1.0	2.0	1.3	1.4	1.6	1.8	2.2	1.9	2.0	2.0	2.0
Thigh	33.2	1.6	-0.2	0.1	0.3	0.6	2.0	0.4	0.8	1.3	1.5	2.2	1.5	1.7	1.8	1.9
Pelvis+Thigh	33.2	1.6	-0.2	0.1	0.3	0.6	2.0	0.4	0.8	1.3	1.5	2.2	1.5	1.7	1.8	1.9
Thigh+Back	33.2	1.6	0.4	0.6	0.8	1.1	2.0	1.5	1.7	1.8	1.9	2.2	1.9	2.0	2.0	2.1
Thigh+Back+Pelvis	33.2	1.6	-0.6	-0.3	0.0	0.4	2.0	-0.1	0.2	0.6	1.1	2.2	0.4	1.0	1.5	1.7

Fig. 2- Heat map of the mean skin temperature shift from neutrality for different local heating and cooling settings

heating and cooling, such as the pelvis+back, pelvis+thigh, thigh+back, thigh+back+pelvis, and hands+feet.

From the results, we could see that the effect of both cooling and heating of the thigh as a single body part has the most influence on the mean skin temperature compared to the other body parts. On the other hand, the hands showed a higher or similar impact compared to the head, chest, and back. Based on the environmental conditions and local heating and cooling power presented in this study, we could see that only cooling or heating the thigh as a single body part could bring the mean skin temperature closer to the mean skin temperature at neutrality, especially at moderate background temperatures of 20°C and 28°C. It is clear that heating or cooling multiple body parts has more potential for bringing the body toward thermal neutrality. The results showed that both hands and feet could be equally compared to the back and pelvis. According to the findings, the thigh is the most important component in shifting any combination toward thermal neutrality and, in some cases, overheating, as in the case of heating the back, pelvis, and thigh at 38°C and 40°C at all three background temperatures, and over cooling when the local temperature was 16°C and 18°C for a background temperature of 28°C.

Tab. 4- Percentage of effectiveness achieved toward *thermal neutrality from local heating and cooling at 30°C and 18°C background environment*

Local tempera ture	Thigh	Pelvis +Back	Hand +Feet	Thigh +Back +Pelvis
T_16°C	33	38	25	106
T_18°C	25	29	17	89
T_20°C	18	19	12	72
T_22°C	13	13	8	44
T_34°C	56	44	45	104
T_36°C	63	49	51	119
T_38°C	69	54	56	140
T_40°C	75	60	61	158

The simulations have been repeated for both male and female where results showed that the female subject showed slightly closer values compared to the men. Here we should acknowledge the influence of the differences in body composition between the male and female subjects that is mainly behind the differences in the mean skin temperature results. Table 4 presents the percentage of effectiveness of different local cooling and heating body parts in terms of bringing the mean skin temperature back to neutrality which can range from 50–80% for hands and feet to 60–100% for the thigh.

3.2 Dynamic results

The thermal state in which the body is just before applying local heating or cooling in HTPM has a big influence on the time required to reach steady state again. Here, in this simulation example, we present the dynamic result of the mean skin temperature changing with time as the environmental parameters change. Figure 3 presents the mean skin temperature for the different cases. All simulations began in a neutral environment defined as 24°C for winter clothing and 25°C for summer clothing. After reaching a steady state, the environmental temperature changed to either 18°C with the winter clothes or 30°C with the summer clothes. Followed by two different cases, first one the solid lines where local heating or cooling started immediately with the cold or hot exposure, second case is when local cooling or heating introduced after one hour of full body heat or cold exposure. The results highlight that the thermal state of the body is in a better position when applying local heating and cooling from the beginning of the cold or hot exposure, and that compared with the delayed local heating and cooling mean skin temperature required even more than 30 min to reach the mean skin temperature of the first case local H/C from the beginning.

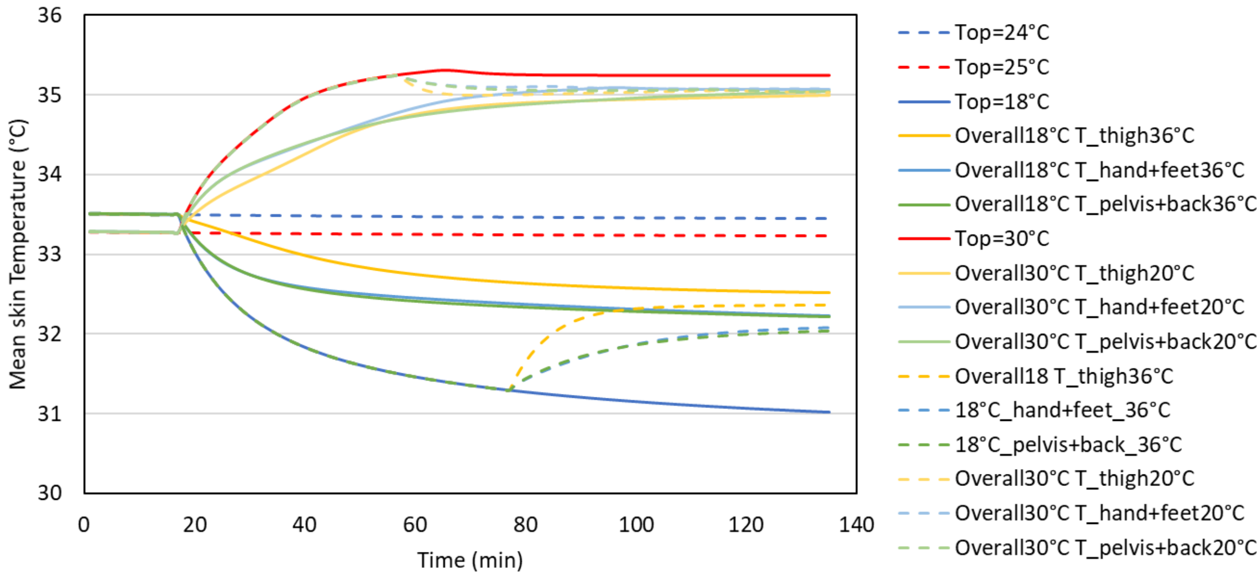

Fig. 3- Dynamic respons of the mean skin temperature during different environmental scenario

3.3 Physiological parameters changes

In this section of the results analyses we focused on the physiological changes happening in local body parts such as the local skin temperature, local skin blood flow and local heat losses compared to thermal neutrality at the start of the simulation. Two sets of data are presented in Figure 4 I and II, first represent a hot exposure (red frame) with local cooling and the second represent a cold exposure (blue frame) with local heating. The graph also presents the local results from two different local heating or cooling strategies, Figure 4-I the hands and feet cooling or heating and Figure 4-II the back, pelvis and thigh local heating at 36°C and cooling at 18°C. The rate of heat losses in the case of back pelvis thigh is more than double the rate of heat loss in the hands and feet.

Skin blood flow in all cases for local body parts has gone back to similar range as thermal neutrality. Looking at local skin temperature, in the local heating case the hands and feet were effective as much as the back pelvis and thigh but not in the local cooling case.

4. Conclusion

In order to assess the human thermal state for individuals and in non-uniform environments, the thermophysiology model become the most suitable tool in this case. The model gives physiological responses to the environmental changes locally and overall. To obtain a high percentage of occupant thermal satisfaction in a building while reducing energy usage for heating and cooling, occupant physiological activity must be more carefully taken into consideration. Individual variables in human physiology (age, gender, and body composition) impact the thermal state of the body and physiological reactions, potentially resulting in differences in thermal comfort and thermal preferences among occupants.

Localized heating or cooling can be an energy-efficient method because it does not require conditioning of the entire room. Further, if occupant comfort can be maintained by heating or cooling a specific body segment with a local heating or cooling device, more energy savings potential can be obtained.

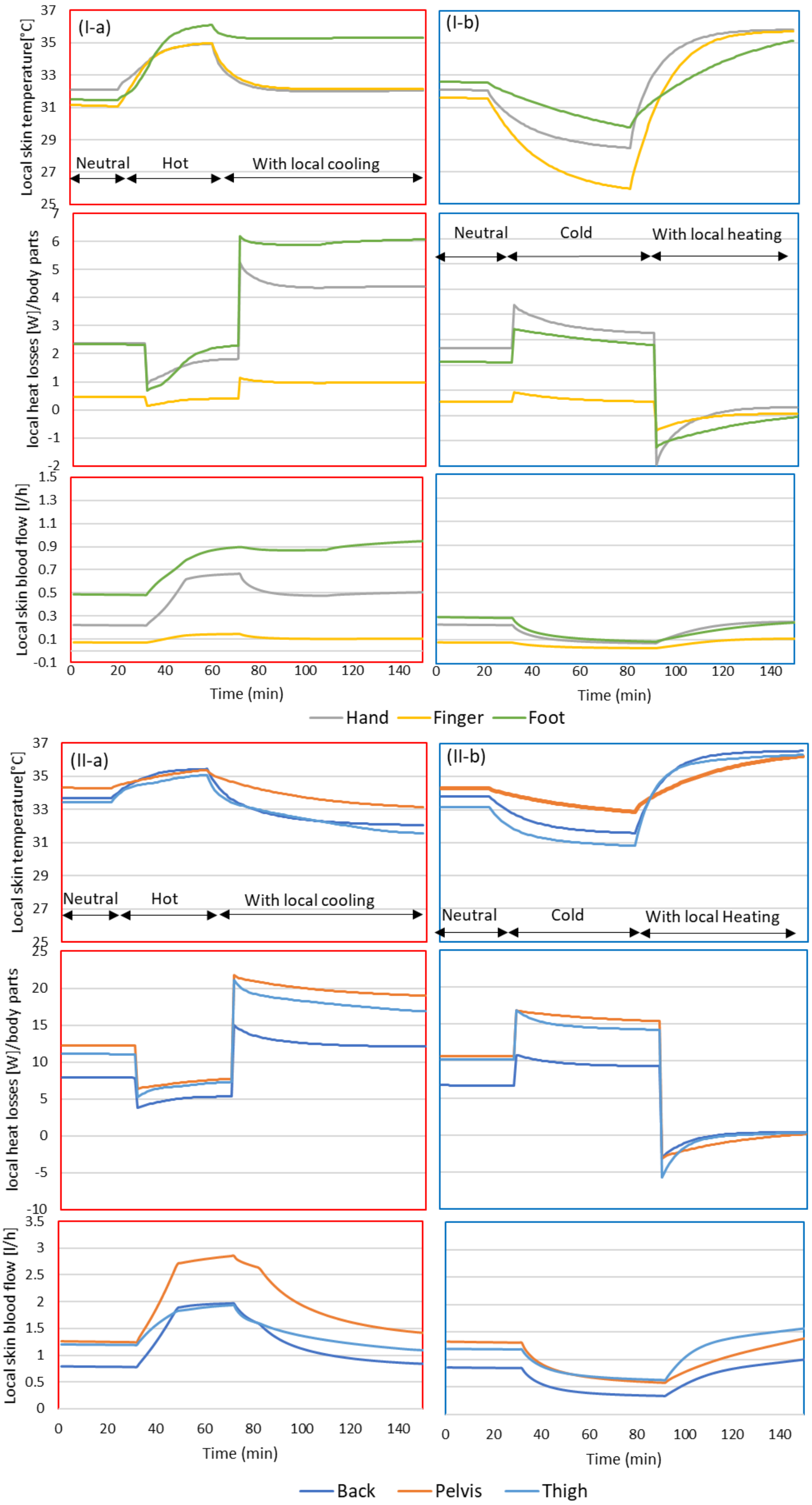

Fig. 4- Physiological parameters of hand, finger and foot (I a,b) and back, pelvis, thigh (II a,b) during locally cooling at 18°C and local heating at 36°C

This study is based on the results from the human thermo-physiology model. Although those models are usually criticized for their accuracy in prediction, we believed that in this study we were able to project the effect of local heating and cooling on the whole body. The results showed the influence of the non-uniform environment on the total thermal state of the human body, as well as the influence of the power of local heating and cooling. We have also highlighted the transient effect and the initial condition before introducing the local heating and cooling on the time required to reach a steady state. For further development, the model requires further improvement to increase its accuracy individual subjects. Moreover, differentiating between the different mean of heat transfer needs to be highlighted in order to see the effect of heat transfer mode.

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