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Simulation-based thermal analysis and validation of clothed thermal manikin

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K E Y W O R D S

Thermal Analysis

Thermal Manikin

Simulations

3D CAD

3D Scanning

Clothing Thermal Resistance

Wear Trial

A B S T R A C T

Human thermal comfort within various environmental conditions is of paramount importance in a wide range of industries, including clothing design, indoor climate control, and occupational safety. Researchers are always in search the sophisticated tools and techniques that simulate the thermal regulation of human body under different environmental conditions. The present research aims to present a precise methodology for the simulation of clothed thermal manikin in controlled environmental conditions. A comprehensive method is recommended that consists of the use of 3D body scanning technology, different 2D and 3D CAD as well as thermal simulation software. The results of the simulations are very satisfactory, which are later validated with the wear trials with the help of the same clothed thermal manikin and under the same environmental conditions. The comparative analysis shows some deviations that are discussed thoroughly and the need for further research is highlighted in the papers as well. Furthermore, the present research gives us a digital platform to understand the clothing's thermal comfort and the parameters that affect it with the consideration of the draping behavior of the clothing, microclimate, thermal properties, and surrounding environmental conditions.

1. Introduction

In recent years, there has been a growing interest in developing accurate and reliable techniques to evaluate human thermal comfort. Achieving optimal comfort is not only essential for individual well-being but also plays a crucial role in determining productivity, safety, and overall satisfaction. As humans spend a significant amount of time indoors and in diverse environmental conditions, it becomes increasingly important to comprehend the complex interactions between the human body, clothing, and the surrounding environment. A comfortable environment may defined as "the condition of mindset that expresses satisfaction with thermal environment" [1]. Clothing plays a vital role in achieving the thermal comfortability of a human body, it has been investigated by many researchers[2–4]. They reported that water vapor resistance, thermal resistance, and air permeability are major clothing

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properties that influence thermal comfort significantly [5–7]. Besides the many other factors like fabric properties, external environment, and activity level of human that effects clothing thermal comfort, microclimate is also a very important influential factor. It develops very next to body and lies between body and clothing surfaces. In the past many scientists conducted their research to investigate the microclimate and its effect on the heat exchange between human body and environment [8–12].

The selection of the clothing is always according to the weather conditions and the specific activity level of the human body. However, the evaluation of clothing performance is a challenging and crucial task. The subjective testing methods involving human subjects have been employed, but these methods are costly, ethically sensitive, and yield widely varying results. To overcome these limitations, thermal manikins have emerged as indispensable tools in comprehensive research and development within the clothing industry. These manikins enable the analysis of the thermal relationship between the human body and the surrounding environment, investigation of clothing's thermal properties, and the assessment of local body heat fluxes in complex environments [13–17]. The introduction of new advancements in the thermal manikin like moving body parts, sweating, and breathing, has opened new possible research opportunities for the researcher [18–22]. Now the researchers are able to measure and investigate the three-dimensional heat exchange behavior for the whole or a segment/part of thermal manikin in order to measure the clothing's thermal as well as evaporative resistance under real-world conditions. Besides the many advantages of the thermal manikin, there are some limitations that are associated with it. These instruments are very expensive and has a high installation cost as well, therefore, it is not accessible for every researcher. Moreover, although thermal manikin integrated with the advanced sensor technologies, but it cannot completely replace the human testing because of the human personal perceptions and physiological behavior.

So, the research community is actively working on the exploring of alternative techniques for fabric testing that involve advanced simulation and modeling methods. The core objective is to make the testing process more efficient with minimum utilization of time. Advanced simulation and modeling based fabric testing techniques have the potential to overcome the complexity and long-time consumption associated with the conventional clothing testing, consequently the testing methods will be more efficient and results for the thermal comfort will also be more authentic and reliable. Especially modeling and simulation of heat transfer and the thermal response of the human body have gained the considerable attention of researchers from academia and industry which have resulted in the development and application of different human thermal response models [23–28] for versatile industrial applications [29–35].

The key objective of present research is to explore thermal simulation and modeling techniques as an alternative to conventional thermal testing of clothing, which involved the use of thermal manikin. The findings of the presents research indicated that it could revolutionize clothing research by providing a more efficient and cost-effective approach for evaluating clothing comfort and its performance, and optimize the design process. Furthermore, the combination of the available 3D CAD, modeling, simulations tools as well as the developed methodology in this research work offered a virtual wear trials of clothing and eliminate the hectic and time taking traditional method of laborious wear trial.

2. Method and Material

Error! Reference source not found. explain the steps that were followed in order to achieve the objective of the research study. In the first step clothing system, textile fabrics, and thermal manikin were defined. Then the preparation phase starts, which has the purpose to prepare the virtual data and clothing for the thermal simulation and the wear trials.

A clothing system (CS) that consists of full-sleeve shirt and trousers were selected for the study. The selection of textile fabrics to develop the clothing system was made by considering the fabrics that are usually used for outdoor clothing. In this regards, R/L knitted fabric (F1) and woven fabric (F2) were chosen for sewing CS (Table 1).

Table 1

Selected fabrics for the clothing systems

Fabric code	Fabric Type	Specification	Clothing	GSM (g/m^2)
F1	Knitted	98% Rec. PES / 2% PES	Full-sleeve shirt	160
F2	Woven	100% PA	Trousers	115

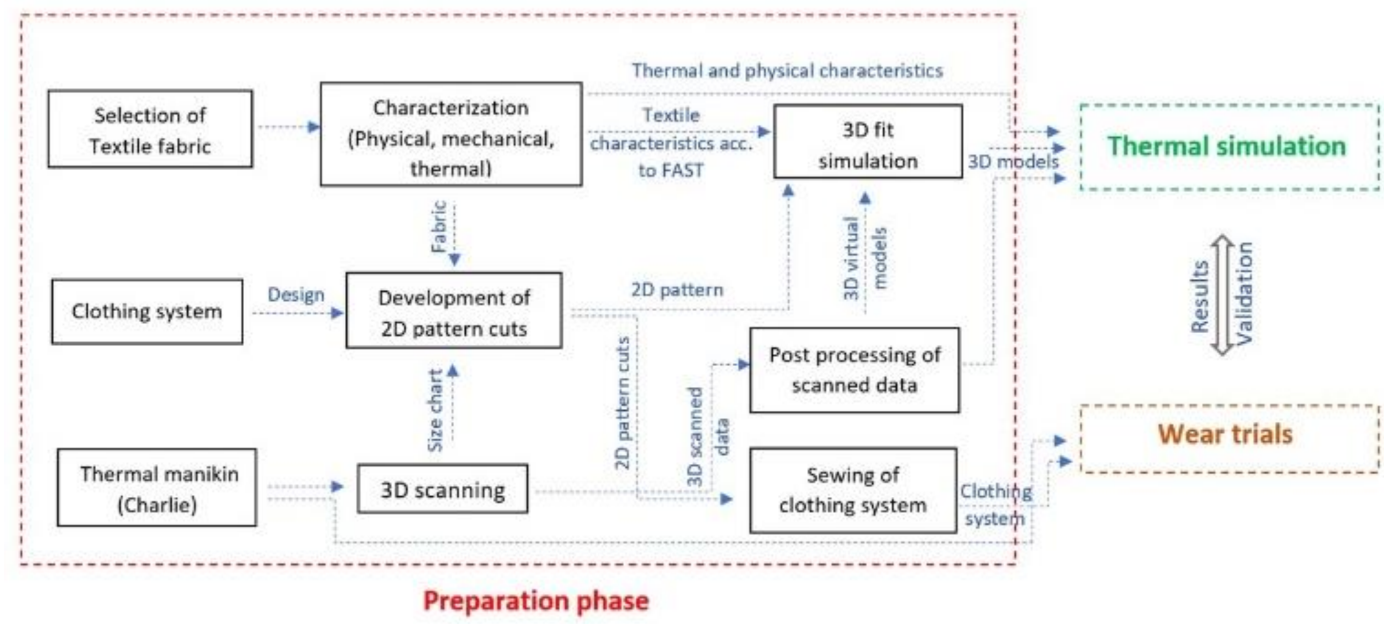

Fig. 1. Schematic flow chart of research methodology

The characterization of the selected fabrics was done according the requirement for the further simulation processes. The following **Error! Reference source not found.** 2 shows the characteristics that were measured in the lab.

Table 2

Material characterization

Characteristics			Apparatuses	Textile material F1	F2
Physical	Fabric thickness [mm]		Karl Schröder KG Material Testing Machine	0.46	0.29
	Average mass per unit area of the fabrics [g/m^{-2}]		Weighing balance, GSM Cutter	161	125
Thermal	Water vapor resistance [m^2 Pa W^{-1}]		Sweat guarded hot plate	1.69	3.18
	Thermal resistance [m^2 K W^{-1}]		Sweat guarded hot plate	0.005	0.009
	Specific heat[Jkg^{-1}K^{-1}]		Calculated	493	295
Mechanical	Bending stiffness [µN m] (warp, weft, 45˚)		Bending Stiffness tester Cantilever ACPM 200	1.18 0.74 0.63	3.22 10.32 4.82
	Elongation [%]				
	5 N/m	Warp	Zwick Tensile Strength Tester	1.15	0.42
		Weft		2.56	0.05
	20 N/m	Warp		4.34	1.09
		Weft		10.00	0.21
	100 N/m	Warp		10.88	2.51
		Weft		19.00	0.98
	Shear stiffness [N/m]			40.46	124.24

Thermal manikin (CHARLIE) was scanned before sewing the clothing system in standard body posture. For this purpose 3D-body scanner VITUS [36] was used to scan the Charlie in the Hohenstein Institut für Textilinnovation. The scanned data was achieved, processed and polygone model was produced. The model was further processed in the software Geomagic Studio 10 [37] for repairing and refining. Fig. 1 shows the polygon models of the CHARLIE. The surface reconstruction of the polygon models was also carried out to develop the non-uniform rational B-splines (NURBS) model, which is mostly used for the parametric representations.

Sr. no.	Description	Measure ments (cm)	Sr. no.	Description	Measure ments (cm)
1	Bust circumference	92.0	12	Inner leg length	78.5
2	Waist circumference	85.0	13	Knee height	46.2
3	Body height	174.8	14	Sleeve length	67.0
4	Ankle circumference	23.4	15	Front nape-waist	46.0
5	Knee circumference	40.0	16	Back nape-waist	40.5
6	Thigh circumference	55.4	17	Shoulder width	12.0
7	Hips circumference	97.0	20	Shoulder inclination (degree)	16.0
8	Wrist circumference	20.0	21	Back width	35.3
9	Top arm circumference	30.5	22	Calf circumference	36
10	Neck circumference	45.5	23	Crotch length	62.8
11	Outer leg length	107.0			

Fig. 1. Polygone model of thermal manikin Charlie and body measurement table

The body measurement will be taken according to the ISO 8559 and DIN EN ISO 7250. Fig. 1 shows some important body measurements that were taken from the virtual model of the thermal manikin. These measurements were used to develop the 2D cut patterns of the selected garment (a long sleeve shirt and a trousers). In order to develop cut patterns of garments 2D CAD software Grafis [38] was used.

These patterns then imported in the 3D CAD software for the fit simulation.

The garments underwent 3D fit simulation using Modaris V8 software [39]. In order to analyze the fabric's draping properties during the fit simulation, a material database was created for each fabric. This involved inputting various material properties, such as elongation, bending and shearing stiffness, mass per unit area, and fabric thickness, into the software. Consequently, the fit simulations (as shown in **Error! Reference source not found.**) were conducted based on the specific materials selected, as detailed in **Error! Reference source not found.**. Furthermore, garments were also prepared according to cut patterns that were developed in Grafis software (**Error! Reference source not found.** (c)).

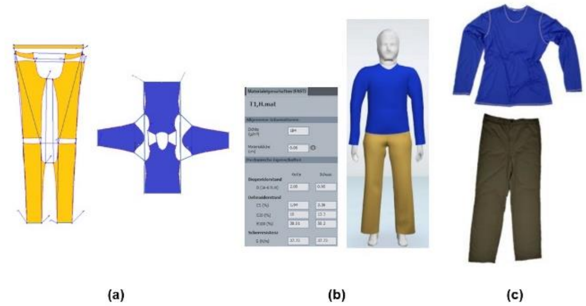

Fig. 3. (a) virtual sewing of the pattern, (b) assigning the draping properties and 3D fit simulation, and (b) sewn garments for the wear trial

The virtual model of thermal manikin and the garment were prepared for the purpose of performing the thermal simulation. Before doing the thermal simulation, the air gap between the garment and the manikin surfaces were measured (as shown in **Error! Reference source not found.** (a)) and analyzed with help of *Geomagic* software [37]. According to the air gaps and the body segments of thermal manikin "CHARLIE", different air zones were developed which can be seen in .Fig. 4. (b). in the next step the heat transfer coefficient of each air zone was calculated.

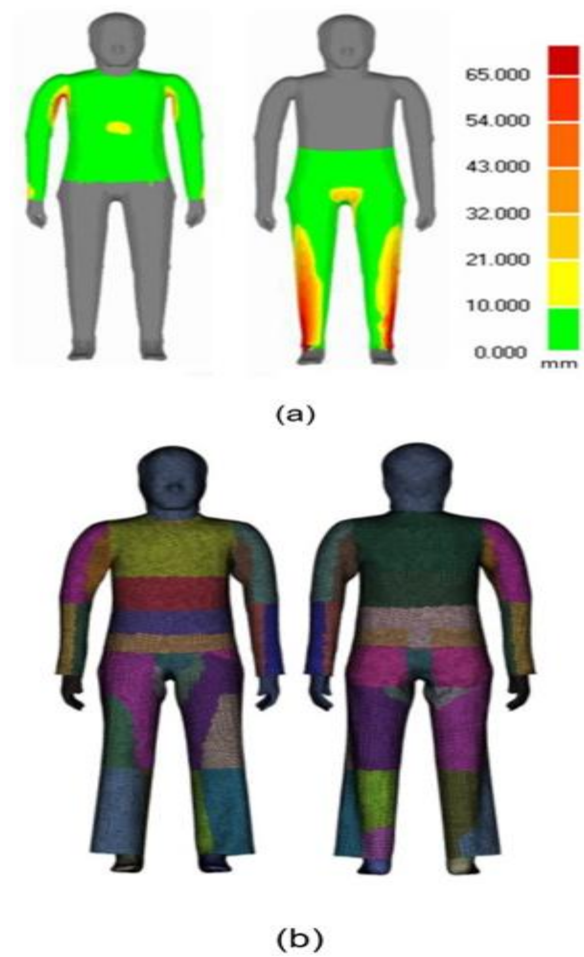

Fig. 4. (a) Air gap analysis and (b) defining air zones by dividing air gaps with respect to their thickness and manikin segments

The mesh models of the thermal manikin and the garment were imported into the Theseus-FE software for thermal simulation. This involved taking into account the thermal properties of the clothing, external environmental conditions, air gaps, and their respective heat transfer coefficients. The simulation process included dividing the air gaps into different zones, calculating the heat transfer coefficient, and defining thermal properties to accurately capture radiative and convective heat transfer. A comprehensive investigation of these procedures can be found in reference [40]

Wear trials of CS were conducted also on the thermal manikin “CHARLIE”. The thermal manikin "CHARLIE" has the anatomical shape of an adult male (standard man: body height 1.76 m, body weight 75.3 kg, body surface 1.85 m^2, clothing size 50), which is subdivided into different body segments as shown in Fig 5 . The segments of the manikin can be heated separately by electrical input to maintain the constant surface temperature at 34 °C. Furthermore, arms and legs of the manikin can be moved to incorporate walking (5 km/h) during wear trial. Therefore, thermal resistance of the clothing can be measured in standing as well as in a walking condition of the manikin.

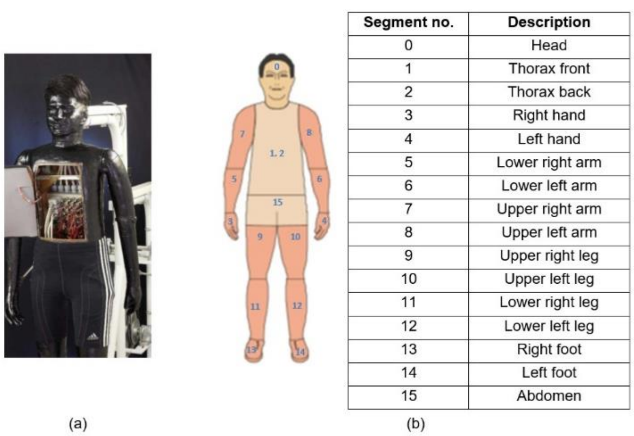

Fig. 5. (a) Thermal manikin “CHARLIE”, (b) segmental representation of thermal manikin

3. Results and Discussion

The wear trial was carried out according to ISO 15831 [41] in a climate chamber under a constant environment of temperature 23 ˚C and relative humidity 50%. The serial model (surface area weighted thermal insulation) was used to calculate the thermal resistance of the clothing in standing as well as in moving conditions. In this model, the power consumption of every segment in order to maintain the surface temperature at 34 ˚C was measured and then thermal resistance of the clothing area for each specific segment, as well as total resistance of the clothing, was calculated as shown in

Description	Thermal resistance of CS standing (m² K/W)		Thermal resistance of CS walking with 5 km/h (m² K/W)	
	MW	Stdev	MW	Stdev
Thorax front	0.056	0.002	0.038	0.001
Thorax back	0.077	0.003	0.042	0.005
Waist	0.101	0.007	0.076	0.002
Upper arm	0.056	0.001	0.030	0.001
Lower arm	0.055	0.004	0.024	0.005
Upper leg	0.066	0.008	0.066	0.002
Lower leg	0.072	0.015	0.074	0.006
Feet	0.096	0.005	0.092	0.004
Total	0.064	0.002	0.043	0.002

3. The following equation was used to calculate the total thermal resistance of the clothing:

$$R_{ci} = \sum f_i \left[\frac{(T_{si}-T_a)a_i}{H_{ci}}\right] - R_{ci0} \quad (1)$$

where,

R_{ci} total thermal resistance of the clothing ensemble with the manikin (Km2/W),

a_i surface area of the body segment i of the manikin (m2),

T_{si} skin surface temperature of the body segment i of the manikin (K),

Ta air temperature with the climatic chamber (K),

H_{ci} heating power supplied to the body segment i of the manikin (W),

R_{ci0} thermal resistance of the boundary air layer (Km^2/W), which was measured by repeating the test procedure with nude manikin, and

f_i fraction of the total manikin surface area represented by the surface area of segment i.

Table 3

Thermal resistance of the clothing system measured with thermal manikin - CHARLIE

Description	Thermal resistance of CS standing (m² K/W)	Thermal resistance of CS walking with 5 km/h (m² K/W)

	MW	Stdev	MW	Stdev
Thorax front	0.056	0.002	0.038	0.001
Thorax back	0.077	0.003	0.042	0.005
Waist	0.101	0.007	0.076	0.002
Upper arm	0.056	0.001	0.030	0.001
Lower arm	0.055	0.004	0.024	0.005
Upper leg	0.066	0.008	0.066	0.002
Lower leg	0.072	0.015	0.074	0.006
Feet	0.096	0.005	0.092	0.004
Total	0.064	0.002	0.043	0.002

The wear trial results of Charlie were measured as the thermal resistance of the clothing against each segment of the thermal manikin to maintain body surface temperature 34°C (**Error! Reference source not found.**). As software Theseus-FE cannot realize body movement, the simulation was performed only in the standing position. In order to compare the results of simulation and wear trial, the results of the thermal simulation were further prepared in the form of segmental thermal resistance offered by the clothing. The following Eq. 2 was used to calculate the thermal resistance from the manikin surface to the clothing outer surface:

$$R_{ct} = \frac{(T_{si} - T_{cl.out})a_i}{Q_T} \quad (2)$$

where,

R_{ct} resistance to dry heat transfer from the skin to the outer surface of the textile fabric (Km2/W),

a_i area of the relevant segment of manikin (m2),

T_{si} surface temperature of the segment (°C),

$T_{cl.out}$ clothing outer surface temperature (°C), and

Q_T total heat loss on the outer surface of the clothing (W), which is equal to the sum of radiative (Q_{rad}) and convective (Q_{conv}) heat loss.

Both types of heat loss i.e. radiative and convective, and clothing outer surface temperature for all parts of the clothing surfaces were calculated during the thermal simulation against each step time. With the help of these values and equation **Error! Reference source not found.**, thermal resistance of clothing for each segment of thermal manikin was calculated. The detailed calculation is presented in Table 4.

Fig. 6 shows a comparison of clothing thermal resistance measured during the wear trial and calculated with thermal simulation. The results can be interpreted as follows.

All the values of thermal resistance calculated by the simulation were higher compared to thermal resistance measured during wear trials. This is due to the air permeability property of clothing that causes the exchange of air during the wear trial between microclimate and the outer environment through the pours of fabric. Whereas, this property of clothing cannot be realized during the simulation and hence results in more thermal resistance.

It was noticed that the clothing thermal resistance is highest at the waist. This is because of the overlapping of the fabrics of trousers and shirt in some areas of the waist, which causes the prevention of heat loss and highest clothing thermal resistance.

The dotted line in Fig. 6 shows the differences in percentage between the simulation and wear trial values. More differences between simulation and wear trial values can be seen at the thorax front (46%), thorax back (12%), lower right arm (31%), lower left arm (16%), waist (17%), lower right leg (21%), and lower left leg (13%). It is due to the openings of the clothing at the neck, cuff, bottom of the shirt, and bottom of the trousers, which help to release the heat by air exchange between microclimate and outer environment. This phenomenon was not considered during the simulation and lead to higher thermal resistance during simulation.

It was also observed that the simulation values of the upper left arm, lower left arm, upper left leg, lower left leg are different from the upper right arm, lower right arm, upper right leg, lower right leg left respectively. It is due to the development of different air gaps on both sides of the CHARLIE, which leads to the different thermal resistance values. Whereas, during the wear trials, the average values were measured of the left and right arms and legs.

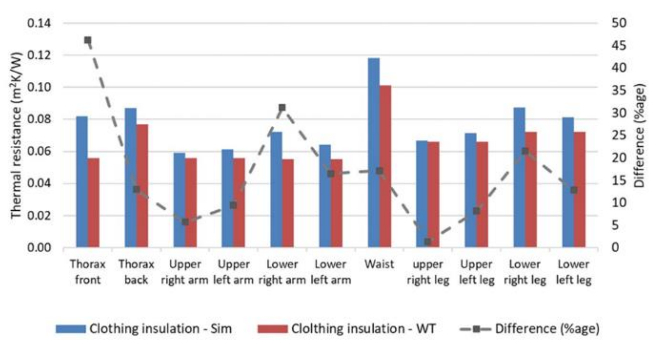

Fig. 6. Comparison of the clothing thermal resistance during wear trial and thermal simulate

Table 4

Calculation of clothing thermal resistance from the results of thermal simulation of clothing system and thermal manikin CHARLIE

Segments of CHARLIE	Q_{conv} (W)	Q_{rad} (W)	Total heat loss (W)	Clothing outer surface temp (°C)	Skin temp (°C)	Area of skin (m^2)	Total area of segment (m^2)	Clothing insulation (m^2K/W)
Thorax front	1.183	1.328	2.511	28.25	34	0.057625	0.207909	0.082
	4.869	5.169	10.038	33.37	34	0.108911		
	0.672	0.6844	1.3564	27.12	34	0.041373		
Thorax back	1.244	1.381	2.625	28.25	34	0.061244	0.204752	0.087
	4.85	5.19	10.04	33.21	34	0.104997		
	0.5855	0.607	1.1925	26.99	34	0.038511		
Upper right arm	0.574	0.355	0.929	27	34	0.026036	0.09388	0.059
	3.259	3.621	6.88	33.33	34	0.067844		
Upper left arm	0.649	0.429	1.078	28.08	34	0.030744	0.09159	0.061
	2.94	3.295	6.235	33.29	34	0.060846		
Lower right arm	0.731	0.949	1.68	27.98	34	0.034161	0.063073	0.072
	1.45	1.199	2.649	32.83	34	0.028912		
Lower left arm	0.698	0.912	1.61	28	34	0.031677	0.063606	0.064
	1.594	1.35	2.944	33.03	34	0.031929		
Waist	0.0544	0.0789	0.1333	26	34	0.006566	0.171577	0.118
	2.612	2.69	5.302	31	34	0.066972		
	0.52	0.469	0.989	27.5	34	0.021798		
	1.687	1.69	3.377	27	34	0.076241		
upper right leg	0.569	0.714	1.283	26.67	34	0.03283	0.191211	0.067
	6.296	6.051	12.347	32.87	34	0.135525		
	0.378	0.263	0.641	27.93	34	0.022856		
Upper left leg	0.741	0.873	1.614	26.9	34	0.042617	0.191181	0.075
	5.681	5.473	11.154	32.85	34	0.122293		
	0.478	0.347	0.825	28.31	34	0.026271		
Lower right leg	1.017	1.297	2.314	26.16	34	0.048463	0.110777	0.087
	1.445	1.199	2.644	32.82	34	0.062314		
Lower left leg	0.799	1.076	1.875	25.88	34	0.036656	0.110885	0.081
	2.754	2.637	5.391	32.81	34	0.060667		
	0.253	0.259	0.512	27.39	34	0.013562		

4. Conclusion

This study introduces a computer-based thermal simulation aimed at conducting virtual wear trials for specific garments. The simulation method takes into account the thermal properties of the textile fabric, its draping behavior on a thermal manikin, non-uniform air gaps, and the external environment. To validate the simulations, physical wear trials were conducted on a thermal manikin inside a climatic chamber. However, the comparison only focused on the manikin in a standing posture as simulation did not consider body movement and the pumping phenomenon developed in microclimate. Discrepancies between the simulations and wear trials were observed at the areas of thorax (front 46%, back 12%), lower arms (right 31%, left 13%), waist (17%), and lower legs (right 21%, left 13%), which is due to the openings of the clothing at different areas and heat exchanging between microclimate and external environment. This simulation method presents a valuable tool for assessing the thermal behavior of clothing through virtual wear trials, eliminating the time-consuming and arduous traditional methods. Nonetheless, further research is required to address the discrepancies and improve the accuracy of wear trial simulations.

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