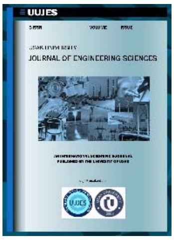

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Review article

TECHNOLOGICAL DEVELOPMENTS IN THERMAL MANNEQUIN SYSTEMS

*Muge Ozyunlu[1], Eren Oner[2]**

[1] Department of Textile Engineering, Graduate Education Institute, Usak University, Türkiye
[2] Department of Textile Engineering, Faculty of Engineering and Natural Sciences, Usak University, Türkiye

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Abstract

Technological advancements in thermal mannequin systems have significantly contributed to the progress of wearable technology and the textile industry. These systems, utilized for testing and measuring garment thermal properties, have undergone notable developments in recent years. Enhanced sensor technologies have enabled thermal mannequin systems to furnish more precise and accurate data, facilitating improved analysis of garment-body interaction. Moreover, refined mannequin designs now more accurately simulate real-world conditions, aiding in the assessment of garment performance. Furthermore, the integration of data analytics and artificial intelligence has emerged as a pivotal aspect, providing valuable insights for optimizing garment thermal performance. Overall, these technological advancements underscore the pivotal role of thermal mannequin systems in driving innovation in wearable technology and textile design, ultimately leading to the development of more functional and performance-oriented garments. The purpose of this article is to assemble the articles on thermal mannequin systems and briefly summarize the latest technological developments.

Keywords: *Thermal mannequin; thermal Comfort; sensor technologies; thermal test modules; performance test.*

1. Introduction

Textile structures have been one of the most basic needs of people since ancient times. For centuries, factors such as "covering" and protection from "external factors" have been the main purposes of use of textile structures. Developments in material science in the 20th century have increased the usage areas of textile structures and enabled the development of many textile-based structures in different fields, such as physics, chemistry, materials, medicine, electronics, machinery, etc. As a result of the joint work of science branches with

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*Corresponding author:
E-mail: eren.oner@usak.edu.tr

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textile science, products with different functions have begun to be developed. One of the main reasons why different disciplines can be applied in the textile field is that textile-based materials are easy to process, abundant and cheap, and can be used easily at every moment of people's daily lives. In this context, interdisciplinary studies in the field of textiles attract much attention today. The comfort features of textile products depend on various factors that ensure the comfort and satisfaction of the user. These features are determined by factors such as the type of fabric, construction, softness, breathability, flexibility, stitching details and the design of the product. One of the comfort features found in textile products is breathability; the fabric's ability to allow air and moisture to pass through provides a comfortable environment inside the garment or textile product.

In order to ensure clothing comfort, textiles should possess the following characteristics; effective regulation of heat and moisture transfer, lightweight construction, controlled air permeability across textile layers, designs that allow ease of movement, skin-friendly properties, ensuring no irritation, which includes attributes like softness, smoothness, or avoiding prickliness from the fabric's surface. Assessing clothing comfort requires a multidisciplinary approach, incorporating insights from physics, physiology, neurophysiology, and comfort physiology. A comprehensive evaluation can only be achieved by synthesizing knowledge from all these fields.

The intricate nature of clothing comfort can be addressed through two main perspectives: subjective measurements which based on the user's sensory experiences and personal perceptions; objective measurements which grounded in measurable physical parameters and scientific principles that describe comfort-related properties. Thermal mannequins are highly realistic tools commonly employed to objectively evaluate textile comfort. Their anatomical design, combined with features like the ability to sweat and simulate movement, allows for experimental conditions that closely mimic those of an actual human.

When introducing thermal comfort features, it is necessary to take a look at the heat transfer mechanisms in the human body. The human body has a very stable structure in terms of heat. However, body temperature changes due to various physical activities or changes in ambient temperature. In this case, heat exchange occurs between the environment and the human body through heat transfer mechanisms. These heat transfer mechanisms are classified as conduction, transport, heating and evaporation [1,2].

The human body uses an active heat balancing system using a full range of heat transfer mechanisms. The heat exchange between the person and the environment can be explained by the following equation (1).

$$M - W = Qsk + Qres = (C + R + E_{sk}) + (C_{res} + E_{res}) \qquad (1)$$

Here, M represents the metabolic energy production (W/m^2), W denotes the mechanical work performed (W/m^2), Q_{res} is the total heat lost through respiration (W/m^2), and Q_{sk} refers to the total heat lost from the skin surface (W/m^2). Additionally, C_{res} indicates the heat lost via convection during respiration (W/m^2), E_{res} represents the heat lost through evaporation during respiration (W/m^2), $C + R$ corresponds to the sensible heat loss from the skin surface (W/m^2), and E_{sk} is the heat loss due to evaporation from the skin surface (W/m^2).

All the above data are calculated as heat production or heat loss rate. The unit of energy gain or energy loss rate is energy per second. This is expressed as Joules/sec or Watts. To standardize this measurement on people of different sizes, this value is divided by the total body surface area (W/m^2).

The temperature of the human body is expressed in two ways: internal body temperature and skin surface temperature. Under normal conditions, while the ambient temperature is

28°C, that is, in a state of thermo-neutrality, the internal body temperature is approximately 37°C (between 36-38°C) and the skin surface temperature is approximately 33.7°C. However, considering that the coldest place on Earth is -50 °C and the hottest place is +50 °C, the temperature difference between the human body and its environment can be up to 80 °C in the coldest part of this scale and 20 °C in the hottest part of this scale and the temperature balance of the human body is disrupted. In addition, people's body temperatures increase during physical activities outside environmental conditions. Under normal conditions, the body temperature of a person doing physical activity can rise up to 40°C and the temperature balance of the human body is disrupted. These temperature differences must be balanced, otherwise it may lead to decreased performance in the person and, if these differences increase further, death. Considering these conditions, thermal mannequins are used to test clothing designs.

2. What is Thermal Mannequin?

Textile Mannequins are used instead of the human body in many different research fields to perform various simulations and obtain various data about the human body. Mannequins and mannequin-like structures are used in various fields, from vehicle safety tests to different industrial applications, from the aviation and space industry to military research. Mannequins can be similar to the human body in terms of appearance, but they can also be structures close to the human body in terms of functionality [3].

In general, the mannequins are anatomically designed to create realistic air layers around both the body and the clothing system. This feature represents a significant advancement that sets them apart from other devices, such as plates or single cylinders, since air layers play a crucial role in heat and mass transfer. Among the mannequins used in the field of science and technology, thermal mannequins constitute a separate research area. Thermal mannequins, as the name suggests, are used to thermally examine the relationships between the human body-environment, human body-clothing or human body-various equipment by simulating the human body in formal and functional terms. The parameters as temperature, humidity, etc. are examined using thermal mannequins [4].

While thermal mannequins can be produced from materials such as copper, aluminum or plastic, different structures are also used on their surfaces to simulate human skin (for example, fabrics produced by the Gore-Tex company that enable sweating). Today, temperature measurements on mannequins are carried out with the help of digital sensors. Depending on the sensitivity of the data to be obtained, the most appropriate sensor is placed in the targeted area [5]. Thermal mannequins are heated by electrical heating plates or water-filled pipes. An example thermal mannequin working principle [6] is depicted in Fig. 1.

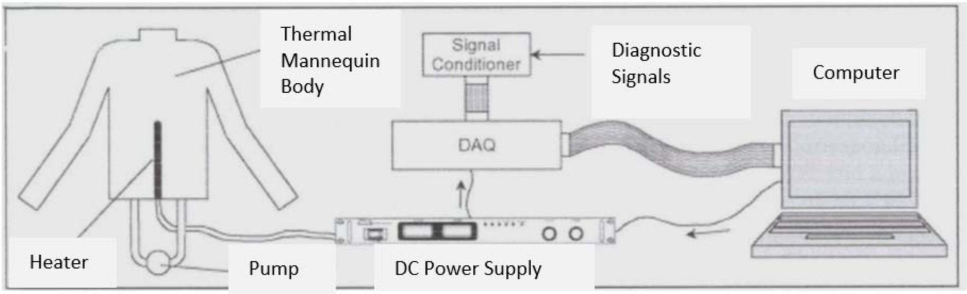


Fig. 1 Schematic representation of thermal mannequins [6]

3. Prominent thermal mannequin systems

Although different thermal mannequin systems have been developed by many researchers around the world, among all the thermal mannequins used, the sweating thermal mannequins “Newton” and “Walter” are the most important. The thermal mannequin “Newton” is a thermal mannequin made by the Measurement Technology Northwest Company (MTNW) in the United States, made of a thermally conductive aluminum-filled carbon epoxy shell with embedded heating and sensor wire elements. The thermal mannequin “Walter” was developed by the Hong Kong Polytechnic University in 2001. “Walter” is the world's first mannequin system made of fabric and water [3]. “Walter” simulates sweating by using “skin,” a waterproof but water vapor permeable fabric that retains water inside the body but allows water vapor to pass through the skin. Walter provides a person-like body temperature distribution by pumping water warmer than body temperature from the center to the ends. However, Gore-tex fabric can only be used to simulate imperceptible perspiration (evaporative sweating in which no liquid sweat is produced).

When other thermal mannequins in the literature are examined, it is seen that most of them have similar features to these two thermal mannequin systems. When these two thermal mannequin systems are examined, it is seen that the "Newton" type thermal mannequins are heavy and bulky due to their raw materials (such as metal or copper plating) and can mostly make limited movements. Problems such as "Walter" type thermal mannequins causing leaks after being worn and removed several times when they have too many leak points and having to use different types of fabric skins to change the sweating rate are observed.

Dionne et al. (2003) stated that since the protective clothing used by people dealing with the cleaning of toxic waste is not permeable, it reduces the evaporation mechanisms that will transfer the heat from their bodies to the environment, and accordingly, the internal body temperatures of individuals increase and cause a significant decrease in the productivity of these people. In their study, they investigated the performance of cooling systems on a sweating mannequin using Coretech personal cooling systems containing hoses of different densities. During the experiments, the mannequin's sweating rate was adjusted so that the entire surface of the mannequin was wet with sweat. The skin temperature of the model was kept constant at 35°C. Experiments were carried out at 35°C and 30% relative humidity. Refrigerated suits using 14.3 m, 24.1 m and 31.4 m long hoses were used during the tests. These cooling suits were worn under two types of chemical-biological suits, and a steel vest was placed inside both suits. As the first stage of the experiment, tests were carried out on 71 mannequins while they were motionless, without wearing SSG. When the model is motionless, the energy required to keep the skin temperature at 35°C is between 80-120 Watts. This amount of energy was used to measure heat transfer during evaporation. In the second stage of the experiment, cooling vests were worn. At approximately 7°C and 10°C, water was pumped into the suit between 250 ml/min and 760 ml/min. Meanwhile, the temperature of the mannequin is 35°C [7].

The effective heat removal rate was found by subtracting the values of the first experiment from the energy input required to keep the temperature of the mannequin at 35ºC during cooling. The total heat removal rate of the personal cooling system was obtained by measuring the inlet and outlet temperatures of the water. As a result, they found that the density of the hose affected the cooling capacity of the clothing. When clothes using the same water flow rate and the same water inlet temperatures are compared, more cooling is observed in clothes with high density hose circulation. There is a 23% difference in heat transfer between low density and high density. This emphasizes the importance of maximizing the surface area for body heat exchange through water-filled hoses. On the other hand, high hose lengths cause large friction losses and high pump power requirements [7].

Nam et al. (2005) made body fit analysis of water-cooled vests using the three-dimensional body scanning method [8]. Thus, it enabled thermal mannequin modeling with body scanning. With this method, mannequin profiles can be created by scanning real bodies, and these mannequins can be produced using various methods.

Cao et al. (2006) tried to find the most suitable inner face fabric for SSGs by testing the properties of the fabrics used on the inner surface of SSGs, such as moisture absorption, wettability, and thermal resistance. They used 18 different types of fabric for this purpose. These fabrics are 80/20% polyester/spandex knitted fabric, 90/10% cotton/cotton coated stainless steel woven fabric, 100% polyamide woven fabric, 100% silver coated polyamide knitted fabric, 100% cotton knitted fabric, 100% polyester fabric, etc. were chosen as fabrics. As a result of the measurement results obtained from the experiments, they determined that fabrics containing 80% PES and 20% spandex gave the most appropriate test results. Because the thermal properties of these fabrics are quite good compared to other fabrics. In addition, the elongation properties of the produced SSGs are very good in terms of being able to fully adapt to the body. Therefore, researchers have decided that this fabric is the most suitable fabric as the inner face [6, 9].

Daniel Ion-Guta et al (2022), thermal comfort in both buildings and vehicles is of great importance in terms of the durability of buildings and sustainability of life in cities. In this study, an attempt was made to balance the neuro-fuzzy temperature regulation of a thermal mannequin designed to consist of 79 superficial areas. Flexible heating elements are used to control the temperature. For this purpose, five digital sensors are positioned. To establish the relationship between heat loss, the thermal mannequin was calibrated in a climate chamber at ambient temperature. And the thermal mannequin was able to detect local sensations through the concept of so-called equivalent temperature (Fig. 2) [10].

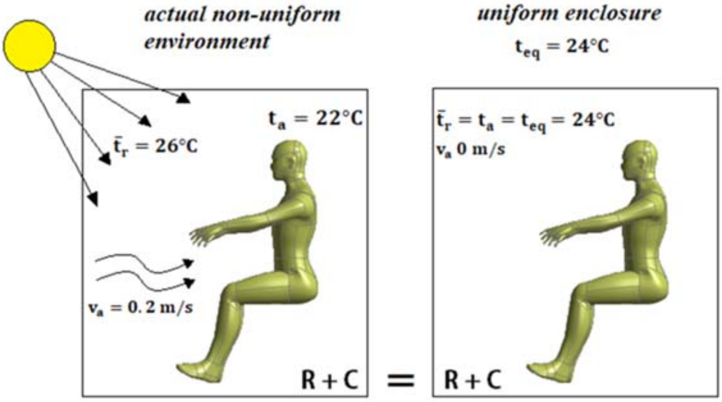
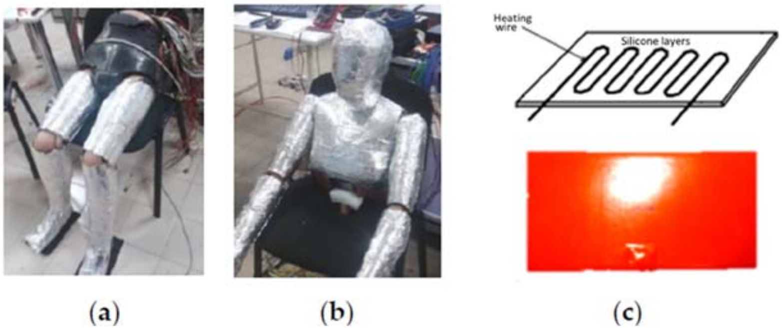


Fig. 2 Equivalent temperature definition [10]

Thermal mannequins can be used in the automotive industry, indoor and outdoor environments, military and textile research [10]. Thermal mannequins have a history of more than 70 years. Their story begins with very simple mannequins designed to test clothing for American soldiers. Nowadays, the complexity of thermal mannequins has increased and can closely match the complexity of the human body. The number of independently controlled areas also increased to 120 [11,12].

Many mannequins are designed to simulate the human body's heat exchange with the environment by measuring heat loss in the immediate environment. Of course, body sweating and heat exchange through evaporation are also simulated by high-performance mannequins. As performance increases, so does the cost of these tools; it allows effective imitation of the presence of the human figure and taking measurements of convective and radiative heat transfer coefficients. This paper presents the development of an advanced thermal mannequin based on intelligent neuro-fuzzy control. The development of this prototype started in 2013 within the framework of the EQUATOR project, and subsequent improvements were made during the QUEST and XTREME projects. This mannequin, known as Suzi, is the most advanced of five different thermal mannequin prototypes produced at the CAMBI Research Centre [10].

As seen in Fig. 3 a, b, the upper and lower body parts were tested. Four different basic flexible patch geometries were selected for the heating system. The patches are manufactured by Keenovo Company and consist of a thin layer of silicone (1.5 mm). They contain a heating circuit made of nickel chrome heating wire, making them a good electrical insulator and a good thermal conductor. Through many solutions tested, flexible heating silicone patches have proven to be the best choice in ensuring good temperature distribution and uniformity [13].



(a) (b) (c)

Fig. 3 Lower body(a), upper body(b), HE embedded silicone part(c) [13]

In the corresponding anatomical regions of the HE, the surface of the thermal mannequin is divided into 79 areas (or sections) and are intended to be controlled independently. Red plots represent regions on the opposite side of the mannequin, black dots indicate attachment points (Fig. 4) [13].

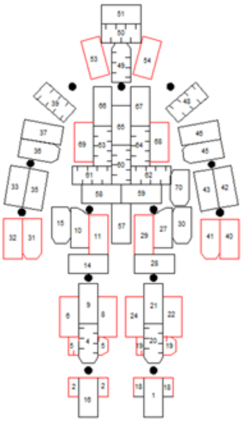


Fig. 4 Distribution of patches on the mannequin [13]

This particular mannequin prototype is designed and manufactured so that it can be placed in a variety of postures, such as lying, sitting or standing positions. The dimensions of this prototype were chosen based on the standardized human skin surface of a female body with a surface area of approximately 1.8m^2. The main structure is made of polyvinyl and its surface is covered with 5 mm elastomer membrane insulation. The role of this membrane is to reduce heat transfer inside the mannequin to prevent overheating of the internal electronics. Hardware components were developed in successive stages of the thermal prototype as shown in the Fig. 5.

Fig. 5 Hardware components in thermal mannequin [13]

Collecting data in different parts of a vehicle's interior space is highly desirable, creating a need for cost-effective and accurate systems that are expected to provide access to local equivalent temperatures and go even further, especially in the case of strong thermal gradients. To simulate the impact of heat exchange on real occupants of buildings and vehicles, real ventilation systems are available if taken into account. The purpose of this article was to present in detail a recently designed and constructed thermal mannequin with 79 superficial zones with independent neuro-fuzzy temperature regulation. Both the component parts of the mannequin and the adoption strategy of this powerful measurement tool are discussed.

Advanced instrumentation, such as dynamic sweating thermal mannequin systems, has revolutionized the realistic evaluation of clothing thermal comfort properties [14, 15, 16]. These systems can measure both dry thermal and evaporative resistance of clothing while replicating varying levels of physical activity. Furthermore, they are often paired with thermophysiological comfort models to simulate human physiological responses [17]. However, a key limitation of these systems is their reduced number of sweat glands compared to human skin, which may affect the precision of sweat distribution and evaporation. Despite this, they offer a significant advantage by simultaneously assessing heat and moisture transport properties—such as dry thermal resistance, wicking, heat of drying, and sorption—a capability not achievable with traditional bench-scale testing methods.

4. Thermal mannequin systems working in different areas

Anica Hursa Šajatovi’c et al. (2022), in their study on the research of protective clothing that provides protection against high temperatures for firefighters, stated that the main feature of clothing that provides protection against heat and flame is to protect the user from external effects and dangers in conditions of exposure to high temperature, flame, fire, smoke and water. In the article, research on the clothing system that provides protection against heat and flame using a fire dummy is presented and the damage that occurs after the test is systematically analyzed. As part of the damage analysis, the presence of microdamage and foreign matter in the garment system was determined using a USB Dino-Lite microscope. Additionally, the concentrations and compositions of gaseous decomposition products were investigated during thermogravimetric analysis of the samples. The results of the study using a fire dummy showed that the user of the studied clothing system will not suffer injuries dangerous to health and life, which confirms the protective properties. The results of TG-FTIR show that the decomposition of the fabric sample consisting of modacrylic-cotton fiber blend occurred in three stages, and the decomposition of the identified gaseous substance occurred in three stages. The degradation products were H2O, CO2 and CO [18]. In the article, the flammability properties of the clothing system that provides protection against heat and flame were investigated and the damage caused by the overalls designed for firefighters to extinguish forest fires was analyzed after being tested using a fire dummy. It is based on testing the underwear fabric, consisting of 70% wool fiber and 30% modacrylic fiber, with thermal mannequins [18].

The fire dummy is equipped with 128 temperature sensors placed on its surface (Fig. 6). The explosive fire simulation system consisted of 12 gas burners placed around the fire dummy. Each test was preceded by calibration in which the naked mannequin was exposed to explosive fire for 3 to 4 seconds. For this reason, the burners must always be placed to provide heat flux values of approximately 80 kW/m2. The data provided by the sensor was collected and displayed using the Labview software solution, and the entire system was controlled by a Mitsubishi Programmable Logic Controller (PLC) unit. Ignition was achieved by lighting the main burners for between 2 and 10 seconds, depending on the duration of the test and the garnish system tested. Turning off the burner extinguishes the fire, and when the fan is turned on for faster ventilation of the test room, 120 s is waited until the end of the test [18].

Fig. 6 Used thermal mannequin and temperature sensor [18]

The clothing system was tested on a fire dummy in accordance with an international standard describing the test method (ISO/DIS13506, 2002). During testing, the clothing system was exposed to open fire for 4 seconds. Using 128 thermo-elements distributed over the entire surface of the fire dummy, temperature increases on the 'skin' during flame action can be measured. Measurements were recorded every 0.5 seconds in each area where the thermo-element was located. Based on the temperature data, heat flux was calculated, which was compared to a human skin model to determine whether a burn occurred. Data were collected for 120 seconds, including the first contact with the flame. Following heat and flame activity, parts of the suit were analyzed using a dynamometer, Dino-Lite USB microscope and thermal gravimetric device. Changes in the structure and properties of the material were examined. The research was carried out with the aim of determining and qualitatively calculating the microdamages of the impurities and gases present (Fig. 7) [18].

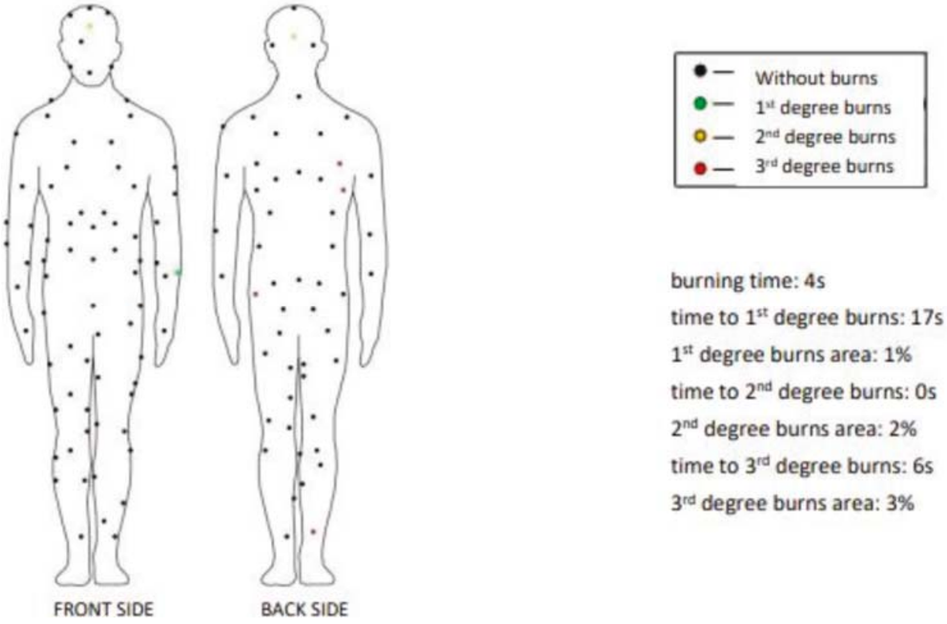


Fig. 7 Computer display of the results obtained from the fire dummy test [18]

Ankit Joshi et al. (2024) investigated the characterization of human exposure to extreme heat using an outdoor thermal mannequin. In the tests, we used a special outdoor thermal mannequin called the “Advanced Newtonian Dynamics Instrument (Thermetrics LLC, Seattle, USA)”. Each area is divided into 35 zones with heating and cooling capability, with each area having a resistive temperature rating (accuracy of ±0.044 °C determined by manufacturer calibration) and heat flow sensors. Each heat flow sensor is custom manufactured and has an accuracy determined by calibration performed by the manufacturer against the heat flow produced by the internal heater [19]. For this thermal dummy, the average absolute heat flux deviation measured from the heat flux generated for 35 sensors was 3.1% (6.2Wm^2) and at most 9% (18Wm^2). The mannequin represents 50% of the western male body, with a height of 1.78m and a surface area of 1.86m2.

The radiation and convection heat exchange on the thermal mannequin's skin at three locations were measured on the Arizona State University campus (Fig. 8). In Tempe, Arizona on clear days from early July to October 2023 (see location maps on SM). These locations represented unobstructed solar radiation and two types of shade (industrial shade under a removable building and natural shade provided by native Palo Verde trees). To calculate the radiation flux absorbed by each region (RaANDIi), the infrared rays emitted from that region to the surroundings were added to the measured net heat flux (2) [19].

$$R_{a\mathrm{ANDI}_i} = R_{e\mathrm{ANDI}_i} - q_{net_i} = \sigma\,\alpha_L\,F_{ie}T^4_{skin_i} - q_{net_i} \tag{2}$$

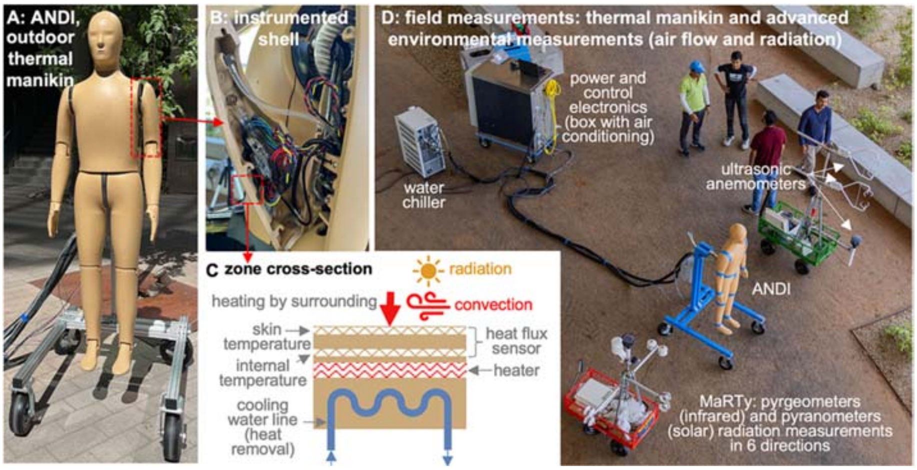


Fig. 8 Thermal mannequin system in the Arizona State [19]

To measure convective heat flow, the skin temperature of the thermal mannequin is kept 5°C below the air temperature. This temperature difference is smaller than the 12 °C specified in the relevant standard for determining the thermal insulation of clothing using a heated thermal mannequin (ASTMF1291-16, 2004) (Fig. 9).

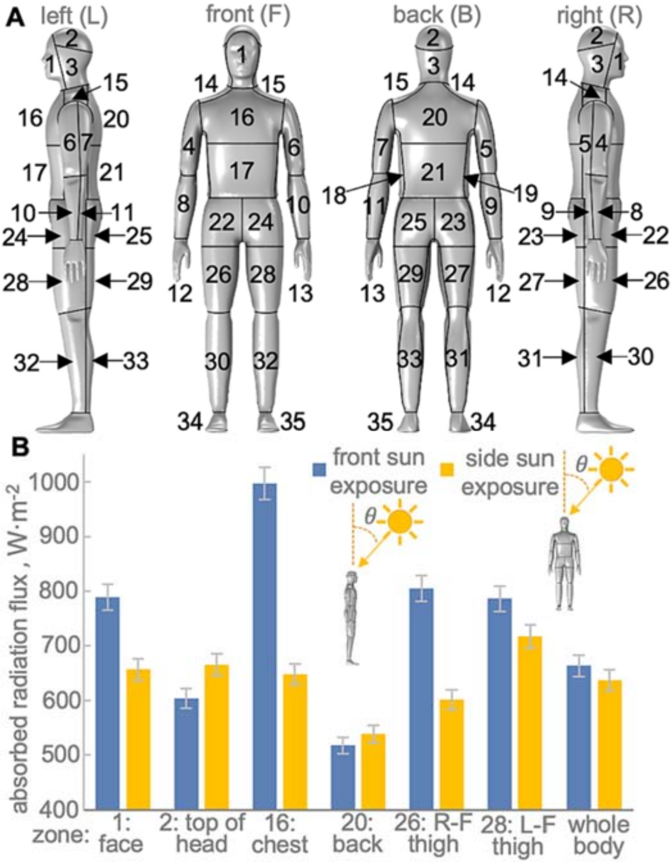


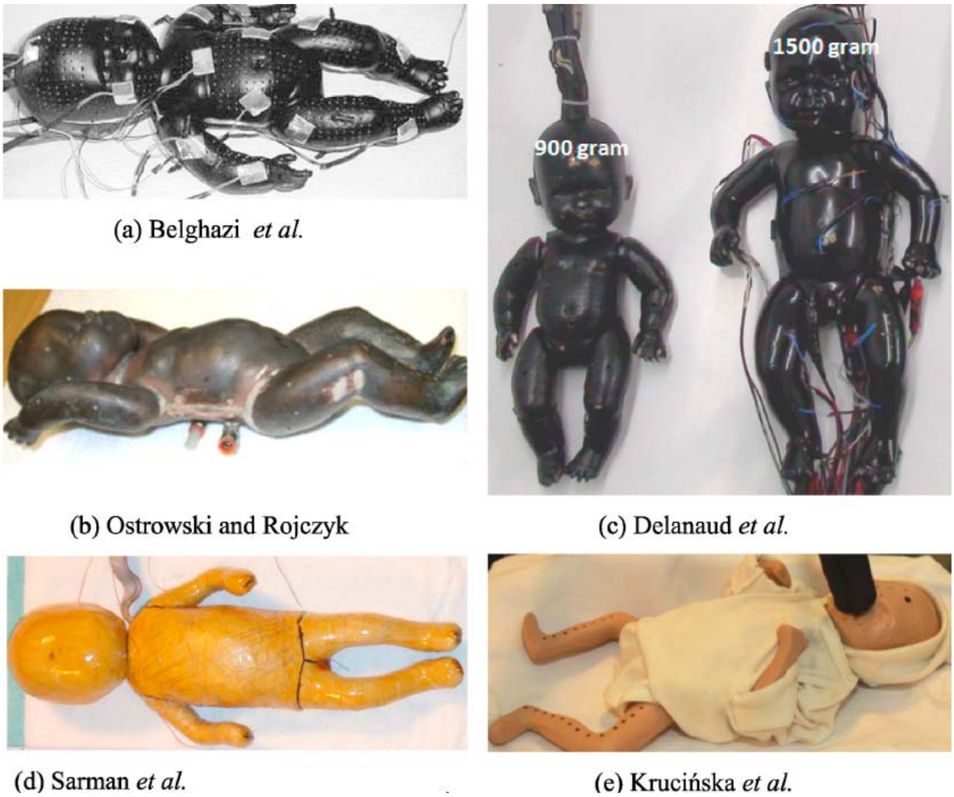
Fig. 9 Temperature measurement on the thermal mannequin system [19]

A bar graph comparing the radiative heat flux (RaANDIi) absorbed in selected frontal and side sun-exposed areas of 35 zones of the thermal mannequin at a solar peak angle of 65°C is as above (values for all 35 zones are shown in SM). Experiments for the two orientations were carried out on separate days but with similar conditions, with maximum directional shortwave radiation of approximately 800 Wm^2 and longwave radiation of approximately 575 Wm^2 [19].

Egeli et al. (2022) produced a thermal mannequin system using 3D printing technology in their study, which will enable the evaluation of important parameters such as thermal, humidity and pressure comfort, which are the most important criteria in determining consumers' clothing preferences, and evaluate them objectively. The thermal mannequin produced to make measurements in different environmental conditions was placed in a climate cabinet. In addition, the thermal mannequin can perform activities such as walking and running by moving it with the dummy mechanism [20]. Fig. 10 shows the movement images of this thermal mannequin.

Fig. 10 Thermal Mannequin System Produced with 3D Printer [20]

The first known neonatal thermal mannequin was developed and studied by Wheldon in 1982 [21]. This mannequin consists of three parts that are a combination of primitive geometries: sphere for the head and cylinders for the torso and limbs. The head is made of thin copper ball, while the body and limbs are made of aluminum. All three sections are heated using electrical resistance wires fixed to the inside of the mannequin. The mannequin can be examined in three different postures: fetal, relaxed, and open eagle [221. Ten years later, in 1992, Sarman et al. developed a more advanced anthropomorphic preterm thermal mannequin consisting of eight sections that were individually heated using resistance wires (Fig. 11-d). The mannequin is made of plastic foam and was used to study the effect of a heated bed in an incubator on reducing heat losses in preterm newborns [22]. Belghazi et al. used the same mannequin and covered its outer surface with wet black fabric to simulate sweating and water evaporation (Fig. 11-a). Thus, they were able to obtain the evaporative heat transfer coefficient under different flow conditions by varying the air velocity, temperature and relative humidity [23]. Latent heat transfer was also evaluated by Kruci'nska et al (Fig. 11-e) [24]. They used a more advanced preterm sweating thermal mannequin. The mannequin consists of seven sections with 450 miniature moisture emission ports on its outer polymeric coated surface. Humidity ports are equipped with the correct regulation for water flow [25]. Ostrowski and Rojczyk built a one-piece copper cast mannequin (Fig. 11-b). Hot water circulates inside the thermal mannequin to heat the mannequin, and an advanced digital controller embedded in the heat pump system is used to control the temperature [26]. Delanaud et al. designed copper infant mannequins, which have different weights, are painted with a thin layer of matt black paint, so that its surface emissivity is similar to that of human skin. Electrical wires placed inside each of the mannequin's members can be used to simulate the regional skin temperature heterogeneity (Fig. 11-b) [27].



(a) Belghazi *et al.*

(b) Ostrowski and Rojczyk

(c) Delanaud *et al.*

(d) Sarman *et al.*

(e) Krucińska *et al.*

Fig. 11 Preterm thermal mannequin types by years [21-27]

Aziza Hannouch et al (2023) conducted a thermal analysis on prematurely born thermal mannequins. In premature birth units, thermal mannequins are essential tools to better understand heat transfer processes in baby incubators. In this study, the 3D printing technique was used to create a new type of thermal mannequin representing a preterm newborn with a gestational age of 35 weeks at the 50th percentile. This mannequin consists of six parts that are heated separately from their inner surfaces using Nichrome resistance wires. The temperature on the outer surface is measured from different positions using J-type thermocouples. The measured temperatures are set as feedback to the proportional integral and derivative regulator, which controls the power input to the heating wires to maintain a constant surface temperature of the different mannequin parts. The mannequin is cared for inside a baby incubator and performs well during the different scenarios analyzed. The effect of air temperature and port opening on convective and radiative heat losses resulting from the thermal mannequin was investigated. The results obtained in this study show a fair agreement with the results obtained in the open literature on other types of virtual and real thermal mannequins [28]. In this study, a new approach is presented for the production of thermal mannequins representing a premature baby (Fig. 12 and Fig. 13). The mannequin is heated from its inner surface using electrical cables, and the temperature on the outer surface is controlled through a PID regulator created using LabVIEW. An anthropomorphic mannequin was designed to represent a moderately preterm baby with a gestational age of 35 weeks.

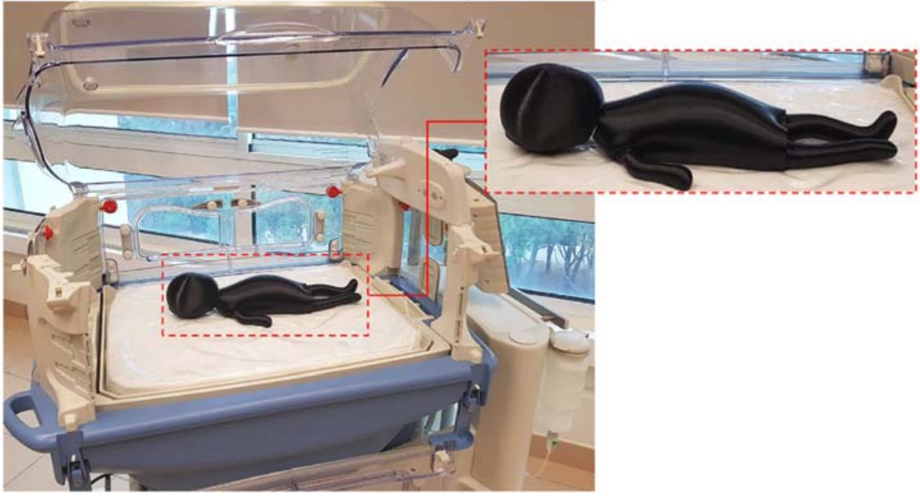
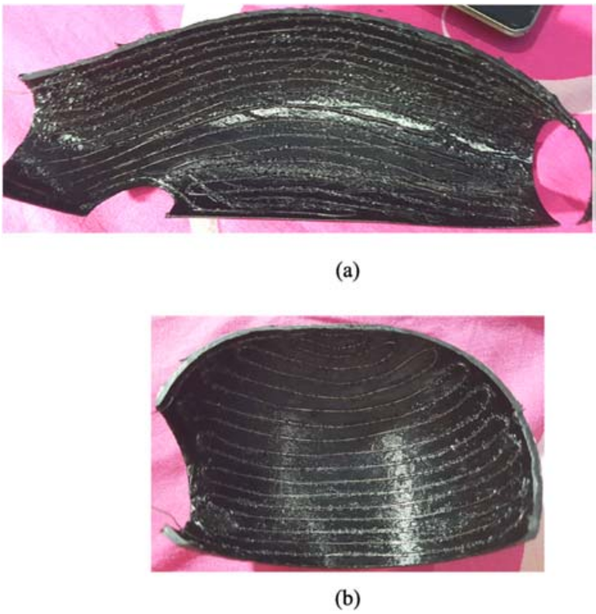


Fig. 12 Preterm thermal mannequin named Calor [28]

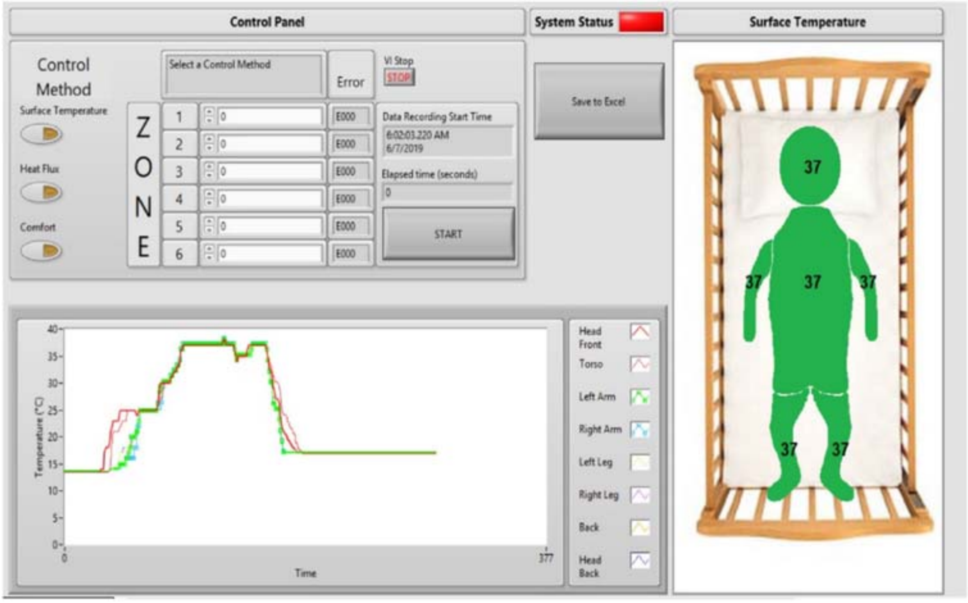


(a)

(b)

Fig. 13 Heating wires fixed to the inner surface of the thermal mannequin for (a) left chest part and (b) left head part [28]

Heating of the thermal mannequin is done using a constant power supply connected to Nichrome heating wires. It was done by fixing heating wires to the inner surface of the mannequin. During the soldering process, the thin plastic layer on the inner surface of the mannequin will melt around the wire and then become embedded into the part. This method allows the wires to be embedded inside the mannequin, the inner surface increases, therefore the contact area increases, which causes the contact thermal resistance to decrease. Heating wires are placed on the inner surface of the mannequin at intervals of maximum 5 mm within each segment for the chest and head part of the thermal device. LabVIEW was used to implement the controller into the system by creating a virtual appliance (Fig. 14). Input is taken from DAQ, which measures the real-world physical conditions of the system. The temperature is measured using thermocouples and the resulting data is converted into digital numerical values that work as input for the controller (Fig. 15) [28].



ZONE		Error
1	0	E000
2	0	E000
3	0	E000
4	0	E000
5	0	E000
6	0	E000

Data Recording Start Time: 6:02:03.220 AM 6/7/2019

Elapsed time (seconds): 0

Fig. 14 LabVIEW graphical user interface showing temperatures set for different body parts, heating method used, and real-time graph of temperature change [28]

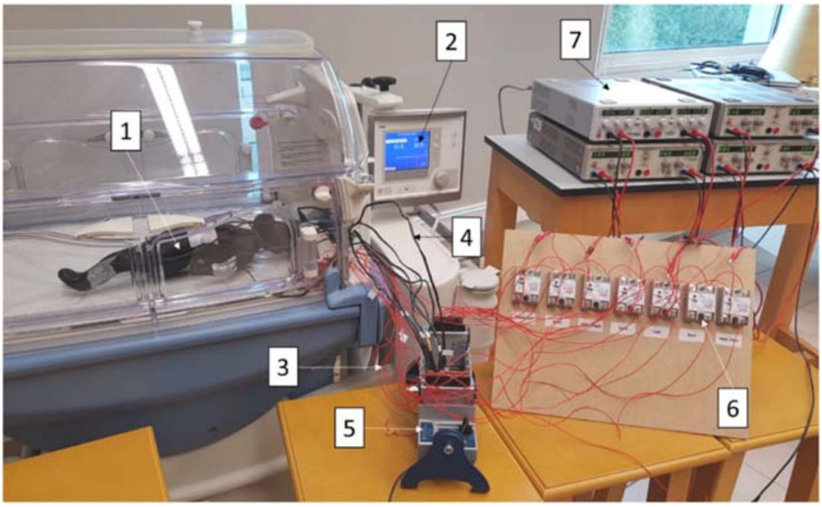
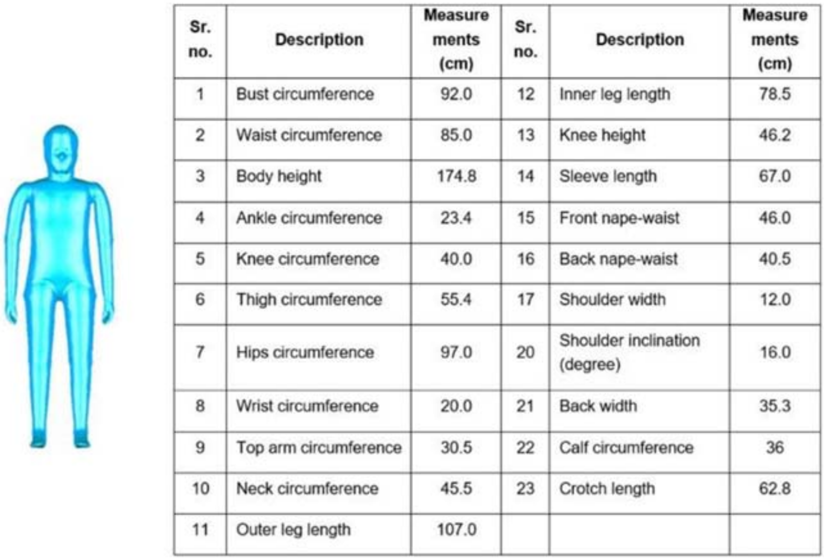


Fig. 15 Thermal mannequin inside the baby incubator (1), incubator temperature and humidity control panel (2), heating wires (3), thermocouples (4) connected to DAQ (5), experimental setup showing the SSR panel (6) and power supplies (7) [28]

Awais et al. (2024) presented a methodology for the simulation of clothed thermal mannequin in controlled environmental conditions. They investigate thermal simulation and modeling methods as an alternative to traditional thermal testing of clothing, which typically relies on the use of thermal mannequins. The thermal mannequin was scanned prior to sewing the clothing system in a standard body posture. The scanned data was collected, processed, and used to create a polygon model. Fig. 16 illustrates the polygon models of the thermal mannequin.



Sr. no.	Description	Measurements (cm)	Sr. no.	Description	Measurements (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. 16 Thermal mannequin polygon model and the measurements [29]

These patterns were then imported into 3D CAD software for fit simulation. A virtual model of the thermal mannequin and the garment was created to facilitate the thermal simulation. Prior to conducting the simulation, the air gap between the garment and the mannequin's surface was measured (Fig. 17).

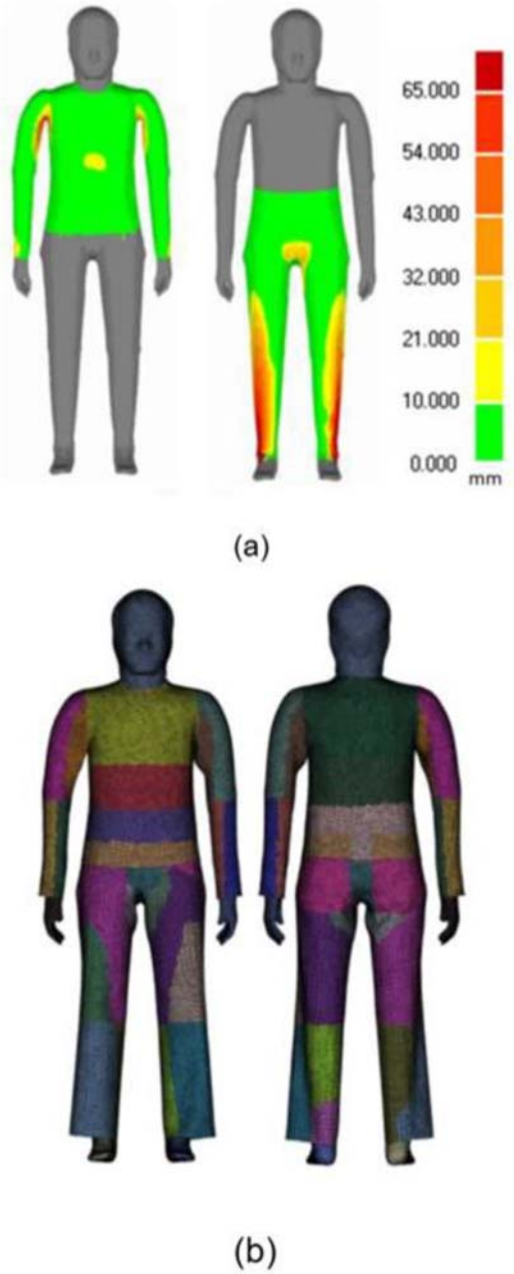


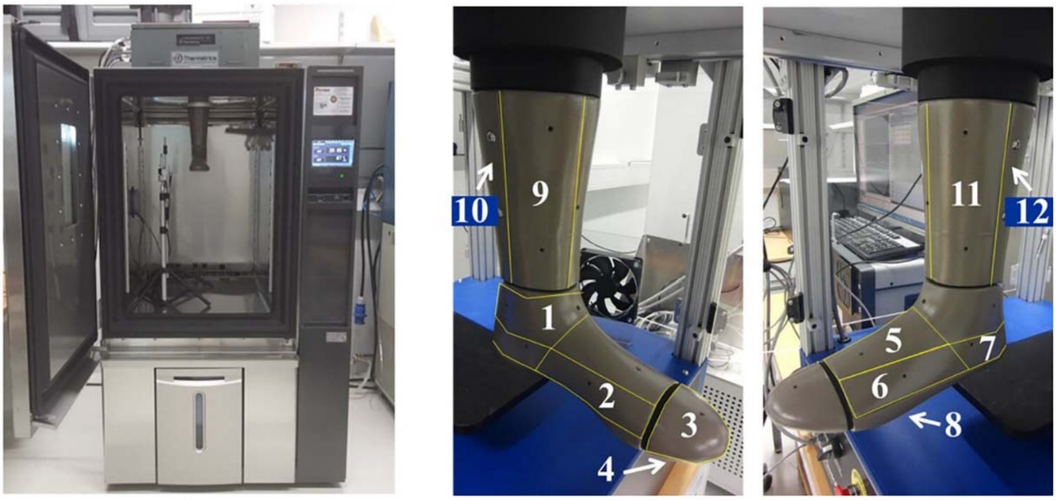
Fig. 17 Air gap analyses of thermal mannequin [29]

The mesh models of the thermal mannequin and the garment were imported into the Theseus-FE software for thermal simulation. This process considered the thermal properties of the clothing, environmental conditions, air gaps, and corresponding heat transfer coefficients. The simulation involved segmenting the air gaps into distinct zones, calculating heat transfer coefficients, and assigning thermal properties to accurately model radiative and convective heat transfer. Additionally, wear trials were performed using the thermal mannequin [29].

Apart from these, some studies have developed thermal foot mannequins to provide the opportunity to measure socks and shoes to be used in different climatic conditions. Kaplan and Karaman (2018) introduced a thermal foot mannequin system to measure the thermal performance of socks [30]. The thermal foot mannequin composes of 11 segments made of polytetraflorethylene covered with copper. The foot parts were produced with a 3D printer and small holes were created inside each part, 1 mm below the surfaces, suitable for temperature/relative humidity sensors and heaters. All surfaces were coated with copper using electrolytic technology. The mannequin is located in a controlled environment chamber with adjustable temperature, relative humidity and air speed. The controlled environment chamber of the mannequin was set to 10°C, 50% relative humidity and 50 cm/s air speed during the tests of this study (Fig. 18).

Fig. 18 Thermal foot mannequin system [30]

West et al (2023) examined the relationship between thermal perceptions during human wear trials and thermal foot manikin measurements of heat and vapor resistance for five running shoes varying in material and construction. Measurements of thermal/evaporative resistance were performed using a 12-zone sweating thermal-foot mannequin [31]. The sweating thermal foot mannequin for heat loss measurements using a 12 zone as given in Fig. 19. The thermal foot mannequin has a total surface area of 0.1069 m2 and is suitable for testing footwear sized 8.5 UK (42 2/3 EU), left shoe only. The thermal foot mannequin is set within a controlled climatic chamber (width 101 × depth 127 × height 169 cm), allowing for the adjustment and monitoring of air temperature, relative humidity and wind speed during testing.



(a) (b)

Fig. 19 a-Climatic chamber, **b-**thermal foot mannequin [31]

They indicated that the thermal foot mannequin provides an effective and sensitive evaluation of the thermal properties of footwear for use in warm environments and with physical activity [31].

5. Results and discussion

Thermal mannequin systems, though complex, sensitive, and expensive, offer advanced and highly useful features. These systems can measure heat losses due to conduction, convection, and radiation across the entire body surface or specific regions using human-made thermal mannequins. The capability to evaluate each limb and body movement separately depends on the number of movable and measurable parts on the mannequin, with some systems containing more than 30 independently adjustable components. The total body heat loss is calculated as the weighted average of the values measured across all regions. Thermal mannequin systems are capable of producing reliable, consistent, and repeatable results when measurements are conducted under identical conditions.

One of the most commonly used methods for studying the thermophysiological interaction between the human body and its environment is the use of thermal mannequin systems. These systems are capable of measuring the entire surface of the body in both mobile and stationary states, evaluating regional heat and liquid/vapor transfers, and analyzing various environments and conditions. Recent advancements have led to the development of mannequins with enhanced features, such as the ability to sweat at different rates and speeds, simulate breathing, and perform realistic movements while maintaining lifelike shapes.

The first thermal mannequin systems were developed by the American army in the 1940s. Although many mannequin systems that could move in the form of a human body were designed during the development process, simple geometric devices were also produced by researchers to be used in the three-dimensional evaluation of thermal comfort parameters such as thermal resistance and water vapor resistance of fabrics. While the first thermal mannequins produced in thermal comfort research were limited in capacity, today's thermal mannequins are able to imitate humans exactly. Thanks to the thermal regulator system placed inside, it can perform many processes such as sweating and dry air transfer. Thanks to more than a hundred sensors placed on the mannequin, the values are instantly processed into the computer as data. In this way, the product to be tested is put on the mannequin and then thermal comfort values are obtained from the computer. Thermal mannequin systems are the best thermal comfort test systems available.

6. Conclusion

In this article, some of the studies conducted to evaluate the developments in thermal mannequin systems used in clothing thermal comfort measurements are examined and summarized. In recent years, the increase in consumers' expectations from textile products and the fact that comfort has become a priority in clothing preferences have caused researchers and textile and ready-made clothing manufacturers to focus their attention on the production of more comfortable clothing systems. In the coming years, it is expected that thanks to the developments to be made in subjective and objective comfort measurement and evaluation methods and new materials to be produced for the purpose, highly improved designs and products can be produced in terms of comfort in both sportswear and protective clothing. In addition, it is anticipated that the measurement sensitivities and measurement ranges of thermal mannequins, which are the closest measurement system to reality in measuring the comfort perception of the human body, will develop according to the comfort expectations of consumers from clothing and the new textile materials that will be developed. It is hoped that this study will be useful for academicians and industrialists working on clothing comfort and test methods and interested in thermal mannequin systems.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

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