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Thermophysiological models and their applications: A review

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ABSTRACT

The human body's heat exchange and its interaction with the surrounding environment has in the past years been the research focus of a number of disciplines. As a result, a number of human thermoregulation models have been developed since the first was developed in 1970. The aim of this paper is to conduct a review of existing thermophysiological models for the whole body and isolated body segments. The course of the development from simple to more complex models is shown, and most recognized thermal models such as Fiala, Berkeley Comfort Model, Tanabe, and ThermoSem model are concisely described. Furthermore, possible applications of the models in various research disciplines are introduced. In the built environment, the developed models are used as part of the methodology for modelling thermal comfort in buildings.

Contents

1. Introduction

Human beings are homeotherms who regulate their internal body temperature with physiological and behavioral actions. The nature of the human body is to maintain a constant body core temperature under different thermal disorders. Under adequate conditions, a constant core body temperature of 36.5 °C [1] is maintained within a narrow range between 36 °C – 38 °C (normal range at rest), and up to 41 °C for heavy exercise [2]. Body temperature regulation represents the balance between heat production from metabolic sources and heat loss (evaporation, radiation, convection, and conduction). Exposure of the human body to extreme environmental conditions can result in poor regulation of the core body temperature thus inducing hyperthermia and hypothermia. In addition, if the body core temperature exceeds the normal narrow range, human body functions could be severely affected [3].

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The human body is a thermodynamic machine that is subject to the fundamental laws of thermodynamics. As a result of human metabolism, thermal energy is emitted and according to the second law of thermodynamics the metabolism heat production undergoes a heat dissipation process [4]. Through history, thermal reactions of the human body and its interaction with the environment have been the focus of a number of research. In a first attempt by Lefevre in 1911, the human body was modelled as a sphere with a core that exchanges heat with the environment (as presented in Ref. [5]). In 1934, Burton presented the first mathematical thermal model that included the human body anatomy and control functions (as presented in Ref. [6]). Since then many different human thermal response models have been developed.

People encounter different thermal conditions on a daily basis in the built environment. The ability to predict human thermal responses in different environmental conditions was the main incentive for developing thermophysiological models [7]. Thermophysiological models are mathematical descriptions of physiological responses and the complex heat transfer of the human body under different environmental conditions [8]. For understanding the human thermoregulation reactions that maintain the deviation in the core temperature, these models are valuable tools [9]. Thermophysiological models are part of the prediction method for evaluating thermal comfort and sensation. The calculated output of the thermophysiological model (core and skin temperature) are used as input for thermal sensation models that predict thermal comfort and sensation. The development of the advanced thermoregulation models started at the United States National Aeronautics and Space Administration (NASA) and the United States army for the sole purpose of assessing the effect of extreme environmental conditions on the human body [10]. In recent years, various thermophysiological models have been developed to improve the prediction of thermal responses of building occupants. The most referenced includes models developed by Tanabe [11], Fiala [7,12,13], the Berkeley Comfort Model [14,15] and ThermoSEM [16,17].

Due to the fact that human extremities play an important role in human body's thermoregulation, and they are the most affected during cold exposure; research has also been directed towards modelling human heat balance for isolated body parts. A variety of models simulating the thermal responses of human extremities and different body parts have as well been developed (Worrall [18], Deshpande [19], Ferreira [20], Shitzer [21]).

Despite all this development, the application of thermophysiological models, as part of the methodology for predicting thermal sensation, is still not recognized by international standards. This is related to the fact that there is still doubt about the predictive abilities of the models, and their application limitations [7,12,22]. The uncertainty of the model's predictability is questioned because validation of the models is often carried out by the developer's own experiments rather than with independent experimental data [9]. Therefore, further research is required before the models can be applied in the built environment for the prediction of thermal comfort and thermal sensation encountered in the indoor thermal environment.

In reviewed publications, a few review papers were found which mainly focused on thermal comfort, such as [4,22–26]. These articles discussed the thermophysiological models in relation to the human thermal comfort research. In this paper, a review of various thermophysiological models is presented, and attention is given to the application and further possibilities of the models. The aim of this literature review is to give a comprehensive overview of thermophysiological models and to discuss the application of the models and the gap between simulated results and practical application in the built environment.

2. Methodology

The review is divided into several sections. In Section 3 a historical overview of the development of thermophysiological models is described. Furthermore, several well-known models were concisely described to provide insights into the features of the models and how the models were developed. In Section 4 studies regarding thermophysiological models of the isolated body parts are introduced. In Section 5 a few applications of the models are given. Lastly, Sections 6 and 7 presents in detail the most relevant discussion points and conclusions of the paper.

A search for scientific publications was performed in the following scientific databases: Science Direct, Web of Science, PubMed and Scopus. Three combinations of keywords were used in the search: "thermophysiological model and thermal comfort", "human thermoregulation and thermal comfort" and "bioheat model and segment". Search results for all databases were sorted by relevance. Total general search in all databases resulted in 2437 papers. The search was then refined to only English articles published in journals. In addition, in Science direct and PubMed the search was limited to papers published from 1930 to 2015, in Scopus and Web of Science from earliest year possible, 1960 and 1945 respectively. Additionally, the search was refined using filters in each database. In Science Direct, the search was refined to journals Building and Environment, International Journal of Heat and Mass Transfer, Energy and Buildings, International Journal of Thermal Sciences, Renewable and Sustainable Energy Reviews. In PubMed, the articles were limited to studies with humans. In Web of Science, search domain and research areas such as physiology or engineering, and biophysics or thermodynamic were used as filters to refine the articles. To refine the search in Scopus, the focus was on subject areas such as Medicine, Biochemistry, Genetics and Molecular Biology, Health Professions, Engineering, Computer Science, Energy, Immunology and Microbiology and Mathematics.

After duplicates were eliminated, the refined search for "thermophysiological model and thermal comfort" resulted in 91 papers. "Human thermoregulation and thermal comfort" resulted in 430 papers. "Bioheat model and segment" resulted in 60 papers.

Based on the title, 120 papers were downloaded. After reading the abstracts, 50 full papers were read. In the end 30 articles were included in the review, which were relevant to the topic and related to thermophysiological models and the application.

Furthermore, "snowballing" method was used where reference tracking was performed. The reference lists of all full text papers were scanned, and an assessment was made to select the papers that were pursued further. For "snowballing" method, paper tracking was conducted in previously mentioned databases and additionally in eScholarship-University of California and Online Journal of Applied Physiology. For non-digitally available dissertations and books, The Eindhoven University Library was browsed. "Snowballing" method resulted in 51 papers that were included in the review. "Personal knowledge" method was also used, where existing resources, personal and academic contacts were used to search for published literature. With "Personal knowledge" method, 12 papers were obtained and included in the review. "Serendipitous discovery" method was also part of the process, where relevant papers were found when searching and reading something else. "Serendipitous discovery" resulted in three papers that were included in the review. The resulting articles were thoroughly reviewed for the purpose of this study.

The conducted review that focuses on thermophysiological models will start with the introduction of the models, their historical development, and several models will be described in more details.

3. Thermophysiological models

Thermal comfort is described as the condition in which 80% or 90% of people do not express dissatisfaction [27,28]. The history of thermal comfort discipline dates back to Blagden [29] and his use of thermometer during experiments that evaluated the ability of people to withstand high temperatures. Furthermore, in 1916 Sir Leonard Hill introduced kata-thermometer that can take dry and wet temperature readings [30]. To determine the effects of air temperature and humidity on thermal comfort Houghton and Yaglou presented an empirical index called “effective temperature” in 1923 (as presented in Ref. [31]). Furthermore, Vernon and Warner [32] introduced the “corrected effective temperature” in 1932 that allowed radiation to be taken into account. The wet-bulb globe temperature index was developed by Yaglou and Minard in 1957 (as presented in Ref. [31]). Dufton [33] defined the “equivalent temperature” in 1929 and Gagge et al. [34] introduced the correction of the “equivalent temperature” in 1971, which was more accurate and took into account activity, clothing and radiation exchange. During the 60s and 70s, Fanger steered thermal comfort research towards the relationship between human physiological parameters, physical environmental parameters and the perceived thermal comfort [35].

One of the most applied models in thermal comfort studies is the PMV (the Predicted Mean Votes) model based on Fanger’s equation for human body heat exchange [3]. An extensive review on Fanger’s research and PMV model was conducted by Hoof et al. [36]. Fanger’s postulation was that human satisfaction or dissatisfaction with the thermal environment is a result of the combination of six variables: activity level, thermal resistance of the clothing, air temperature, mean radiant temperature, relative air velocity and water vapour pressure in ambient air. In developing the model, heat balance theories and the physiology of thermoregulation were combined to determine a range of thermal conditions in which building occupants would feel comfortable. A general comfort equation was empirically obtained and it assumes a linear relationship between activity level and sweat rate, as well as activity level and mean skin temperature. These relationships were used in formulating the human body heat balance equations. Using the proposed equation, it was possible to calculate the combination of these six variables and to determine thermal comfort conditions in which occupants should feel thermally neutral for any activity level and clothing [35]. Fanger’s empirical model has been generally used in practice in building design process as index for maintaining indoor thermal comfort [8]. The predicted mean votes (PMV) are expressed on the 7-point ASHRAE thermal sensation scale and widely accepted and used [8]. In the PMV model, the body is treated as a whole and the model is used for predicting responses in the steady-state air-conditioned environment. However, the environments where humans carry out their daily activities are often nonuniform and transient. Previous research showed that in these type of environment thermal sensation of the local body parts strongly influences the whole body thermal comfort [37]. In response to these findings, the development of thermophysiological models has gained more importance. The models like Berkeley Comfort Model, Tanabe and ThermoSEM are able to predict the skin’s temperature for different regions of the human body and the body’s core temperature [22] under asymmetric environmental conditions [8].

The thermophysiological models include two systems (see Fig.1), a controlled passive system and the active system [7]:

- The passive system simulates the physical human body and models heat transfer within the human body, and between the human body and its environment [13]. Heat is continuously generated in the human body by metabolic processes and distributed over the body areas by blood circulation. For the calculation of internal heat transfer and body heat exchange, thermal properties of the blood, muscle, fat and bones are critical parameters [38]. Through the body tissue layers, heat is transferred to the clothing insulated body surface by conduction [7]. Heat is then exchanged with the environment through a complex combination of conduction, convection, radiation and evaporation [39]. The clothing worn by humans is an influential factor on heat exchange with the environment as well.
- The passive system is controlled by a human body’s active system [9] in order to regulate temperature in a changing environment [14]. The active system simulates the human body’s regulatory responses of vasoconstriction, vasodilation, shivering and sweating [12]. The mean skin temperature, core temperature and the rate of the change in skin temperature are the main signals for the active system [13]. The change in brain temperature above the set point results in vasodilation. When vasodilation is not sufficient to lose heat from the body, sweating is activated for the heat losing process. Vasoconstriction is a result of reduction in the skin temperature [38]. However, if the body is exposed to a cold environment and vasoconstriction is not enough to maintain the heat in the body, the body will start to shiver in order to retain heat. Furthermore, the skin blood flow is controlled by the mechanisms of vasodilation and vasoconstriction.

The thermal balance of the body is influenced by local environmental conditions and individual physiological characteristics. The environmental parameters (air temperature, mean radiant temperature, air velocity and relative humidity) and human physiological inputs (metabolic rate, height, weight, fat percentage, blood flow rate, gender, skin surface area etc.) serve as model inputs (Fig. 2). As output, the models are able to predict local skin temperature and the body’s core temperature.

Thermophysiological models can present the human body as a single segment or the body can be divided into several body parts. Furthermore, the models can be classified as one-node thermal models, two-node thermal models, multi-node thermal models and multi-element thermal models [5]. Fig. 3 [6,23] presents different thermophysiological models, from simple to more complex models.

One-node models are empirical models that predict thermal responses based on formulas that were derived from experimental conditions. These models simulate a human body as one unit and the thermoregulatory system is not included in the model. Givoni and Goldman developed a one-node model for application in hot environments in 1971. In their model the equations for the metabolic costs of walking, running and carrying load were proposed [5] [41].

In two-node models, the human body is divided into two concentric shells of core and skin and the temperature of each shell is considered uniform. Gagge’s model is a well-known example of two-node thermal models. The model was developed in 1971 [34] and improved in 1986 (as presented by Foda and Sirén [42]). The model is fit to simulate the skin and core temperatures under uniform and transient environmental conditions with moderate activity levels [6,43]. The body is simulated as two concentric cylinders, the outer layer of skin and the inner cylinder that presents the body core (Fig. 4). In the two-node Gagge’s model, the temperature within each compartment is assumed to be uniform. Skin and core temperatures are simulated with a physiological model that includes heat transfers between two layers, and between the outer layer and the environment. The heat transfer of the body is controlled by the thermoregulatory control functions for sweating,

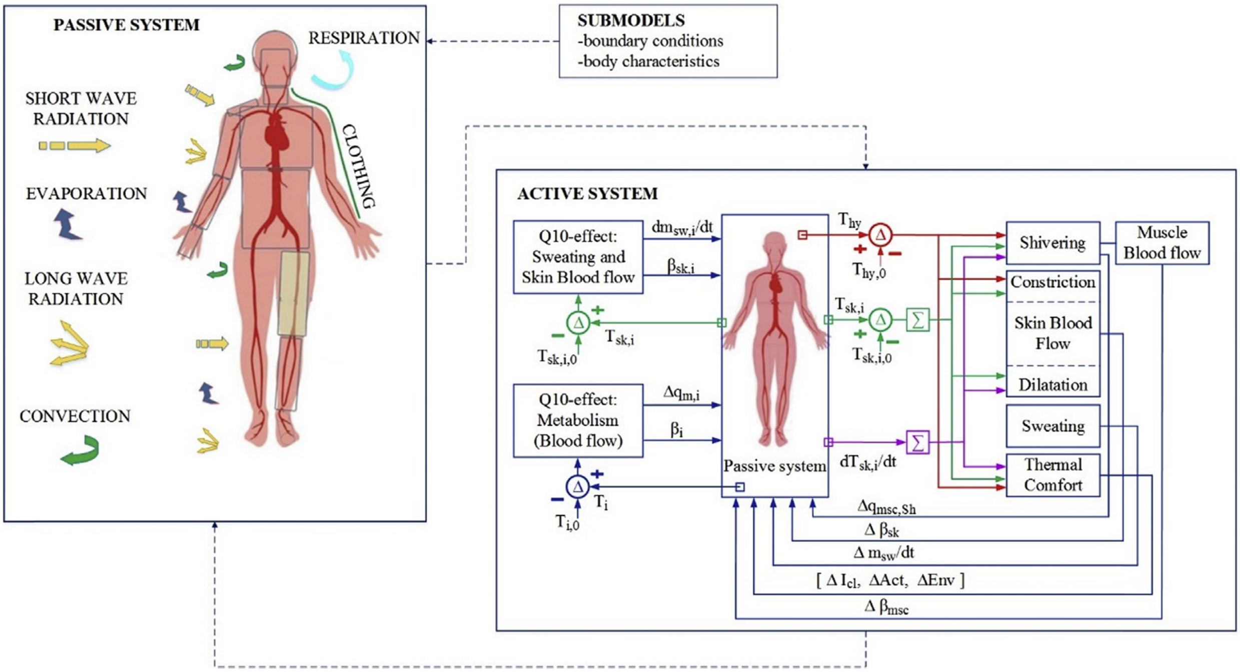

Fig. 1. Schematic diagram of the thermophysiological models (modified from Fiala et al. [13] and [40]).

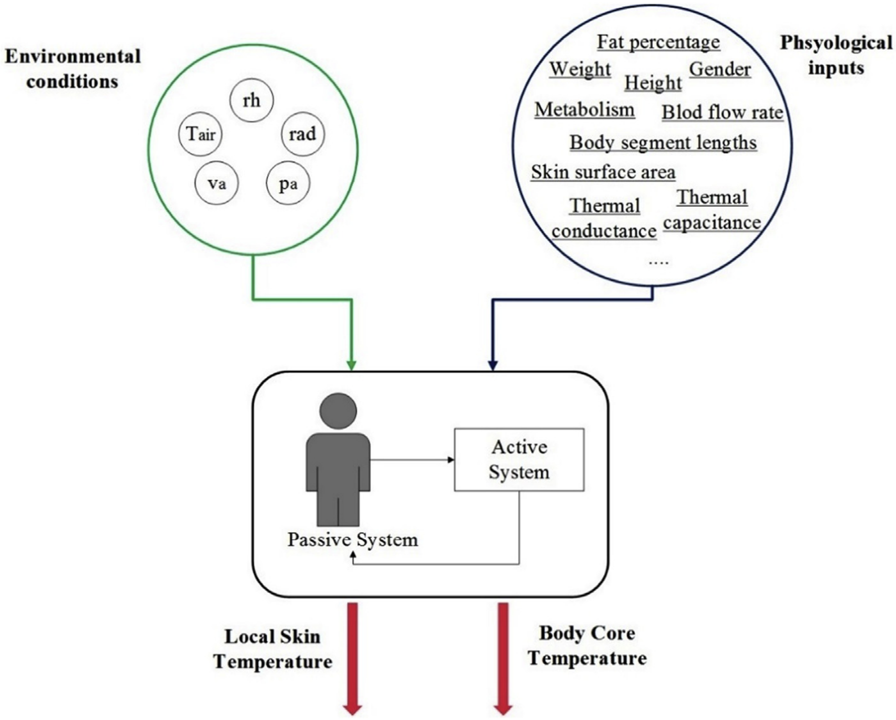

Fig. 2. Schematic view of the inputs and outputs for thermophysiological model.

vasodilatation and vasoconstriction, and shivering [43]. Zolfaghari and Maerefat developed a two-node model combining the Gagge model with Pennes equation [43]. Other examples of the two-node models are: a single segment model developed by Kingma et al. [44], a dispersed two-node model developed by Kohri and Mochida et al. [45], a two-node model for different body parts developed by Foda and Siren et al. [42], a two-node model developed by Takada et al. [46] and a two-node model for different body parts developed by Kaynakli and Kilic [47,48]. As it was mentioned above, two-node models represent body as skin, and a central core that represents muscle, subcutaneous tissue and bone. If more detailed temperature distribution is acquired, the body should be divided into more than two nodes that will represent every tissue separately.

Multi-node human thermal models are extended and more intricate versions of the two-node model. The first multi-node

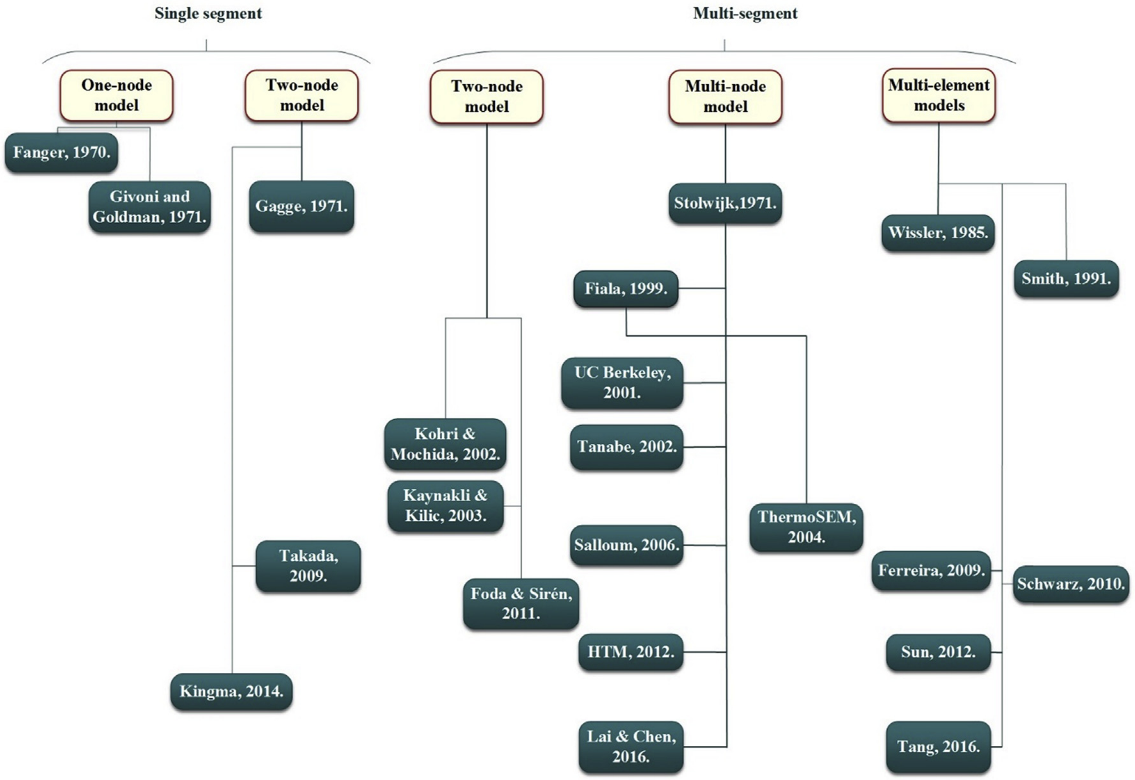

Fig. 3. Schematic diagram of the development of thermophysiological models through the years.

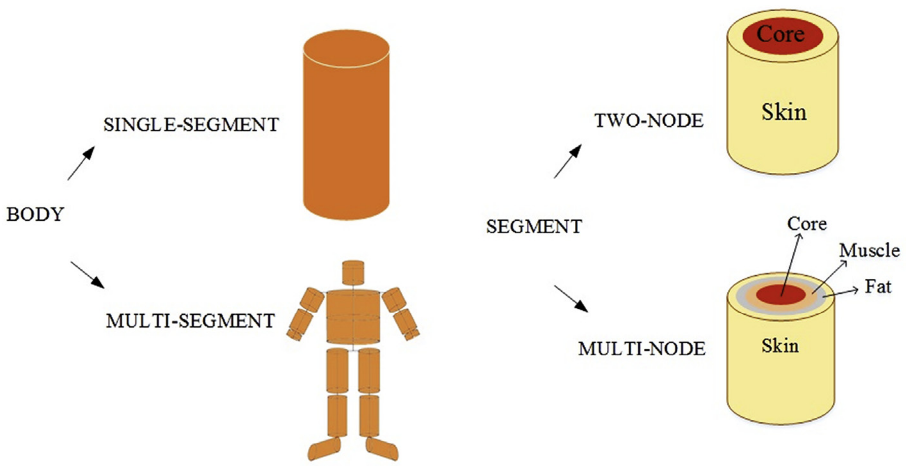

Fig. 4. Comparison of the model segmentation, and the two-node models and multi-node models.

model was developed by Crosbie [49] and this was the first time that analogue computer was used for the simulation of physiological temperature regulation of the human body [49]. Multi-node models consider an inhomogeneous distribution of temperature and thermoregulatory responses over the body's surface. Vasoconstriction and vasodilatation dispense blood flow to the extremities to control the heat loss from the skin to the environment [3]. Multi-node models with advanced vasomotion models are able to simulate the local skin temperatures of individual body parts (Fig. 4).

The most influential multi-node model that paved the foundations for many human thermal-modelling studies was developed by Stolwijk [50]. The 25-node thermoregulation model was developed for NASA during the Apollo program in order to create a mathematical model that can predict thermal responses of astronauts while performing their activities in space outside a spacecraft [51]. The model was developed for investigating changes during heat stress situations. Although the control equations for cold exposures were included, predictability during the cold exposures was limited and the model is restricted to constant environment conditions [51].

The passive part of the Stolwijk model consists of six segments (head, trunk, arms, legs, hands and feet) and each segment is divided into four layers: the core, fat, muscles and skin [10]. The model includes a central blood compartment at a uniform temperature (without distinguishing arteries and veins flow) that is thermally connected to all the other nodes. The effects of countercurrent heat exchange in the blood flow and the blood flow characteristics in local tissue are not included in the Stolwijk model. The control system (active system) is presented as functions of two tissue temperature signals, hot/cold signal and rate of tissue temperature change signal [52]. The constant temperature blood node exchanges heat with the tissue layers by convection only, while the tissue layers' exchange heat in the segment by conduction only. The Stolwijk model accurately predicts both the absolute and the tendency of the transient mean skin temperature of an "average" person under low activity conditions [53]. Stolwijk's approach for modelling the active system is still used in most of the recent advanced models, such as Tanabe model and Berkeley model. In 2009. Munir et al. [53] presented re-evaluation of Stolwijk's 25-node human thermal model under thermal-transient conditions. Other examples of the multi-node models are Tanabe model [11], Fiala model [7,12,13], Berkeley Comfort Model [14,15], ThermoSEM [16,17], Salloum et al. model [52], Al- Othmani et al. model [54], Novieto model for elderly people [55], Zhou et al. model [56], Lai and Chen model [57] and Dongmei et al. model for sleeping person [58].

According to the classification, the last type of models are multi-element models. Multi-element thermal models in contrast to the multi-node models simulate the human body as several body parts, and no further division is made into nodes. The assumption of uniform node temperatures is not applied and most of the body's different geometric properties are included. All this information must be available thus making these models the most complicated ones [5,6]. Wissler developed a mathematical multi-element model in 1985 [51] that is primarily a thermal model but it also contains mass balances for oxygen, carbon dioxide and lactic acid in ventilation. His first model from 1961 [59] was based on Pennes [60] steady state heat conduction equation and the body was presented as a human thermal system consisting six cylindrical elements. The improved model has detailed passive system that consists of 15 elements connected by the arteries, veins and capillaries. The heat loss through the respiratory system is considered, as well as the countercurrent heat exchange between arteries and veins. One of the limitations of the model is that in each cylindrical element, an axial symmetry had to be assumed because of lower memory capacity of the computer at the time. Nowadays this assumption can be dropped. The model is capable of describing human responses under thermally demanding conditions [51]. Other examples of multi-element models are Ferreira et al. [61], Sun et al. [62], Schwarz et al. [63] and Tang et al. [64].

Recent advanced models are modifications and improvements of the Stolwijk model. Table 1 summarizes the main characteristics of recently developed advanced thermophysiological models that will be reviewed in the following paragraphs.

The Fiala model is a multi-node model that extensively simulates the human body including the predictions of overall and local physiological responses. The model presents an average person with a detailed multi-layered structure of the human body that makes it possible to avoid errors during transient conditions due to the use of lumped data. The body division into layers was made whenever a change of a body tissue properties is present in the human body [7]. The environmental heat exchange was modelled including local heat losses and gains from the body by free and forced convection, solar irradiation, long-wave radiation, evaporation of moisture from the skin and insulation effect of the clothing [7].

The active part that models the thermoregulatory control reactions is included in the Fiala model. When in the state of thermal discomfort, the human body copes with thermal stress by physiological adaptation in order to acclimatize. The body's thermoregulatory control mechanisms are activated when the body is in a state of discomfort. The methodology for modelling essential regulatory responses of the central nervous system is based on a regression analysis of the physiological response of unacclimatised subjects (Fig. 5).

The first step in modelling the active system is to select the adequate physiological experiments from literature that contain sufficient information about boundary conditions and physiological variables. Several experiments were chosen that cover wide ranges of steady state and transient ambient conditions (sever cold, cold, neutral, warm, and hot) and exercise intensities. For each experiment, the passive system was exposed to experimental boundary conditions. Thermoregulatory responses observed in experiments were imposed on the passive system for each moment of exposure. This simulation forms the basis for establishing the line of thermophysiological variables and the measured regulatory responses were subjected to a multi-linear regression to obtain control equations. Furthermore, equations were implemented into the model and re-simulated with experimental data to determine further control equations. The validation of the core and skin temperatures, and thermoregulatory responses are well correlated with the experimental data that cover a wide range of environmental exposure (moderate, hot and cold stress) and activity levels [12].

The UC Berkeley multi-node model is based on the Stolwijk model and the Tanabe model. In developing the model, 16 body segments were used. An advantage of this model is that fine segmentation can be used in environments with local temperature variations. The blood compartments are represented as a separate series of nodes that are responsible for heat transfer between segments and tissue nodes [15]. Thermoregulatory responses of vasomotion, sweating and metabolic heat production are explicitly considered. Table 2 shows that apart from the ability to model an unlimited number of body segments there are several other improvements that have been made compared with the Stolwijk model.

The physiological differences between individuals (height, weight, gender, body fat, hip, neck and abdomen dimensions, and skin color) influence thermal responses. The approach of the Berkeley team is to incorporate the body builder model [14]. The model defines a set of physiological parameters which can be used to study variations in thermal response between different body characteristics [14].

The model was validated by comparing the model results (skin temperatures) with studies from other scientific studies. For steady state conditions, results from Werner et al. were used [65], for transient conditions studies from Raven et al. [66] and Stolwijk and Hardy et al. [67,68] were employed for model validation. The validation shows the acceptable accuracy of the core temperature and extremities skin temperature under a range of environmental conditions.

Among the models that were developed based on Stolwijk model are three thermoregulatory models developed by Tanabe and his associates; 65 MN, 3DM and Jointed Circulation System (JOS) model [69]. The Tanabe 65-node thermoregulation model (see Fig. 6), that represents an average man is able to predict the variation of physiological conditions for various parts of the body [11]. The 65th node in the model represents the central blood compartment. As a part of the passive system, heat equations for each layer were calculated and the heat balance between local tissues and central blood pool was simplified. The physiological reactions were formed using control equations that contained sensor signals relating to the head core signal and integrated signals from skin thermoreceptors [11].

Table 1
Characteristics of recently developed thermophysiological models.

Model	Description	Body characteristics	Environmental conditions	Active system
Tanabe 2002 [11].	- 16 segments - 65-node - Four layers: Core, muscle, fat and skin	Average man, physical parameters can be changed	Transient and non-uniform conditions	Based on Stolwijk
Fiala 1999 [7,12].	- 15 segments - 187-node - three sectors: anterior, posterior and inferior - Seven tissues: brain, lung, bone, muscle, fat, skin and viscera	Average person	Steady-state and transient conditions	Regression based
UC Berkeley 2001 [14] [15],	- Multi-node (arbitrary number of segments) - Five layers: core, muscle, fat and skin + clothing layer	Body builder -individual physiological differences	Transient and non-uniform	Based on Stolwijk
ThermoSEM 2004 [16,17].	- Multi-node - 19 segments - Spatial subdivision: anterior, posterior and interior	Individual differences (height, weight and fat percentage) are taken into account	Transient and non-uniform conditions	Incorporates neurophysiology of thermal reception in the skin blood flow model

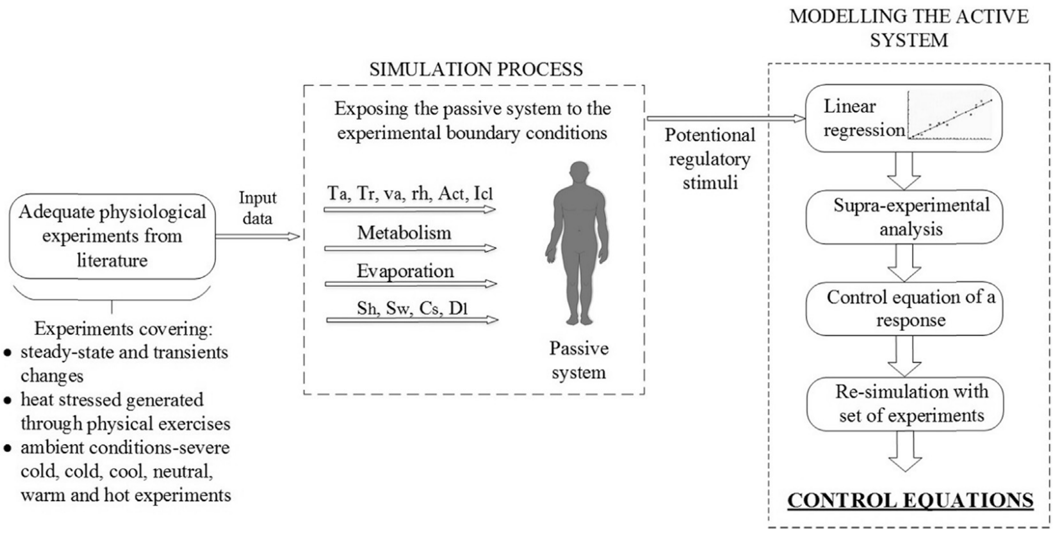

Fig. 5. Modelling thermoregulatory control mechanisms in Fiala model (modified from Ref. [12]).

Table 2
Improvements and addition to the model compared to Stolwijk [15].

Improvement	
Stolwijk	UC Berkeley
- Six body segments	- Can simulate arbitrary number of body segments
- Arterial blood flow temperature assumed to be uniformed	- Central artery/vein counter-current heat exchange
- Simplified heat exchange local tissue-blood	- Improved estimation of the blood flow to local tissue
- Combined convection and radiation heat transfer coefficients	- Model separates convective and radiative heat transfer
Addition in the UC Berkeley model	
- Clothing node for modelling heat and moisture capacitance of clothing	
- Body segments exchange heat by conduction to surface in contact with the skin or clothed skin	
- Radiation heat flux model is separated into short wave and long wave radiation components	

In 2013, the Jointed Circulation System-2 (JOS-2) model was introduced that could be applied to women and elderly under transient and non-uniform conditions [69]. JOS-2 simulates the human body divided into 17 segments. The head segment consists of two layers in contrast to other body segments. The reason is that the human head is directly exposed to the environment and has to quickly respond to any thermal changes in the surroundings [69]. All the body segments have artery and vein blood pools; core layer and skin layer. Also, superficial veins and arteriovenous anastomoses (AVA) are included in the vascular system of the limbs. With different percent of openness, AVA controls the blood flow to the

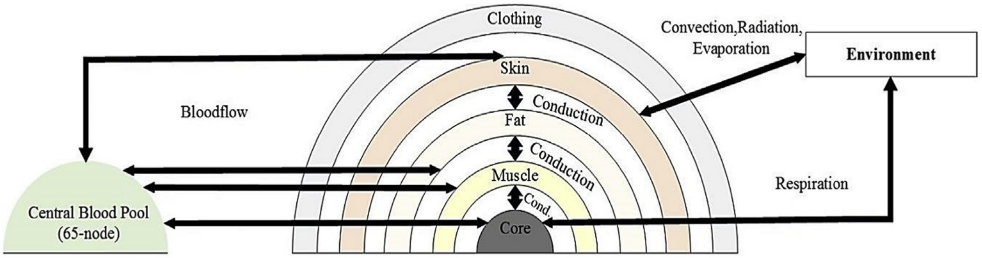

Fig. 6. Concept of the one segment in 65 MN model.

vein blood pool [69]. With increasing age, the physical activity level in the elderly is reduced. This causes lower cardiovascular reserve and a lower capacity for thermoregulation [70]. Gender difference affects thermal preferences as well [71] and individual body characteristics (fat percentage, weight, height) influence the thermal state of the body [8]. As the heat characteristics of the human body depend on height, weight, sex, age, body fat percentage, basal metabolic rate and cardiac index these physical parameters in this model can be changed [69]. The model was validated for stable conditions, non-uniform and transient conditions. For validating predicted core and skin temperatures under stable conditions, the simulation results were compared with the results from subjective tests by Werner et al. [65]. For validating the predicted skin temperatures under transient and non-uniform conditions, the results were compared with subjective tests done by Yoshimura et al. (as presented in Ref. [69]).

The dynamic mathematical thermo-sensation model (ThermoSEM) was developed based on the Fiala model [8]. Like other models, ThermoSEM consists of passive and active components as well, and the model is suitable to simulate transient condition. There are small differences in the passive part of the model in comparison with Fiala's model. In ThermoSEM, the extremities were split into upper and lower parts and the skin perfusion was corrected for tissue volume [72]. The human body segments were spatially subdivided into three sectors: anterior, posterior and interior sector. With this subdivision, the asymmetric boundary conditions could be taken into account [16]. Within the body, heat transfer by conduction and convection was modelled with Pennes' Eq. (a) [60], and calculation for heat transfer between the body and environment are based on Fiala et al. [16].

$$\rho c\frac{dT}{dt} = k\left(\frac{d^2T}{dr^2} + \frac{g}{r}\frac{dT}{dr}\right) + q_m + q_{bl}w_{bl}c_{bl}(T_{bl} - T) \tag{a}$$

where ρ = the tissue density [kg/m3]; c = heat capacitance [J/kgK]; k = conductivity [W/mK]; T = is the tissue temperature [°C]; t = time [s]; r = radius [m]; g = geometry factor (1 and 2 for polar and spherical co-ordinates); q_m = metabolism [W/m^3]; ρ_{bl} = blood density [kg/m^3]; w_{bl} = blood perfusion rate [m^3/s m^3]; c_{bl} = heat capacitance of blood [J kg^{-1} K^{-1}] and T_{bla} = arterial blood temperature [°C].

In the model, individual characteristics such as height, weight and fat percentage can be taken into account [8]. The model was validated for mild environmental exposures.

The main difference between the ThermoSEM model and Fiala's model, is in the active part. By studying the neurophysiological concepts for thermoregulation in the active part, Kingma et al. [16] developed a model for skin blood flow with neurophysiological concepts integrated in the model. The new model incorporates thermal reception data and the neural pathways involved in thermoregulatory skin blood flow control. To develop and validate the new skin blood flow model experimental data sets were used including a data set for the development and two independent sets for the validation of the model [73].

The neurophysiological skin blood flow model simulates five phases of the thermoregulatory tract:

1. In the first phase, local skin temperatures are transduced into the dynamic fire rates of warm and cold temperature sensitive neurons.
2. Following the first phase, in accordance with the neurophysiological pathways, the skin neuron fire rates are integrated.
3. The integrated peripheral warm and cold sensing pathways project to the medial pre-optic area (MPO) of the hypothalamus where local warm sensitive neurons are inhibited.
4. The fourth phase represents the inhibition of the ventromedial medulla neurons.
5. In the last phase, from the ventromedial medulla skin blood flow is controlled by efferent neurons [16].

Thermophysiological models introduced so far, simulate physiological responses of the whole body. Several studies that focus on modelling the heat balance of one isolated body segment will be addressed in the following section.

4. Modelling isolated body segments

Mathematical thermophysiological models that considered the whole body introduced in earlier sections of this paper became the basis for modelling isolated body parts. Modelling isolated body segments became valuable in medicine, as well as in built environment for assessing the sensitivity of human extremities and other body parts in the different thermal environment (Table 3).

A human torso was modelled to investigate how adipose tissue, metabolism heat generation and winter clothes influence the human body's ability to resist hypothermia when exposed to the extreme cold environment [18]. Another research for medical purposes was conducted where thermal analysis using a human finger model was proposed to assess the risk of coronary heart disease. Indirect measurement of vascular health can be the human fingertip temperature variation during the blood flow occlusion. The mathematical model of the heat transfer for the human finger was introduced to show the connection between vascular reactivity and changes in the finger temperature during blood flow occlusion [19].

Ferreira et al. [20] developed a steady state heat transfer model of the human upper limb that includes circular cylinders representing the arm, forearm, five fingers and a slab representing the hand. The body segments were subdivided into two layers, skin and core. The main focus of the model was on the detailed circulatory model. The model of macro-circulation considers blood vessels larger than 1000 μm. The circulatory model includes superficial veins in the arm and forearm, Arterio-Venous Anastomoses (AVA)

Table 3
Mathematical bioheat models of isolated human body parts.

Body part	Purpose	Reference
Torso	The effect of the adipose tissue, metabolic heat and winter wear on a body protection from hypothermia and frostbite.	Doug Worrall; Margaret Hay; David Friedrich; Stephanie Wong [18]
Finger	The analysis of the fundamental physics influencing the fingertip temperature during a blockage of a blood vessel and hyperemia.	Chinmay Deshpande [19]
Arm, Forearm, Hand, Finger	The impact of the blood flow in upper extremities on the heat transfer between the body segment and the environment.	M.S. Ferreira; J.I. Yanagihara [20]
Finger	Thermal behavior of extremities in a cold environment	Avraham Shitzer [21]

and subcutaneous venous plexus in the hand as well as the countercurrent heat exchange between the arteries and veins. Heat transfer equations were introduced for each segment, however control thermoregulatory equations are not included in this model. Steady state simulation was performed using two sets of blood flow data (Salloum [52] and Takemori [74]) to predict the skin temperature of the segments. The results from Takemori's data [74] showed better results in all the segments except in the finger. According to the results presented by the author, where experimental data were compared to the results, the model was capable to simulate skin temperature in neutral and hot environment exposure. In a cold environment, the simulated results were not in a good agreement with experimental data. Along with the skin temperature predictions, the influence of superficial veins blood flow on the heat loss was estimated. The heat transfer improvement when the circulatory model includes superficial veins was noticed only when the body segments were exposed to neutral environment [20].

Modelling of extremities (fingers) as an independent body segment has been done by Shitzer [21,75]. Shitzer et al. [21] developed a model that simulates thermal behavior of a finger exposed to a cold environment. The cylindrical body segment is subdivided into core, muscle, fat and skin layer. The model consists of the heat balance equations that simulate conduction, heat exchange with the environment, metabolic heat generation, heat transport by blood perfusion, heat exchange between the tissue and large vein and artery countercurrent heat exchange between main blood vessels and AVA heat exchange. The model does not include active control mechanisms. The model was used to simulate the fingertip temperature in a cold environment, under different wind conditions and insulation (bare and gloved finger) [21].

Human hands and fingers contain a significantly higher number of arteriovenous anastomoses valves that control vasomotion then the rest of the body parts. The opening of these valves causes the hand temperature to vary in a wide range [76]. In order to achieve an accurate prediction of thermal responses of the extremities, thermophysiological models have to include detailed vascular system. The reason for the less accurate prediction in a whole body model is due to the fact that they do not simulate complex skin blood flow model in the extremities [77]. In order to achieve accurate thermal responses of the extremities, it is necessary to look at the nature of the human brain and heat transfer efficiency connection. When the human body is exposed to a hot or cold environment, heat transfer and the skin blood flow in the circulator system is affected by the central nervous system that has variant reactions during the different exposures. To model isolated body segments it is necessary to have an empirical input of the blood flow crossing the segment that is modelled [77].

A plethora of studies have been done on modelling human extremities [20,21,75,78] as they are the most vulnerable body parts when exposed to the cold environment. Thermal comfort is closely related to the skin temperature of the body extremities. Wang et al. [76] presented that in a cold environment, the finger temperature is a good indicator of both thermal sensation and comfort. It was reported that when the finger temperature was above 30 °C there was no cool discomfort, and when the temperature was below 30 °C there was a high probability of cool discomfort occurrence [76]. Furthermore, the fingertip temperature can be used to determine blood flow rate [79,80] and skin temperature difference between the forearm and fingertip when used as an accurate measure of peripheral vasoconstriction [77]. When the temperature difference between the forearm and fingertip is higher than 4 °C, vasoconstriction occurs [77]. When we observe the type of jobs that humans carry out daily, many of them involve handwork in different thermal environment. For instance, it becomes essential to maintain thermal comfort to avoid a decrease in proficiency or even injuries of the hand when working in the colder environment.

So far thermophysiological models for the whole body and isolated body segments have been described, the next section will focus on the possible application of these models.

5. Application of the thermophysiological model

Many different disciplines acknowledged that there is a necessity for predicting human thermal responses in different thermal environments throughout various activities that people are involved in. Considering that, thermophysiological models are a good possibility for different applications in the field of biometeorology, the auto industry, clothing research, medical application, etc. In the following paragraphs, some examples of application will be introduced.

5.1. *The Universal Thermal Climate Index (UTCI)*

Currently, there is a lot of concern on how humans are affected by the climate and weather, and vice versa. Because of the important emerging issues in the field of climate and health, research is focusing on the human thermal comfort assessments that are a subfield of biometeorology. The ground surface covered types at the urban environments affect the thermal conditions [81]. In different fields of human biometeorology, a need has arisen for a universal index that aims to asses physiological responses across a broad spectrum of outdoor thermal conditions (influence of humidity and heat radiation on a human body in a hot environment, as well as wind speed in the cold conditions) [82]. Additionally, local cooling of exposed skin is considered in order to gain more insight in preventing frostbite, pain and numbness. The initiative to work towards the development of a Universal Thermal Climate Index (UTCI) was proposed by Prof. Peter Höppe. In 2005, the COST

Table 4
Issues addressed and working groups related to Universal Thermal Climate Index [83].

Working groups	Issue addressed
WG1-Thermo-physiological modelling and testing	- Physiological modelling of the human body and its heat balance - Physiologically relevant assessment of heat balance model outcomes including acclimatisation
WG2-Meteorological and environmental data	- Testing results against available field data - Identification and pre-processing of meteorological input data
WG3-Applications	- Estimating radiation quantities - Addressing the specific needs of various applications

Action 730 strengthened the process by involving more experts from 19 European countries, Australia, New Zealand, Canada and Israel, who had regular meetings. The purpose of these meetings was to work towards merging new knowledge into creating an index that would be international accepted. A potential application of the index is in the field of public weather services (weather reports, warnings) and environmental agencies, public health systems, city authorities, urban planning, tourism and recreation and climate impact research [83–85]. The issues addressed in the UTCI development process is shown in Table 4.

The UTCI enables the calculation of the equivalent temperatures using the thermophysiological model for a given combination of wind, radiation, humidity and air temperature. The UTCI equivalent temperature presents the air temperature of the reference environment that gives the same strain index [82]. For the purpose of creating a new UTCI, different human thermoregulation models were evaluated and the Fiala model [7,12] was selected. The original Fiala model was adapted and expanded into UTCI-Fiala model [13]. UTCI-Fiala is formed as an 187-node model that consists of 12 spherical or cylindrical compartments. The left and right extremities are joined and each extremity is presented as unity. One of the new implementations in the new model is adaptive clothing model that combines outdoor environmental factors, clothing permeability and behavioral adaptation of the clothing insulation [13].

5.2. Predicting the temperature of the patients during heart surgery

At Maastricht University and Eindhoven University of Technology, research on predicting physiological responses of anesthetic patients during open heart surgery was conducted [86]. The Fiala model [7,12] was adapted in order to create a model that will predict patient's temperature during heart surgery. The purpose is to provide more insight into the effect of different protocols on temperature distribution and human thermoregulatory system during anesthesia. The whole body thermal model consists of 3 parts (Fig. 7).

The passive part of the model was based on the passive model of Fiala. The patient's body was divided into 19 segments that consist of multiple layers presenting different body tissue [86]. The second part of the model represents the impaired thermoregulation during heart surgery and it includes vasoconstriction responses. To develop the vasoconstriction model, it was necessary to include the effect of the anesthetic drugs that are administrated to the patients during surgery. The pharmacological model that divides the body into compartments (organs and tissue groupings) was developed in order to obtain propofol concentration [86]. The third section represents sub-models where different boundary conditions and individual body characteristics can be implemented to represent different conditions during specific cardiac surgery.

The model was validated by comparing the calculation results with the measurement results of three surgical procedures: aortic valve surgery at 30 °C, coronary artery bypass surgery at 32 °C and aortic valve surgery at 30 °C with forced-air heating. The model results show good agreement with the temperature responses obtained from the cardiac procedures mentioned above [86].

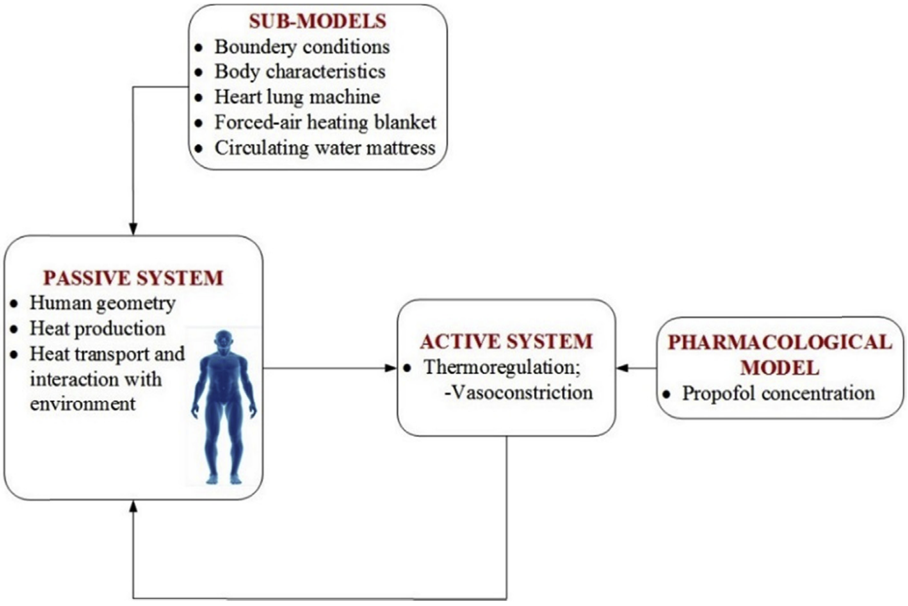

Fig. 7. Schematic diagram of the thermal model for predicting patient temperature during heart surgery (modified from Ref. [86]).

The model can be applied to evaluate patient's temperature distribution during heart surgery. During cardiac surgery, hypothermia is induced to protect vital organs. Towards the end of the surgery, the core body temperature is restored to the pre-surgery condition. The consequence of the re-warming process is that heat transfer is faster to the trunk and brain then to the extremities. When the by-pass is disconnected, the heat is distributed to the colder extremities causing "afterdrop" in temperature in core body organs. This "afterdrop" can cause post-surgery complications and there is the need to understand how it can be reduced and prevented. The valuable use of the thermophysiological model is in assessing the effect of changing conditions on the body temperature distribution and thermoregulatory responses when exposing patients to different protocols [86].

5.3. Thermophysiological human simulator for the clothing research

Clothing has a primary impact on thermal comfort and on human thermophysiological responses. Likewise, the clothing envelope is influenced by sweating, movement and temperature distribution of the human body. The interaction of clothing and the human body is investigated with thermal sweating manikins. The development of manikins that accurately represent human thermal behavior is of significant importance [87,88]. To design a more accurate tool for simulating physiological human responses under the different environmental condition, Psikuta et al. coupled the Fiala model with the sweating heated device [87–89].

Fig. 8 demonstrates the coupling method of real-time data exchange between the heated sweating cylinder and Fiala model. The Fiala model provides averaged local skin temperatures and sweat rates that are used as control signals for a sweating device. Heat flux from the sweating manikin that presents the mean amount of the heat exchanged with the environment is then used as a feedback. The main aim was to apply the single-sector simulator for measuring thermo-physical properties of different clothing and sleeping assemblies (sleeping bags, mattresses) under real environmental conditions [87,88,90].

5.4. Application of the model to support the design of sports stadiums

The Fiala model of human thermoregulation and thermal comfort model was used to support the design of sports stadium [91]. The Stadium Australia (2000 Olympics) is used as an example. Thermophysiological model was used to predict the physiological state of the spectators exposed to two types of conditions: normal ambient conditions and conditions when spectators are sitting below a semi-transparent stadium roof. The impact of the solar radiation on the thermal state in spectators was analyzed. Results revealed that acute hot stress in spectators can be prevented by different roof design (shading the roof or opaque cover) [91].

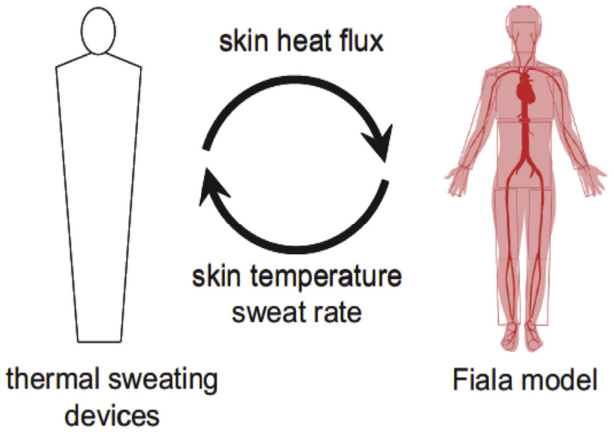

Fig. 8. Coupling sweating device and thermophysiological model – data exchange scheme [88].

The use of thermophysiological models in combination with thermal comfort models to predict physiological responses can identify the reasons for thermal stress and can be used in the analysis of different thermal situations that endangers occupant's health and safety. These predictions can be valuable information when creating optimal design of buildings. Observing the sport stadium example, if the stadium is not adequately designed the spectators in the upper seat can be exposed to the acute hot stress during the hot summer days in warm climates [91].

5.5. Assessing the thermal comfort in a car cabin

As a part of thermal comfort simulation of the car occupant exposed to the inhomogeneous environmental conditions, it is necessary to have a simulation representing heat and moisture transfer of human body. The thermophysiological model simulates the heat transfer phenomena and the physiological responses in order to represent realistic thermal responses of the human body in the complex thermal conditions in a car cabin. The Fiala model was implemented in the thermal simulation software THESEUS-FE that is used to solve steady state and transient heat transfer applying Finite Element Method. With assessment and optimization of occupant's thermal comfort in modern vehicles as the main goal, the thermophysiological model coupled with the detailed car CFD simulation becomes a valuable tool in the automotive industry as a part of the product development process [90].

6. Discussion

Thermal satisfaction with the environment is a complex phenomenon influenced by a large number of physical, physiological and non-physical factors, making comfort prediction in the building design phase complicated. Therefore, thermal comfort assessment has been an attractive research topic throughout the years. Since research on physiological responses of the human body started, different models of human thermoregulation have been developed. In this paper, advanced thermoregulation models that were developed in recent years were reviewed. Particular emphasis was given to the existing application of the models.

Through the years, models gradually developed from homogeneous cylinder to two-node models, and further to multi-node models that simulate human body and its regulatory responses in detailed and extensive ways. The developed models are not identical; however certain characteristics are shared. All models have the modelling of the heat exchange within the body and the body with the environment in common. They differ in modelling the geometry of the human body (one-node models, multi-segments models). The heat balances within the model are straightforward and well explained.

Another difference between the models is in the modelling of the active part that determines physiological responses of the body. The models used different empirical relationships that correlate to diverse physiological responses (sweat rate factors, blood flow rates). Thermal responses under different environmental conditions vary from person to person. To avoid rough representation of the thermal physiological stress responses and to be able to exactly simulate what occurs in the human body, individual responses have to be adequately understood and explored.

Table 5
Studies in which the models were compared with other ones.

Model	Model used for comparison	Outputs compared
Zolfaghari and Maerefat [43]	- Berkeley [14,15]	- Mean skin temperature
Salloum et al. [93]	- Berkeley [14,15]	- Local skin temperature for a step change environment from 28 °C to 4.7 °C
	- Smith (as presented in Ref. [94])	- The predicted mean skin and rectal temperature (constant environment with step change in metabolic rate)
Fiala [7,12,13]	- Stolwijk [50]	- Mean skin and rectal temperature
Re-evaluated Stolwijk model [53]	- Stolwijk [50]	- Mean and local skin temperature
Foda [95]	- Fiala [7,12,13] - Berkeley [14,15]	- Mean and local skin temperature
Kaynakli et al. [48]	- Berkeley [14,15]	- Skin temperature and evaporative heat loss
Al-Othmani et al. [54]	- Salloum et al. [93]	- Mean and local skin temperature
	- Berkeley [14,15]	- Mean latent heat loss
	- Fu [94]	- Latent heat loss and gain
Novieto [55]	- Fiala [7,12,13]	- Mean skin and rectal temperature

Human thermoregulation modelling and developed thermophysiological models are relevant instruments for understanding the complex thermal behavior of the human body. The developed thermophysiological models offer an opportunity to explore the reactions of the human body in different environmental conditions. The models simulate physiological outputs via computer code. The accuracy of the models is validated by comparing the simulation results with the experimental data. Yang et al. [92] discusses the methods of evaluating the accuracy of thermophysiological models. In his study, Yang et al. [92] observed that the prediction accuracy of different models for the same thermal responses and their comparison is not often discussed [92]. One of the possible reasons is that often the models are not available. Therefore, the only way to see the simulation results for a specific environment is to observe the figures presented by the authors in published literature. One

Table 6
Summary of the main attributes and constrains of selected models.

Model	Attributes	Constraints
Gagge [34]	- Whole body, single segment, two layers [43,52] - Easy to implement [52] - Short calculation time [42]	- Only uniform conditions [52] - Moderate activity level [52] - One hour exposure time [23] - No local body part outputs
Foda [42]	- Two nodes: core and skin - 17 segments - Adjusted two-node model for individual body parts - Skin set-points based on neutral condition measurements	- Steady state conditions - Lower predictability at the limbs in extremely cold environment - Similar average of subjects - Normal office clothing - Sedentary activities
Stolwijk [50]	- Local skin temperatures: six segments, four layers [50]	- Constant environment [23] - Assumes that every node of a segment has the same blood temperature [52] - Prediction of the core temperature in the cold environment is less accurate [12,15]
Tanabe [69]	- Local skin and core temperatures: 17 segments - Validated for steady state and non-uniform transient conditions - Physical characteristics can be changed	- Based on set point temperatures of each segment
Berkeley [14,15]	- Validated for steady state conditions, transient and non-uniform environment - Local physiological output possible of arbitrary number of segments - Each body segment can be exposed to different environmental conditions - Model structure is very flexible and the model can be modified and implemented easily - Individualization	- During transient conditions simulated arm temperature is lower than the measured one, but the final stable arm temperature has very good agreement
Fiala [12]	- Extensive validation covering steady state and transient conditions, and various activity intensities - Environmental temperatures: 5 °C – 50 °C - Activity intensity: 0.8 met – 10 met - Average rms deviation of 0.7 °C and 0.9 °C for the mean and local skin temperatures for moderate, hot and cold stress conditions - Average of 0.2 °C rms deviation for body core temperature	- Lower predictability of skin temperatures during exercise in cold environments - Regression based
ThermoSem [8,16]	- Local skin temperatures: 19 segments [16] - Sub-division into sectors-asymmetric conditions possible [8] - Based on neurophysiology [16] - Individualization [8]	- Validated for mild conditions [17]

possibility that could improve the methodology for comparing the accuracy of the models is creating a database that researches could access. The database could include information on simulation accuracy of different models for specific environmental condition and conditions regarding clothing and activity. Table 5 shows the studies, in which the prediction accuracy of different models was compared.

The literature review shows the evolution of models in time and how researchers modified the models to match their research needs. The intention is not to criticize or discuss which model is better, but to offer a summary of the main attributes of the models (Table 6). Hopefully, this could be helpful for researches when making a decision which model better suits their needs.

The literature review indicates that even though sophisticated models were developed with advancement in computer evolution, the models are still not ordinarily used when considering daily applications in the built environment. One reason is that the accuracy of the inputs has to be assured in order to incorporate models in the design processes of buildings and daily application of thermal comfort. For example, the study of Veselá et al. [96] accentuated the need for accurate and reliable input data. Another reason is although it is commonly assumed that the physiological state of the human body presents some predictable comfort response, the relation between the simulated outputs of the model and perceived thermal comfort still has to be affirmed.

7. Conclusions

The thermophysiological model that provides physiological responses coupled with other non-physical parameters (behavioral and cultural) that influence perceived thermal comfort, is a valuable part of the methodology for modelling thermal sensation. To enable the practical use of a thermophysiological model several topics still need to be explored.

To achieve a high percentage of occupant thermal satisfaction in building with reduction of energy use for heating and cooling, occupant's physiological behavior must be taken into account more precisely. Individual differences in human physiology (age, gender, body composition) influence the thermal state of the body and physiological responses, thus creating possible differences in thermal comfort and thermal preferences of occupants. People from different climate areas and different ethnic background may experience thermal comfort and sensation differently in the same environmental conditions. Including physiological and psychological differences can provide more accurate thermal comfort assessment.

Till now, human physiological behavior was not integrated into control processes, and including the human being could benefit the process of achieving extended management of energy demand based on the individual occupant. When considering the control of individual comfort in built environment, it is necessary to find critical parameters that predict changes in occupants' comfort. Upper-extremity skin temperature shows a potential as a control indicator (for slightly cool office environments) for individual control of personal conditioning. Previous research introduced modelling isolated human extremities exposed to the extreme environment. The approach of using the simplified thermoregulation model for human extremities exposed to the office environment, that includes human thermoregulatory responses, should be considered for evaluating the skin temperature for human body extremities. The model of human extremities might provide an insight into the relationship between local skin temperature and local thermal comfort, as well as the influence on overall thermal comfort and sensation. Further research should aim to improve the prediction of the local and overall thermal comfort and make a step towards bringing the models closer to the everyday comfort application.

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