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Original Article

An integrated approach to develop, validate and operate thermo-physiological human simulator for the development of protective clothing

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Abstract: Following the growing interest in the further development of manikins to simulate human thermal behaviour more adequately, thermo-physiological human simulators have been developed by coupling a thermal sweating manikin with a thermo-physiology model. Despite their availability and obvious advantages, the number of studies involving these devices is only marginal, which plausibly results from the high complexity of the development and evaluation process and need of multidisciplinary expertise. The aim of this paper is to present an integrated approach to develop, validate and operate such devices including technical challenges and limitations of thermo-physiological human simulators, their application and measurement protocol, strategy for setting test scenarios, and the comparison to standard methods and human studies including details which have not been published so far. A physical manikin controlled by a human thermoregulation model overcame the limitations of mathematical clothing models and provided a complementary method to investigate thermal interactions between the human body, protective clothing, and its environment. The opportunities of these devices include not only realistic assessment of protective clothing assemblies and equipment but also potential application in many research fields ranging from biometeorology, automotive industry, environmental engineering, and urban climate to clinical and safety applications.

Key words: Thermo-physiological human simulator, Human thermoregulation model, Thermal manikin, Protective clothing, Clothing benchmark

Introduction

The increasing expectations of consumers regarding comfort and performance have made the requirements addressed to clothing and protective equipment more demanding. This entails new concepts of protective and functional apparel to ensure health and safety, while maintaining well-being, thermal comfort, and productivity of users. Hence, designers working especially in the field of functional clothing consider not only an artistic expression but more importantly the scientific approach to address specific requirements. Thus, designing special protective clothing often requires a multidisciplinary approach including textile technology, nanotechnology, engineering

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of smart textiles, and textile and garment production as well as the understanding of thermal processes in clothing and their thermo-physiological consequences.

To master the challenges posed on functional clothing, advanced and reliable analytical methods are required that can realistically relate to human thermal behaviour and sensational perception. Nowadays, thermal manikins are the most realistic devices widely used for the assessment of heat and mass transfer from the human body to the environment. Their anatomic shape and ability to sweat and move provide experimental conditions representing more accurately heat and mass transfer occurring at the human surface[1)]. This includes the formation of realistic air layers around the body including air penetration and compression by wind, body posture and movement. Furthermore, it includes clothing fit , altering size and shape of the layers[2)], which have major influence on the local heat, as well as vapour and liquid exchange[3)]. On the other hand, present thermal manikins are usually operated at uniform, steady-state conditions[4−6)], which are insufficient for the evaluation of the dynamic properties of ensembles in realistic wearing conditions and for predicting their thermo-physiological effects on a wearer. These features enable standard thermal manikins to be recommendable instruments only for physical characterization, for various benchmarks, and for classification endeavours of clothing systems and protective equipment.

For a more realistic investigation of transient processes, human subject tests are conducted entailing some drawbacks such as high costs, ethical restrictions, and intra- and inter-subject variability. To reduce this burden standards and simulation tools have been developed based on a large number of physiological experiments with the intention to prevent physiological strain at the workplace through proper clothing, hydration level, and limiting working time[7, 8)] or to predict thermal perception of the occupants[9)]. More sophisticated human thermoregulation models have been developed and validated to predict heat and mass transfer through the clothing to the environment[10−14)]. The major limitation of these models is the lack of equally complex and reliable clothing models including fabrics and air layers.

Over the past decade, there has been growing interest in the further development of measurement methodologies for existing devices to simulate human thermal behaviour together with complex heat and moisture transfer in clothing more adequately. The so-called thermo-physiological human simulators have been developed by coupling a thermal sweating manikin with a thermo-physiology model. In such a case a thermal manikin becomes an adaptive manikin that is capable of mimicking realistic dynamic human thermo-physiological responses to a given static or dynamic environment including even very sophisticated protective clothing and equipment. Today, there are already several such manikins in operation, mainly in clothing research field but also in built environment research[15)]. The common drawback of all existing systems is the scarcity of validation evidence and its proper reporting necessary for obtaining confidence in the measurement outcome of such devices. They also require a different approach to the experimental design that is more application-oriented as opposed to standardized measurement methodology typically applied for manikins and other benchmark devices. Consequently, despite availability (with one system being even offered commercially) and obvious advantages of these devices, the number of studies was only marginal in the recent years[16, 17)]. This fact plausibly results from the high complexity of the development and demanding evaluation process of the human simulators and the need of multi-disciplinary expertise (mainly in apparel and human physiology) necessary for developing proper experimental design and interpretation of the experiment outcome. Therefore, the aim of this paper is to present an integrated approach to develop, validate, and operate such devices including technical challenges and limitations of thermo-physiological human simulators, their application, and measurement protocol strategy for setting test scenarios. Furthermore, it elucidates the comparison to standard methods and human studies including details not published so far. Finally, several case studies are described as an inspiration for using human simulators to realistically and efficiently evaluate the protective systems and thermal environments.

Methods

Definition of the thermo-physiological human simulator

The thermo-physiological human simulator is a sweating thermal manikin that is controlled by a human thermoregulation model, and thus, dynamically responds to the thermal environment similar to a human. The role of the thermal manikin is to measure the resultant influence of the environmental conditions (e.g. clothing and personal protective equipment, radiant asymmetries, temporal and spatial changes of the local air movement around the manikin body, ambient temperature and its shifts as well as heat transfer through surface contact). To successfully couple a full body manikin with a thermo-physiological model,

Table 1. Summary of the thermo-physiological human simulators developed up to date

	Manikin	Thermoregulation model	Number of sectors	Laboratory	Reference
1	ADvanced Automotive Manikin ADAM	Computational Fluid Dynamics thermoregulation model	126	National Renewable Energy Laboratory, USA	[21, 65, 66]
2	Sweating thermal cylinder Torso[53] (Fig. 1a)	Thermoregulation model by Fiala *et al.*[67], Fiala *et al.*[68]	1	Empa, Switzerland	[19, 22]
3	Sweating Agile thermal Manikin SAM[31]	Thermoregulation model by Fiala *et al.*[67], Fiala *et al.*[68]	22	Empa, Switzerland	[23]
4	Thermal sweating manikin Newton (Fig. 1b)	Manikin PC[220]	26/34	Thermetrics & Thermo Analytics, USA	[24, 51, 59, 60]
5	Thermal sweating manikin Newton (Fig. 1b)	Improved thermoregulation model by Xu and Werner[26]	38	Decathlon, France	[25]
6	Thermal sweating manikin Newton (Fig. 1b)	Improved thermoregulation model by Tanabe *et al.*[14]	20	Tsinghua University, China	[27]
7	Therminator[69]	Thermoregulation model by Foda and Siren[70]	24	Aalto University, Finland	[69]
8	Sweating thermal head manikin[29] (Fig. 1c)	Thermoregulation model by Fiala and Havenith[30]	4	Empa, Switzerland	[28]

the manikin responsiveness, precision, and accuracy under transient conditions, such as temporally and spatially varying surface temperature, heat loss and sweating, must be ensured[18]. The role of the thermoregulation model is to provide a reliable prediction of the human thermoregulatory response under both steady-state and transient conditions. This prediction is used to control the manikin surface parameters, such as sweat rate, surface temperature or heat loss. The correspondence of the division into body parts between the manikin and the model needs to be addressed in the coupling procedure if the thermal manikin represents more than one sector. The majority of the manikins are divided into a larger number of segments[6]. At the same time the body division in the thermoregulation models follows a similar division into individual body parts with individual tissue configuration, metabolic heat generation, blood flow, shivering thermogenesis, and sweat production. This fact suggests that even though the manikin segmentation may be limited, it is still sufficient to fully use the advantage of the spatial resolution of the thermophysiological model.

The coupling method is based on a feedback loop involving real-time iterative exchange of the relevant data between the manikin and the thermoregulation model. There are two emerging trends in coupling methodology discriminating between the selection of controlled and controlling parameters. One of the coupling methods assumes that the skin temperatures and sweat rates from the thermophysiological model are used to control the manikin (so-called boundary condition type 2 or Neumann approach, which defines a surface with a prescribed heat flux). According to this method the local heat losses measured by the thermal manikin are used as an integral feedback representing the amount of heat exchanged with the environment in the present climate and clothing conditions. These heat losses are used by the coupled thermoregulation model to predict the physiological state of the body for the next time interval[19]. The predicted skin temperatures and sweat rates are then set on the segments of the thermal manikin as their surface temperature and sweating flow rate. After a predefined time interval the local heat loss is measured and passed to the thermoregulation model again closing the feedback loop. Another coupling strategy is to provide the metabolic heat production and sweat rate for each body part of the manikin, where the metabolic heat production is set as a heating power delivered to the manikin individual segments (so-called boundary condition type 1 or Dirichlet approach, which defines the fixed value of the surface temperature)[20]. In both coupling methods, other physiological and perceptual parameters derived from the thermoregulation model, such as core temperature, skin blood flow, heart rate and thermal sensation, are also calculated and provided for the entire body or individual body parts.

Overview of existing thermo-physiological human simulators

Table 1 lists the thermo-physiological human simulators developed up to date.

A forerunner (case 1 in Table 1) of such a thermo-physiologically-controlled manikins was developed for the American National Renewable Energy Laboratory (NREL, Denver, USA) for comfort testing (ADvanced Automotive Manikin (ADAM) controlled by a computational fluid dynamics (CFD) implementation of a human thermoregu-

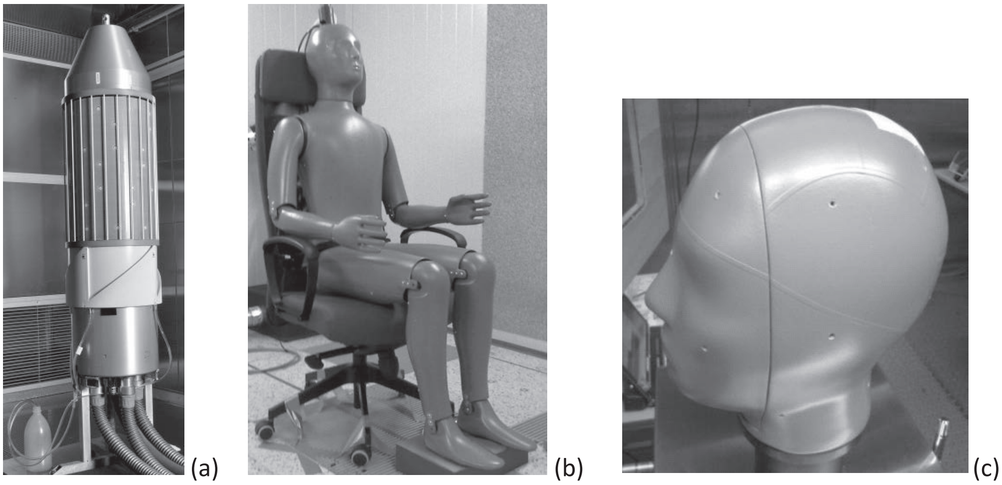

Fig. 1. Thermo-physiological human simulators with the greatest successful validation record, namely (a) Torso cylinder with air layer spacer coupled with the thermoregulation model by Fiala (19, 22), 11 validation cases), (b) thermal manikin Newton coupled with Manikin PC^2 model (24, 71), 8 validation cases), (c) thermal head Alex coupled with the thermoregulation model by Fiala (28), 10 validation cases).

latory model[21)]. Another initiative (cases 2 and 3 in Table 1) to develop a thermo-physiological human simulator took place at the Swiss Federal Laboratories for Materials Science and Technology (Empa, St. Gallen, Switzerland) in 2005[19, 22)]. The coupling procedure was divided into two stages of coupling a single-sector device based on the sweating cylinder Torso (Fig. 1a) followed by a multi-sector full body manikin SAM to break down the challenge of the coupling and allow easier troubleshooting[23)]. In 2009 an integration of the ManikinPC^2 thermoregulation model (Thermoanalytics Inc, USA) to the Newton sweating manikin (Thermetrics, USA) (case 4 in Table 1, Fig. 1b) was achieved[20, 24)] as the only one off-the-shelf manikin of this kind so far. This is also the only coupled system using the skin temperature as an input to the model (type 1 boundary conditions). Some other attempts to couple Newton have been undertaken. Redortier and Voelcker[25)] have coupled Newton with a thermoregulation model by Xu and Werner[26)] (case 5 in Table 1) using external transducers instead of manikin power input for measuring the heat flux from the manikin surface. Another example of a Newton-manikin-based coupled system (case 6 in Table 1) was developed at Tshinghua University using a multi-node thermoregulation model 65MN by Tanabe *et al.*[13, 14, 27)]. The attempts to couple thermal full-body manikins with thermo-physiological models made a path for yet another variety of a coupled system, namely, a body part manikin with a mathematical human thermoregulation model (case 8 in Table 1). A forerunner of this type of coupled system is the nine-zone thermal head manikin[28, 29)] (Fig. 1c) together with the thermo-physiological model by Fiala and Havenith[30)], where the head was the only body part actually dressed and exposed to the environment and the rest of the body was simulated virtually.

Technical challenges and limitations of thermo-physiological human simulators

Heat loss of thermal manikin

Both coupling methodologies reveal some drawbacks related to the measurement of the controlling parameters. In the coupling method with boundary conditions type 2 (heat flux from manikin surface is the feedback to the thermoregulation model), the heat loss at manikin surface is typically calculated based on the heating power output. This is a correct calculation method at steady-state conditions but is limited in strongly transient conditions. If the set-point temperature changes more than the manikin heating or cooling capacity, the resultant momentarily heating power output will reach its maximum or null, respectively, and not the actual heat loss to the environment drawn from the heat stored in the manikin material volume. In some extreme cases such situation may last several minutes during which the incorrect heat loss feedback will affect the accuracy of the thermo-physiological prediction. The solution to this problem is the application of surficial heat flux sensors to record the actual heat loss, which is still a technological challenge and has not yet been successfully applied in existing manikins apart from a first attempt of water-perfused hot plate system introduced by Thermetrics (USA) during 10th Manikin and Modelling Meeting in Tampere, Finland in 2014. In the coupling method with boundary conditions type 1 (manikin surface temperature is the feedback to the thermoregulation model), some of the heating power in transient conditions is used to heat up the entire manikin material volume and not only its surface (or is drawn from manikin material during cooling) leading consequently to some prediction inaccuracy. Finally, since present manikins involved in coupling with human thermoregulations models neither represent human thermal capacity (composite of air, metal, and polymers with specific heat capacity of 1,000, 460–920 and 880–1,550 J/kg/K, respectively, summing up per weight to a value close to 1,000 J/kg/K for a typical manikin) compared to human body (composed of bone, muscle, fat, skin, and blood with up to 60% of water content with total specific heat capacity of 3,500 J/kg/K) nor are they equipped with an active cooling system. The exposure of such a system to higher ambient temperatures and/or radiation resulting in uncompensated heat gain of the human body is impossible.

Sweating

Some further potential sources of inaccuracy are related to the simulation of the insensible and sensible perspiration. The insensible perspiration from the human skin might be impossible to simulate with the manikin sweating system, since the amount of sweating water needed for this evaporative heat loss is so low (as little as 9–14 W/m^2) that the water would evaporate before spreading over the distance from the sweating outlets to the surface temperature sensors and remain undetected. Typically the insensible perspiration is simulated virtually. Secondly, in some thermoregulation models the sweat rate predicted by the central nervous system is reduced locally due to the hidromeiosis process (swelling of the skin saturated with sweat that reduces the clearance of the sweating duct). This effect is controlled by the skin wetness, which cannot be measured by the thermal manikin, and consequently, the predicted sweat rate will not be reduced due to this effect.

Thirdly, to accurately simulate the heat losses in scenarios when sweating occurs, the thermo-physiological human simulator should be equipped with a sweating system capable of mimicking humanlike sweating and its evaporation. Manikins with a dynamic supply of water to a textile skin used to spread the sweat water from the outlets over a larger manikin area , e.g. 'SAM'[31] and 'Newton' (Thermetrics, Seattle, US) are able to imitate a humanlike superficial wetting. The fabric for the skin should be hydrophilic, be able to spread the moisture fast and over a possibly largest area with or against the gravitational force[32]. These properties are particularly important at the onset of sweating as the cooling effect can only be measured once the water reached the sensors embedded in the surface of the manikin and for the proper moisture wicking to the clothing layers if applied. Maximal moisture content and drying rate of the fabric skin determine its cooling potential and duration. According to Berglund[33] the thickness of a water layer on the human body without dripping off approximates 37.6 g/m^2 of body surface. However, the sweat droplets on the human skin may not behave the same way as water trapped inside a fabric skin. It is known that part of the evaporative heat might be taken from the environment reducing the cooling effect on the body; although the thermoregulation models assume 100% of the cooling efficiency (entire latent heat for evaporation of sweat is taken from the body). For fabric skins, the cooling efficiency in iso-thermal conditions has been reported to range from 0.7 to 0.85 meaning that 15 to 30% of the evaporative heat was taken from the environment[32, 34–36]. This implies that the evaporative heat loss from the manikin should be theoretically corrected for that inefficiency to match the assumption of the thermoregulation model, although the cooling efficiency for the sweat evaporating from the human body has not been thoroughly investigated yet.

Finally, the textile skin is not divided into sectors as the manikin is and some gravitational migration of the sweated moisture between sectors is unavoidable. In such a case the evaporation of moisture excreted in one body part may actually occur at the next body part below, and hence, relocating possibly an excessive portion of the evaporative heat loss, which might lead to changed prediction of the thermo-physiological state.

Applying a fabric skin adds onto the insulation of the adjacent air layer of about 6–22% (total dry resistance with fabric skin of 0.103–0.118 m^{2}K/W and without of 0.097 m^{2}K/W) for regular manikin shape such as a cylinder[32] and up to 39% (total dry resistance with fabric skin of 0.146 m^{2}K/W and without of 0.105 m^{2}K/W) for an anatomical full body manikin[37]. This suggests that the heat loss from the manikin needs to be adjusted for this extra isolative effect to match the skin condition assumed in the thermoregulation model as it was done in the single sector thermo-physiological simulator by Psikuta *et al.*[19]. The thermal insulation of the fabric skin varies between its maximal value in dry state and the wet insulation value, which was measured for four typical skin fabrics to be about 20 to 25% lower than in the dry state[32].

Clothing

The clothing is made from a two-dimensional pattern to cover the complex three-dimensional geometry of the human body. Depending on the garment fit (difference between the garment and the body girths as so-called ease allowance) either it conforms to the body geometry or sags creating mostly heterogeneous air layers underneath the garment[38−40]. Since the air layers usually constitute the bulk of garment thermal and evaporative resistances, the thermal behaviour of garments is affected by the size and shape of the air layer and the magnitude of the contact area[3, 41], which in turn, depends on the factors associated with construction and use of the clothing, such as body posture[42], body movement[43−45], compression on the clothing by wind, clothing design and fit[39, 40, 43]. It was found that the air gap thickness remains nearly constant regardless of the garment fit at the convex body regions (upper and lower chest and back, and anterior and posterior pelvis) due to gravitational resting on non-vertical body regions on the chest and back, and adjustment to stay in place at the pelvis area. At the remaining body regions the air gap thickness is linearly dependent on the ease allowances[2]. When changing the posture the air gap thickness and contact area will obviously change at and in proximity of the bent joint[42, 46], and hence, the thermal properties of the garment will change too[47]. Bending the elbow or knee and hip to 90 degrees will reduce the air gap thickness on average at the whole arm by 1.4 mm and magnify the contact area by 8% (for upper arm by up to 1.1 mm and 5%, for lower arm by up to 2.2 mm and 12%) and the whole leg by 6.2 mm and contact area by 20% (for upper by up to leg 5.8 mm and 36%, lower leg by up to 6.7 mm and 10%), respectively. When the entire posture will change from standing to sitting, these parameters will change not only for the body parts staying in contact with the seat (back, lumbus, posterior pelvis and thigh) but also for the remaining body regions on average by 3.4 mm and 12% (a maximum reduction of air gap thickness by 15.5 mm at anterior pelvis and a maximum increase of contact area at shin by 33%), and hence, the heat and mass transfer will change correspondingly[2].

Using thermal human simulator based on anatomically-shaped full body manikin allows for realistic body coverage to be obtained, the distribution of the air layers and contact area over the body regions, and their change due to posture (if manikin is agile). This, in turn, will result in realistic thermal and evaporative resistances of the ensemble and its effect on the thermo-physiological response of the human body. Furthermore, if a walking option is available for the manikin and the climatic chamber size allows for simulation of wind, also the effect of these conditions on the human thermo-physiological response can be effectively captured using this tool. This is especially important for complex ensembles and protective equipment (geometry and material) that are difficult or impracticable to simulate virtually at the state of current knowledge.

Using the thermo-physiological human simulator based on a sweating cylinder, the realistic simulation of the air layers, the contact area and the body coverage is technically more challenging and the use of simplified geometry may lead to some prediction inaccuracy. The use of uniform heat loss from the cylinder as a feedback for the thermoregulation model to be applied at body parts with diverse heat transfer conditions (geometry, projection to surrounding surfaces, orientation) was shown to have only small effect on coupled system accuracy[19]. Secondly, the application of clothing is limited to cases with rather homogenously distributed thermal and evaporative ensemble properties and relatively small uncovered skin area since the entire cylinder is typically covered with a homogeneous fabric sample or assembly for multi-layer systems[22]. The formation of the air layers underneath the clothing and between clothing layers can be achieved in a simplified form using spacers with defined air gap thickness. Both homogeneous and to some extend heterogeneous air layers (regular folds) can be formed as shown in the study by Mert *et al.*[3]. Besides, in multi-layer systems these spacers can be placed between the layers, for example, having tight underwear fabric fitted tightly on the cylinder surface and the outer layer fixed on the spacer with homogenous air gap or regular folds. Clothing compression by wind, body posture and movement cannot be properly simulated when using the thermal cylinder, which is a greatest drawback of the single-cylinder-based thermo-physiological human simulator.

For human simulators based on body parts, manikins represent yet another challenge in setting an experiment. Since the real clothing or protective equipment can be worn only on the body parts represented by the coupled manikin, the rest of the body and covering clothing needs to be simulated virtually. This means that the simulation accuracy of the virtual part of the body is limited especially for highly complex ensembles, protective equipment, and heterogeneous environments. Thus, this kind of simulator is recommended for scenarios where the complex exposure is related to the body part represented by the manikin in the coupled system. An example of such a system is the head manikin coupled with the thermoregulation model by

Fiala *et al.*[11, 28]. This system is used for evaluation of the headgear typically with complex geometry, material composition, and air flow patterns when exposed to headwind to be simulated with manikin in a conditioned wind tunnel and at the same time with relatively simple clothing and environmental exposure of the rest of the body to be simulated virtually.

Validation

The most important confirmation of the human simulator performance is achieved through a thorough validation. This is usually done by comparing human experimental physiological response with the response simulated by the thermo-physiological simulator exposed to the same conditions including clothing, body posture, possible contact with objects such as chair, and the environmental conditions. However, several issues hinder a validation, specifically, the details of published experiments are often scarcely reported and enforce assumptions, and the experimental clothing is not available for the measurements using the thermo-physiological human simulator. Effectively, the proof of performance of the human thermo-physiological simulator is reduced to only few validation cases (1 – 11 cases as reported by Psikuta *et al.*[15]). Psikuta *et al.*[48] proposed the creation of a database of validation exposures as a public domain resource to support validation and standardisation of thermo-physiological simulation tools. A systematic approach to the validation of thermo-physiological models and human simulators was suggested based on groups of selected human trials with increasing complexity of exposure, such as basic (exposures to a wide range of steady-state and transient environmental conditions with low activity level (≤1 met) and no clothing), active (exposures with exercise at a wide range of activity levels and environmental conditions with no clothing), and complete exposures (exposures including clothing under steady-state, and spatial and temporal transient conditions).

The results of the validation of the thermo-physiological human simulator should be preferably reported as the root-mean-square deviations (rmsd, so-called goodness of fit, the average absolute difference between a prediction and the corresponding human experiment results,[49]), the bias (the averaged literal difference between a prediction and the corresponding human experiment results including its sign[50]), and assessing whether the model output falls within the 95% confidence interval of the experimental human data to exclude unsatisfactory validation due to poor quality of the experimental data. The goodness-of-fit is assessed practically by comparing rmsd values and the average standard deviation of the experimental data, which should be lower than the latter one for an acceptable fit. Ideally, the bias should equal or be close to zero to ensure unbiased model prediction. Nevertheless, none of these indicators accounts directly for the sample size (number of human subjects participating in the experiment) and the spread of the data (variance), which characterize experiment reliability. Information about how the simulation results relate to the confidence interval of the experimental data gives a balanced perspective on the rmsd and the bias by adding gravity to more reliable experiments (greater number of human subjects with consequently lower spread of the results). Furthermore, for a more in-depth assessment of the human thermo-physiological simulator a detailed analysis might still be necessary, e.g., time dependent propagation of error, analysis of transient vs. steady-state intervals in the exposure.

Application and measurement protocol

The expertise and the amount of technical details to consider when developing and applying the thermo-physiological human simulator might be overwhelming especially that these tools are relatively new and not well-investigated yet. If considering the application of such a device optimally the following preparatory steps should be undertaken:

(1) The manikin anticipated for the coupling should be evaluated for its accuracy and responsiveness using for example protocols and requirements described by Psikuta *et al.*[18];

(2) The fabric skin to be used for spreading the sweating on the manikin should be selected based on the evaluation and guidelines described by Koelblen *et al.*[32];

(3) The thermoregulation model anticipated for the coupling should be thoroughly validated for possibly many diverse human experiments including wide range of environmental conditions and activity levels in steady-state and transient exposures (basic and active exposures as described in section 2.4[51]). Complete exposures (as described in section 2.4) are only relevant for systems with body part manikins where the virtual body simulation requires using the clothing model together with the thermoregulation model. This step will provide information on the magnitude of an inherent error of the thermoregulation model in comparison to the error of the thermo-physiological human simulator including also errors of the hardware and the environmental setting;

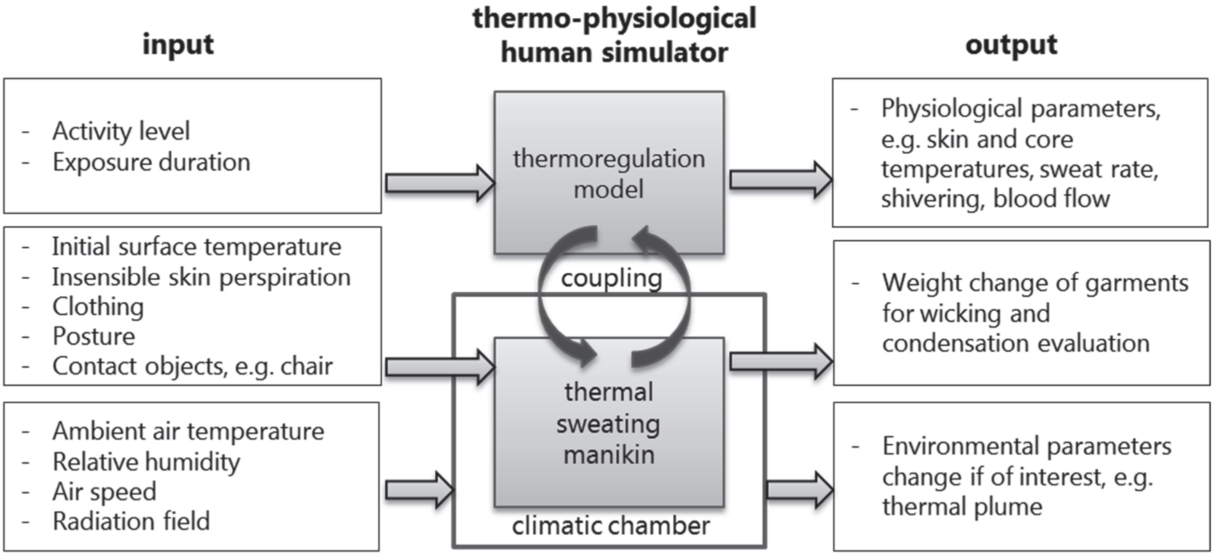

Fig. 2. Scheme of information flow in the measurement process using the thermo-physiological human simulator.

(4) Evaluation of any other possible errors, for example, an error due to simplified geometry of the thermal manikin (e.g cylinder), coarser resolution of manikin segmentation in comparison to segmentation of the human thermoregulation model should be performed[19];

(5) The final evaluation of the thermo-physiological human simulator using human datasets, the same environmental condition and body configuration as well as the same clothing (material and fit) as in the experimental human trial should be incorporated[11, 12].

Once this evaluation is accomplished, the full picture of the thermo-physiological human simulator reliability and limitations will be revealed. Depending on the outcome of this analysis its range of application can be determined using lowest errors as a guideline for best performance range. Finally, it is recommendable to use the simulator for evaluation of new independent exposures within that best-performance range using the measurement protocol as depicted in Fig. 2.

Strategy for setting measurements

Test scenarios

Using a manikin measurement system with a thermo-physiological control opens new opportunities for evaluation of the interaction between the environment, clothing and protective equipment, and the human body. The major principle of using this system is its application-oriented deployment as opposed to standard methods where ensembles for different applications are tested under the same homogeneous conditions. Depending on the research interest either the performance of the protective system or the well-being of the individual could be in focus for a particular exposure. In the first case, the typical and/or extreme conditions of use of the protective system should be selected to compare the performance of the systems under these conditions based on relevant thermo-physiological parameters. In the second case, usually only one protective system (alternatively, an adjustable system) is evaluated for a variety of environmental and activity scenarios to determine comfort and safety limits of the protective system or even the survival time in a worst-case scenario. The frequently used relevant thermo-physiological parameters for evaluation of protective performance and safety limits are core temperature, sweat production and dehydration, cardiac output, evaporative cooling, and body heat storage in heat, and core temperature, shivering thermogenesis, and skin temperatures especially when risk of freezing or non-freezing cold injury is presumed in cold. If thermal sensation and comfort is also of interest the local and mean skin temperatures, their rate of change, core temperature and skin wetness are the parameters of interest.

Comparison to standard methods

The standard textile and clothing evaluation methods, such as hot plate[52], Torso sweating cylinder[53], thermal sweating manikins[4−6] offer a basic characterization of the fabric/clothing including thermal and evaporative resistance. In addition, Torso evaluation system offers a more functional method involving adjustable activity and sweating rate (e.g. cooling dynamics during and after physical activity)[54, 55]. Nevertheless, these instruments and methodologies alone are insufficient for making any sensible judgment on the thermo-physiological effect of the clothing on the wearer[56]. On the other hand, the differences between clothing samples were more pronounced when using benchmark methods as these listed in this section. For example, Psikuta *et al.*[22] demonstrated that the Torso method presented a difference between the two samples of over four times larger than the thermo-physiological human simulator method, based on the same device and environmental conditions (2.53°C for Torso as compared to 0.56°C for human simulator). Thus, the use of the standard method is more useful to compare functional properties of textile samples between each other, for example, during the development process of a clothing system, rather than evaluating clothing performance in real use. In such a case only the final significantly improved prototype should be tested using the human simulator to quantify its improvement actually sensed by the wearer, which is typically less than what the improvement based on standard test would suggest.

Comparison to human studies

The major interest in performing human trials with protective ensembles and equipment is focused on determining the real thermo-physiological effect of the evaluated system on an individual under selected conditions of use. However, such tests are limited by ethical and medical concerns with regard to harshness of the exposure, number and type of sensors possible to be used, and costs since such trials are labour-intensive and time consuming. Furthermore, the evaluation of protective ensembles and equipment is limited by a considerable inter- and intra-subject variation. On the other hand, the evaluation of even very sophisticated garments and protective equipment in complex environmental scenarios by simply placing the manikin in the actual gear and environment is a major merit of the thermo-physiological human simulator. Further, 24-h operational readiness, high repeatability, low cost operation and high time effectiveness compared to human trials, and with no ethical concern often seem to outweigh the investment cost. However, at the same time, the technical limitations and best-performance validation range of the thermo-physiological human simulator as described in sections 2.3 – 5 should be observed[56].

Case Studies

Single-sector thermo-physiological human simulator for fire-fighter and cooling garments

Human subject studies to investigate the heat-impact on firefighters during physical activity are cumbersome, costly, and restricted due to ethical considerations. Therefore, there is a need for simulations facilitating and accelerating such investigations. Thermo-physiological simulators bear a great potential for this purpose. Psikuta *et al.*[19] showed in a validation study of the single-sector thermo-physiological human simulator, that combining the Fiala multi-node model of human physiology and thermal comfort with the sweating heated cylinder Torso, relevant physiological parameters, such as skin and core temperatures can be simulated accurately for semi-nude humans. Furthermore, Psikuta *et al.*[22] validated this system (Table 1, case 2) for various types of protective clothing (from thin single-layered to thick multi-layered) with varying properties (e.g. water vapour permeable and impermeable) and for various activity levels (reclining, sitting, walking, and running). The limited sensitivity of the single-sector human simulator to the functional clothing properties as described by Psikuta *et al.*[22] was further investigated by Fontana *et al.*[54] and Fontana *et al.*[55]. They confirmed the limitation and pointed out that this sensitivity was noticeably affected by exercise intensity followed by work duration[57]. Due to expected uncompensable and health threatening heat stress, such protocols cannot be applied in a human subject trial, whereas human simulator can offer the possibility to simulate such harsh exposures. Because of its accuracy and at the same time relative simplicity of operation, the thermo-physiological human simulator based on Torso device is being considered for thermal assessment of fire-fighter gear in ISO/DIS18640[58].

Another application of a single-sector thermo-physiological human simulator was related to the evaluation of the cooling garments using sweating agile thermal manikin SAM as basis of the simulator (treated as one sector with only one skin temperature, sweat rate, and heat loss value applied homogenously to all manikin and model sectors[23]) and compared to the manikin alone and the human subject trial[56]. The results showed that the cooling power determined with the thermal manikin was not comparable to the measurement with humans. This disagreement was partly reduced when using the human simulator. The simulator also successfully predicted core and mean skin temperatures upon the application of the mild intensity of cooling and core but not mean skin temperatures upon the application of the strong intensity of cooling. This was caused by the local heat extraction executed by the intensively cooling vest being too heterogeneous. This effect would be properly addressed when using multi-sector thermo-physiological human simulator with simulation of local skin temperatures and heat losses, and hence, higher sensitivity to local thermo-physiological effects.

Multi-sector thermo-physiological human simulator

The Newton thermal manikin together with the models of thermo-physiology and comfort ManikinPC^2 remains the only commercially available thermal human simulator system up to date[24, 59)]. It has been applied to reproduce a complex scenario with a firefighter turnout gear, involving walk and rest cycles[60)] to demonstrate its benefits for evaluation of protective systems. Although the trends in core and skin temperatures course were analogous to the experimental data collected in a human subject study, the prediction accuracy was not quantified (qualitative analysis in graphs without rmsd, bias and confidence interval report). The Newton-ManikinPC^2 system has also been used for comparing the performance of different body-mapped sportswear[17)] or personal cooling systems[16)]. In both studies, tests were performed with the manikin operated at constant temperature, showing which systems were most efficiently dissipating the heat away from the human body by comparing the manikin's heat loss. However, only the additional measurements carried out with the manikin controlled by the thermo-physiological model allowed the evaluation of the systems in realistic conditions such as exercise-rest scenarios, providing also information about the predicted thermal sensation. The studies performed so far on the Newton-ManikinPC^2 system show that this system can be used for examining the impact of high-performance or protective clothing on the state of the human body, allowing a comparison between different prototypes. However, it is necessary to conduct thorough qualitative and quantitative validation for a wide range of conditions including scenarios with clothing.

Head thermo-physiological simulator for bicycle headgear

As the head is a body part of high thermal sensitivity[61–64)], the prediction of thermal comfort for protective headgear is of particular interest for occupational safety, professional sports, and leisure time activities. Thermal head manikins enable a systematic investigation of heat transfer occurring through headgear including its classification and offer crucial inputs for the development and improvement of headgear thermal performance. However, they provide physical data on heat transfer with limited value for the assessment of its impact on local and whole-body thermoregulation as well as thermal sensation and comfort perception. In order to assess the thermo-physiological impact of headgear, a multi-sector thermo-physiological head simulator has been developed[28)]. The device peculiarity consists of the combination of experimental simulation of heat transfer at head site and the numerical simulation of heat transfer for the rest of the body. In this way, realistic heat transfer phenomena including moisture absorption-desorption cycles, condensation or moisture migration across fabric and material layers with the application of headgear can be investigated with regard to predicted whole-body thermo-physiological responses. This enables a more sophisticated assessment of head gear with regard to specific applications and environmental conditions like occupational safety (e.g. minimized thermal impact of fire fighter helmets), professional sports (e.g. optimal ventilation of aerodynamic bicycle helmets for time trial competitions) and leisure time activities (e.g. optimised wearing comfort for bike helmets) in order to increase productivity, physical performance or thermal comfort, and thus user acceptance.

Conclusions

The new approach presented in this paper combines the physical manikin and a mathematical human thermoregulation model to a thermo-physiological human simulator that helps to overcome the limitations of both components used stand-alone. The detailed methodology of development, validation, and operation of such devices including technical challenges and limitations of thermo-physiological human simulators, their application and measurement protocol, strategy for setting test scenarios, and the comparison to standard methods and human studies has been presented. In summary, the thermo-physiological human simulator provides a complementary method to investigate and assess thermal interactions between the human body, protective clothing and equipment, and its environment including complex heat and moisture transfer occurring in clothing assemblies. It can provide the information about the long or short term impact of protective clothing on the thermo-physiological state of the human body, and hence, it can be used to predict the working time in hazardous conditions for a specific physical activity until any dangerous state may occur, for example, time to heat stress, time to health risk, survival time. The fluid requirement (fluid loss) to prevent dehydration can be also obtained for different kinds of protective clothing systems. On the cold side, the human thermal simulator can help to predict the occurrence risk of local freezing and non-freezing injury and whole body hypothermia in very cold conditions. Therefore, it provides the basis to set health related references and to investigate and compare protective properties of clothing systems, both at low costs and without any ethical concerns.

Use of Human Simulators in the Future

Since the first commercial adaptive manikin has already appeared on the market and in general the number of such human simulators is increasing, some opportunities emerged to use them in various disciplines dealing with human health, safety, and well-being. The next step to make these human simulators even more accurate tools for the research is to put more effort into the proper evaluation of their reliability. Specifically, the manikin and the thermo-physiological model need to be evaluated prior to the coupling. Secondly, there is a need for a public validation database and standardised process of performing validation for both human thermoregulation models and thermo-physiological human simulators. Furthermore, the increased resolution of body segments in physical manikins would offer an opportunity to capture accurately local heat transfer related to human body, clothing and environment heterogeneity (asymmetric environmental conditions, non-uniform clothing properties and body coverage, sweat production and skin sensitivity mapping available since recent). In order to apply the manikins in field studies more mobile or self-contained manikins would be of advantage. With regard to the mathematical models for thermo-physiological responses, an increase in the spatial complexity including variations in local tissue properties would help to more accurately assess local thermal interactions and its effect on whole body thermoregulation for healthy people. The (thermo-physiological) personalisation of the model in order to represent particular populations of interest (e.g. elderly, sleeping, or suffering from illnesses such as diabetes) further broadens the range of application for thermo-physiological human simulators.

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