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Future Trends in the Development of Thermal Manikins Applied for the Design of Clothing Thermal Insulation

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Abstract
Thermal manikins were created with the intention to design and model protective clothing insulation for specific conditions, e.g. military clothing and clothing for divers. At present thermal manikins have a broader use, i.e. to assess the effect of clothing on a human body, to assess its influence on thermal comfort during work in a given clothing ensemble and to test innovative solutions bringing about a reduction in the thermal heat load. When using thermal manikins it should be borne in mind that heat exchange through clothing is, to a large extent, determined by the temperature distribution on human skin. The aim of the study was to find out to what extent thermal manikins can be used to represent the correct distribution of temperature on human skin. To this end, comparative measurements of the temperature distribution on the surface of a standard thermal manikin with a structure generally used and on the surface of the skin of volunteers were performed. The tests conducted showed that for the further development of thermal manikins computer software should be developed which would help to predict the temperature distribution on the manikin surface corresponding to the skin temperature of volunteers. Such software should allow for the simulation of thermal regulatory mechanisms in a human, i.e. an increase in skin temperature caused by vasoconstriction and shivering, as well as a decrease in skin temperature due to vasodilatation and sweating. In a thermally neutral environment, the methods which are currently used to control the thermal manikin seem to be sufficient.

Key words: *thermal manikin, skin temperature, thermal insulation, protective clothing.*

Introduction

Thermal manikins are devices by means of which it is possible to simulate heat exchange between the human and the environment. The first one was a one-segment copper manikin made for the US Army in the early 1940s of the 20th century [1, 2]. From the very beginning, this thermal measurement device was designated for the clothing industry, mainly in the design of specialised clothes, primarily for the Army [3]. Hence development of the structure of a thermal manikin reflected the specificity of this branch of industry. In the ensuing years further modifications of the structure of manikins were introduced, i.e. the number of segments (parts of the body) of a manikin was increased, and the possibility of simulating movement and the sweating process were introduced [4 - 6]. As a result, a more precise representation of a human was created. At the same time, those devices became increasingly lighter and "friendlier" in terms of their operating modes and the possibility of putting the clothes on. The first female thermal manikin appeared in laboratories in 1989. A change of sex was due to the fact that female manikins were shorter and lighter in comparison to their male counterparts. In addition, given the female tendency to have plenty of outfits, scientists hoped for better use of manikins. Recently thermal manikins representing new born and small babies have been developed [7]. As studies show [8 - 11], the sex of a manikin has no influence on the measurement of clothing thermal insulation.

In recent years it has been observed that studies on manikins are of two kinds: on the one hand very complex and technologically advanced manikins are being constructed, being made of 132 segments and equipped for the sweating process [12]. Those types of manikins are used to perform highly specialised tests, mainly to examine the thermal environment in closed spaces and vehicles. On the other hand, a branch of industry which manufactures simple manikins has been developed. Simple manikins are equipped only with the basic function of heating and are designed to make measurements of clothing thermal insulation. They are used by companies producing sports and protective clothing.

The introduction of computerised methods of the control and adjustment of automatic system operations was a considerable step in the development of the thermal manikin structure, as a result of which it was possible to conduct more accurate studies by setting more precise temperature values on the surface of particular segments.

Presently thermal manikins are used in the clothing industry to determine clothing and sleeping bag thermal insulation [13], as well as the parameters of a surrounding environment in which the use of a sleeping bag will not cause the cooling or overheating of the body [7, 14]. Furthermore they are used to assess thermal comfort during work performed in clothes in a given thermal environment, to test heat and water vapour transfer through clothing etc. There are also standards developed for testing clothing insulation and clothing evaporative resistance [15, 16]. Apart from standardised tests, manikins can also be used to assess the cooling capacity of phase transformation compounds used in clothes which are designed for performing work in a hot climate. They can also be used to model thermal insulation on every part of the human body so that the clothing ensemble can be customised precisely to the specificity of its application in a cold or hot climate.

Given that tests with the use of manikins are not difficult to carry out and that the results of such tests are more accurate

Table 1. Parameters of the environment in the climatic chamber.

Phase of the test	I	II	II	IV
Air temperature, °C	15	20	25	30
Air velocity, m/s	0.05			
Relative air humidity, %	50			

than with the participation of people [18], those devices should be used primarily at the design stage, and also later, in a subsequent phase, where ideas for the improvement of clothes are verified.

As transpires from the information presented above, thermal manikins are a very useful tool for making a quick assessment of clothing thermal insulation. In accordance with ISO 15831:2004 Clothing - Physiological effects - Measurement of thermal insulation by means of a thermal manikin, during the testing of clothing insulation, the manikin surface temperature should be constant and equivalent to 34 °C. In reality, however, human skin temperature assumes various values in different body parts. Temperature values result from parameters of a thermal environment occupied by a human and from the functioning of the thermoregulatory system of a human body [19, 20]. In order to make tests more precise, it appears necessary to strive to achieve congruence between the temperature distribution on the manikin surface and human skin. This aspect can be of vital importance when designing and testing clothing used for work in a cold environment where it is the sole element guarding a worker against hypothermia.

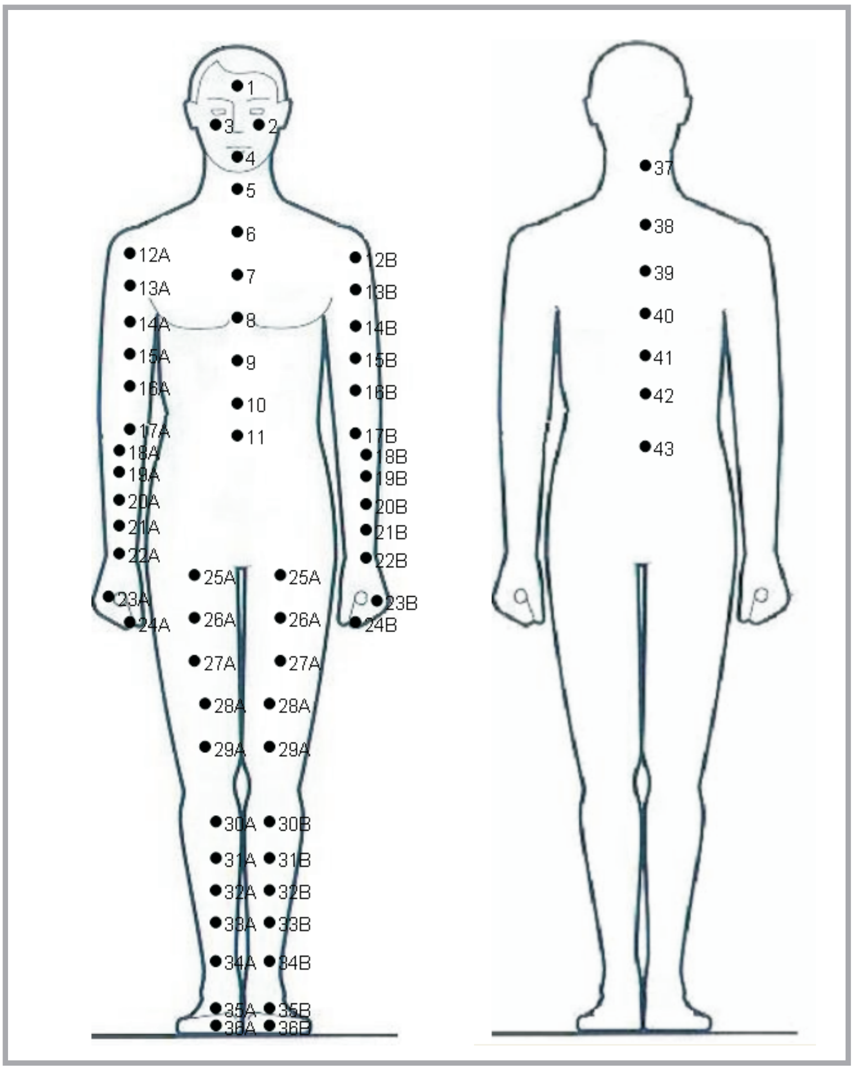

Figure 1. Distribution of measurement points in which the skin/manikin surface temperature was examined.

Objective of the case study

The objective of the case study was to find out to what extent a thermal manikin can be used to map the temperature distribution of human skin. Tests were conducted with the use of a standard thermal manikin of a structure generally used, called Diana, which is a Danish type of a manikin. Such manikins are successfully used in numerous laboratories dealing with the testing of protective clothing. The focus of the tests was to investigate the possibility of obtaining a statistically significant compliance between the manikin surface temperature and human skin temperature. Furthermore tests were conducted with a view to finding out how significant the differences between those two values were. The test results obtained provided the grounds for determining which direction should be chosen for the further development of thermal manikins.

The use of thermal manikins

Thermal manikins used in laboratories specialising in the testing of clothes are usually composed of segments (14 to 32). The segments are equipped with an independent power source; each segment representing a different part of the body [1]. The functioning of a thermal manikin can be controlled by applying 4 modes [21]:

- no heating – the thermal manikin reads a temperature on the surface of particular segments, none of which is warmed up,
- maintaining a stable temperature – a changing amount of power is supplied to the segments to maintain a constant, set temperature on the manikin's surface,
- maintaining a constant power supply - a constant set power supply is maintained in the segments, and the temperature on the surface is a result of the power supply and conditions of the surrounding environment
- changing the temperature and power supply – the so-called "comfort" mode, in which the temperature on the manikin's surface is determined by ***Equation 1*** [22].

$$T_s = 36.4 - 0.054\, H_c \qquad (1)$$

where:

T_s – temperature on the surface of the segment, ^oC,

H_c – segment heat loss, W/m^2.

In the 'comfort' mode the temperature on the segment surface and segment heat losses result from thermal environment conditions surrounding the manikin. These values are read from manikin software. This mode makes it possible to obtain such a temperature distribution on the manikin surface which very closely reflects human skin temperature. For this reason the "comfort" mode is very frequently used to simulate heat exchange between the human and the environment.

Methodology

In the present studies a nude thermal manikin 'Diana' was used. It is the property of the Thermal Load Laboratory at CIOP-PIB [13, 18]. During the tests, the 'comfort' mode was applied so that a comparable temperature distribution between the manikin surface and human skin could be achieved. During the tests, the thermal manikin was placed in a climatic chamber. Air parameters which were created in the chamber are shown in ***Table 1***. Once the heat exchange between the manikin and the environment had been established, the temperature on the manikin surface was measured. To this end, a FLIR ThermaCAM™ SC660 was used. Upon completion of tests with the thermal manikin, measurements were carried out with the participation of 14 volunteers (men within the age bracket 20 - 25, height 1.78 m, sd = ± 0.05 m, weight 71.8 kg, sd = ±7.9 kg). Each subject participated in the test during one day. The volunteers were required to be in good shape for the measurement exercise, i.e. after a good night's sleep and breakfast. Additionally they were requested not to drink alcohol for 48 hours prior to the experiment. Tests in a climatic chamber were commenced invariably at the same hour, i.e. 9 a.m. . Semi-nude volunteers were exposed to exactly the same thermal conditions in which the thermal manikin was placed (***Table 1***). In the given laboratory conditions (***Table 1***) the subject was asked to remain for 1 hour, The tests began at an ambient temperature equivalent to 15 °C. When heat exchange between the body of the volunteer and the environment had been established (a steady state was achieved after 1 h), thermographic measurements of the skin temperature were taken. Next the ambient temperature was changed by 5 °C, and the subject was again exposed to set thermal conditions for 1 hour. Further temperature changes were conducted in a similar manner to the variant described above.

Tests performed by [23] confirmed the degree of precision with which the skin temperature was examined, using a thermographic camera.

The thermografic measurements provided the grounds for determining the temperature on the surface of the manikin and on the skin of the volunteers. The measurement points are shown in ***Figure 1***. The structure of the thermal manikin and its control system do not allow the possibility of adjusting the surface temperature in particular parts of each segment. However, it is possible to control the mean temperature of the whole segment. The temperature at given points of the segment results from the distribution of heating wires under the surface of the manikin. For this reason, when the temperature at a given measurement point of the manikin surface was determined, mean temperature values were also specified for the manikin/volunteer's skin on particular segments/parts of the body (marking of the segments as shown in ***Figure 2***). The mean skin temperature for all the volunteers was compared with the temperature on the manikin's surface. In the statistical analysis of cases where the analysis of variance showed a lack of normal distribution, the Wilcoxon signed-rank test was applied ($p < 0.05$), and in cases where the variance distribution had a normal/regular distribution, the t-test ($p < 0.05$) was used. Additionally points were determined at which an error of lower than 5% occurred between the manikin surface temperature and mean skin temperature.

Results

The aim of the first phase of the analysis was to verify the precision of the results obtained, i.e. the accuracy with which the skin temperature distribution was

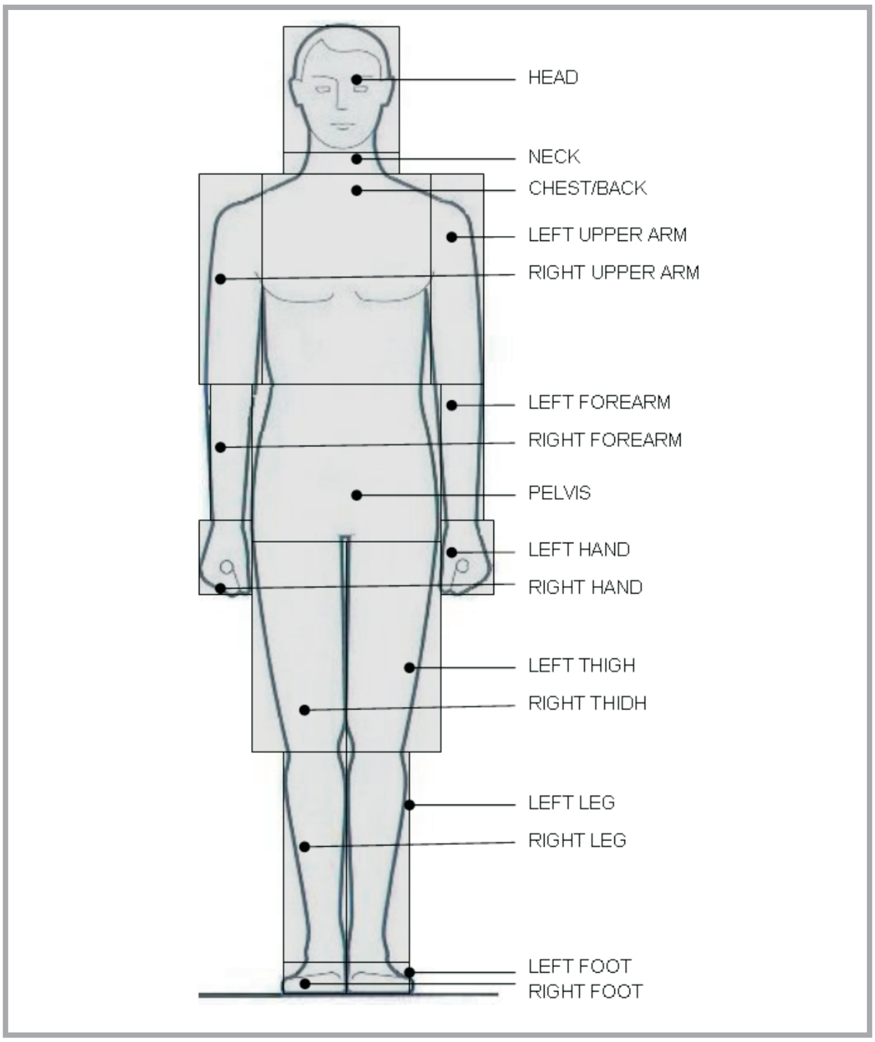

Figure 2. *Assumed division into segments/body parts of the manikin/volunteers.*

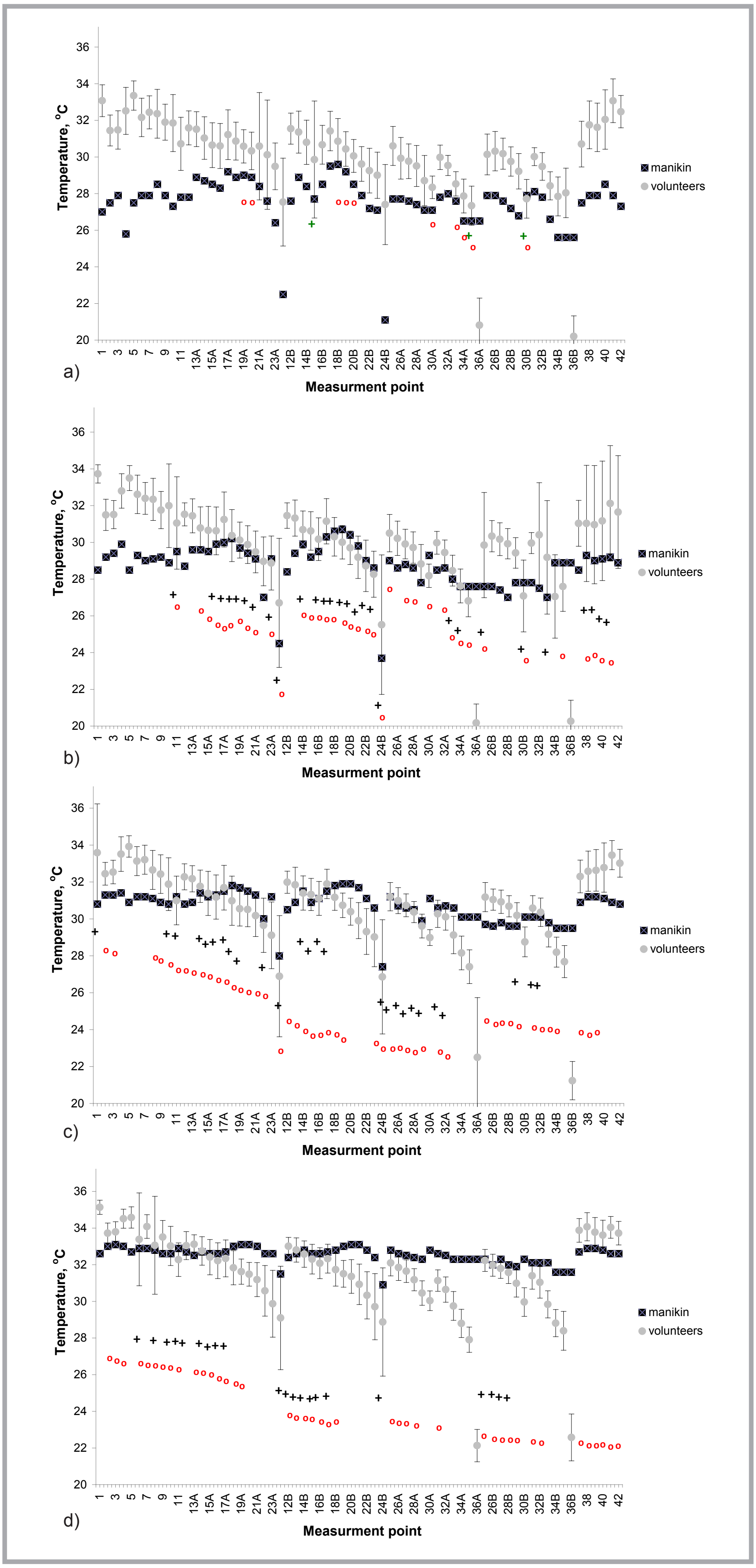

***Figure 3.** Mean temperature values for volunteer skin and for the thermal manikin at the measurement points (ambient temperature equivalent to a) 15 °C, b) 20 °C, c) 25oC and d) 30 °C; + - lack of statistical significant differences; circle – error below 5%).*

mapped on the thermal manikin. To this end, measurements at 68 measurement points were taken, shown in ***Figure 1*** (see page 90). ***Figure 3*** show temperature values for the manikin surface compared with mean values of the skin temperature for all 14 volunteers. The drawings also present results of the statistical analysis of the results obtained (cross) and points (circle) where the error was below 5%.

At an ambient temperature equivalent to 15 °C considerable differences were observed between the temperature on the manikin surface and the mean skin temperature of the volunteers; a higher temperature was noted on the skin of volunteers. The biggest differences were observed on the head, amounting to even 6.7 °C. Slightly smaller ones (ca. 5 °C) occurred on the neck, back, feet and hands, while the smallest (below 2 °C) were on the forearms and calves. A statistical analysis revealed that there were no statistically significant differences in the 3 measurement points, whereas an error of below 5% occurred at 10 measurement points. Such significant differences are probably caused by the shivering observed on volunteers. Muscle shivering appears in a human body in a cold environment, leading to additional heat production and, in consequence, an increase in skin temperature [33]. ***Equation 1*** does not allow for a temperature increase as a result of shivering, which is due to the fact that it is formulated on the assumption that ambient thermal conditions are moderate. It can be therefore concluded that a thermal manikin should not be used to represent the temperature distribution of a semi-nude human in an environment with an ambient temperature equivalent to 15 °C.

At an ambient temperature equivalent to 20 °C, as before, the biggest differences in the mean skin temperature of the volunteers occurred at measurement points located on the head (even 5.2 °C) and feet (even 8.6 °C); in all cases, with the exception of feet, the temperature of the volunteers' skin was higher than that of the manikin's surface. Differences within the range 2 - 3 °C occurred at measurement points located on the chest, back, thighs and calves. The smallest differences, below 1.5 °C, occurred on the arms and hands. A statistical analysis proved there was a lack of statistically significant differences in the 26 measurement points located on the thighs, left and right forearm, on the hand and on the back. In addition, an error of below 5% occurred at 37 measurement points.

It can be therefore concluded that at the points mentioned above, the temperature distribution on semi-nude human skin is very well represented, ergo the equation for thermal manikin control can be regarded as a sufficient solution.

At an ambient temperature equivalent to 25 °C, the manikin surface temperature was higher than the volunteers' mean skin temperature at the following measurement points: forearms, hands, calves and feet; the difference between those values was a maximum of 8.3 °C on the feet and below 2 °C at other measurement points. On other parts of the body/segments, the skin temperature was higher than the manikin surface temperature by a maximum of 2.6 °C (head, neck, back) and below 1.5 °C. On the basis of the statistical analysis, it can be concluded that at 25 measurement points there are no statistically significant differences in the results obtained for the thermal manikin and human skin temperature. Analogous to the previous variant of the test, a lack of differences occurred on the forehead, thighs, left and right forearm, hands and partly on the calves. An error of lower than 5% occurred at 47 measurement points. It can be therefore concluded that in such thermal conditions the skin temperature distribution on semi-nude volunteers was well mapped, hence changing the software controlling the thermal manikin is not required.

At an ambient temperature equivalent to 30 °C, the manikin surface temperature was higher than the mean skin temperature on forearms, hands, thighs, calves and feet. At most, differences on those parts of the body/segments amounted to 2.7 °C for the hands and 10 °C for feet. In other cases the differences were below 1.8 °C. For the head, neck, chest, arms and back the highest values were observed for volunteers as opposed to the manikin. Differences in those temperatures ranged between 0.7 – 2.5 °C for the head, 0.3 – 1.2 °C for the chest and reached a maximum of 0.6 °C for arms. A statistical analysis showed the lack of a statistically significant difference at 20 measurement points located on the chest, pelvis, left and right arm and right thigh. An error of below 5% occurred at 41 measurement points. It can be therefore concluded that the skin temperature distribu-

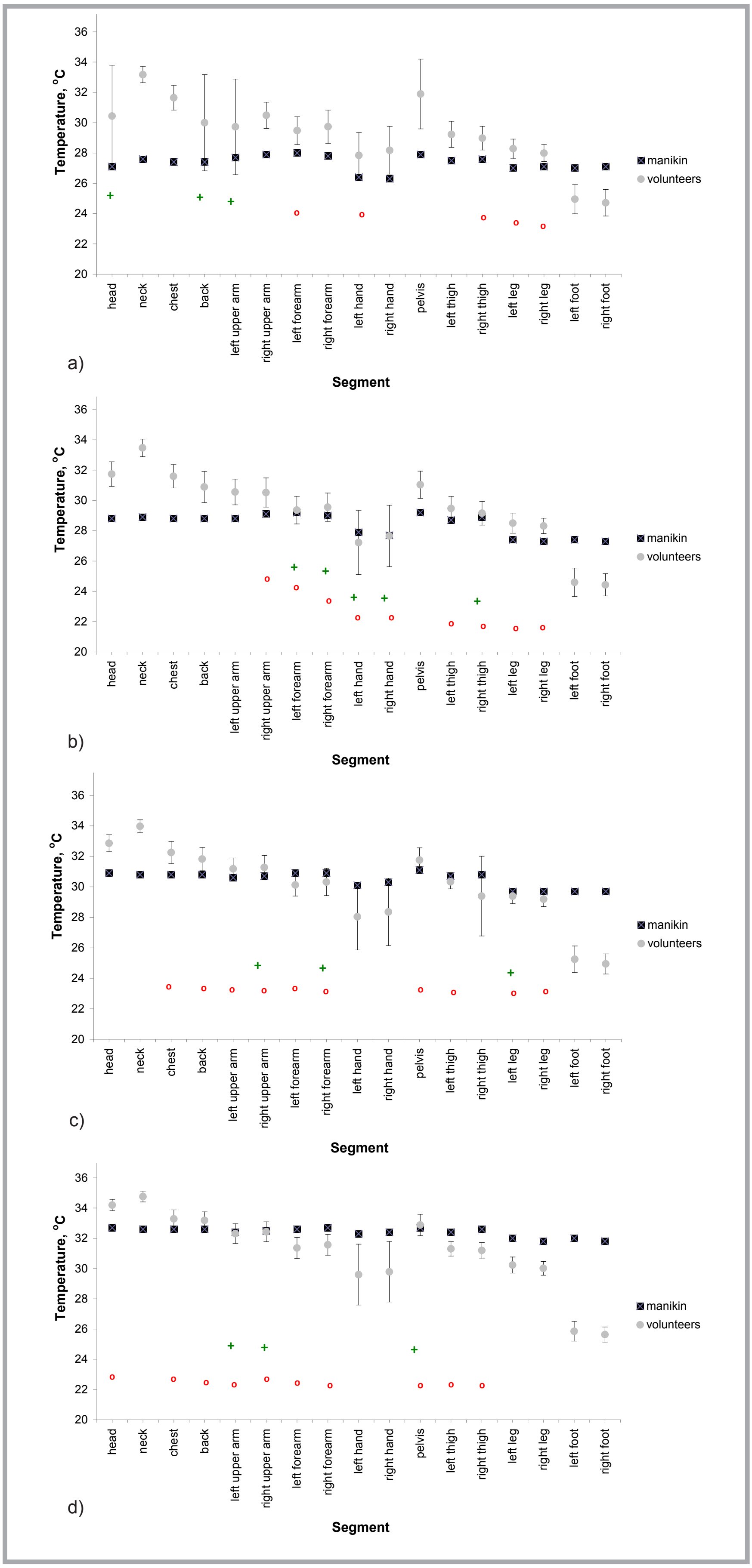

__Figure 4.__ Mean temperature values for particular body parts of the volunteers or segments of the thermal manikin (ambient temperature equivalent to: a) 15 °C, b) 20 °C, c) 25 °C and d) 30 °C; + - lack of statistical significant differences; circle – error below 5%).

tion on semi-nude volunteers is mapped well enough on a thermal manikin.

In the case of this analysis it can be concluded that at an ambient temperature equivalent to 15 °C it should not be expected that the skin temperature distribution on the surface of the thermal manikin will represent the real temperature on the skin of the volunteers. In the remaining instances the most truthful representation was noted for measurement points located on the arms and forearms of the manikin and partly for the thighs. The biggest number of measurement points at which no statistically significant differences occurred were determined for an ambient temperature equivalent to 20 °C. The highest number of points for which the error was lower than 5% occurred at an ambient temperature equivalent to 26 °C.

Next the mean temperature values for particular parts of the body of the volunteers were compared with those determined for analogous segments of the manikin (parts of the body marked as shown in ***Figure 2***). ***Figure 4*** (see page 93) present mean temperature values on particular parts of the body with marked results of a statistical analysis (crosses) and with an error of below 5%.

At an ambient temperature equivalent to 15 °C, differences in temperature values ranging from 2 to 5 °C occurred on the head, neck, chest, back, arms and feet. On the remaining parts of the body/segments those differences were within the range 1.3 to 1.9 °C. A statistical analysis showed a lack of statistically significant differences on 3 segments, i.e. head, back and left upper arm. An error of below 5% occurred on 5 segments.

At an ambient temperature equivalent to 20 °C the biggest differences in the mean temperature on the surface of the segment/volunteers' skin occurred on the head, neck, chest, back, feet (up to 2.8 °C), arms (1.8 °C) and calves (ca. 1 °C). In the remaining cases the differences were 0.7 °C at most. A statistical analysis showed a lack of statistically significant differences on 5 segments, i.e. left and right forearm, left and right arm and right thigh. An error of below 5% occurred on 9 segments.

At an ambient temperature equivalent to 25 °C, once again the biggest differences were observed on the feet (ca. 4.5 °C), neck (3.2 °C), hands (ca. 2 °C) and head (1.9 °C). On the chest, back and thighs the difference was below 1.5 °C, on the remaining parts of the body/segments - below 0.7 °C. A statistical analysis showed a lack of statistically significant differences on 3 segments, i.e. right upper arm, right forearm and left leg. An error of below 5% occurred on 10 segments.

At an ambient temperature equivalent to 30 °C the biggest differences in the mean temperatures of particular parts of the body/segments were observed for feet (ca. 6 °C), the head, neck (1.5 °C and 2.1 °C) and hands (2.6 °C). On the remaining parts of the body/segments the difference in temperature was 1.7 °C at most. The smallest differences (below 0.5 °C) were noted on the chest, back and arms. A statistical analysis showed a lack of statistically significant differences on 3 segments, i.e. left and right upper arm and pelvis. An error of below 5% occurred on 10 segments. Also, in this case the best temperature correspondence was obtained at an ambient temperature equivalent to 20 °C. The highest number of segments with a statistical error lower than 5% occurred at an ambient temperature above 20 °C.

Conclusions

On the basis of the test conducted , the following conclusions have been drawn:

1. Considering the accuracy with which the human skin distribution was represented at the measurement points of the manikin, the best results were achieved at an ambient temperature equivalent to 20 °C and 25 °C.
2. At an ambient temperature equivalent to 15 °C a statistical correspondence was achieved only at 3 measurement points, which was attributable to muscle shivering observed on volunteers. This phenomenon is not taken into account by software controlling the thermal manikin.
3. At an ambient temperature equivalent to 20, 25 and 30 °C, the best correspondence was achieved for the arms and forearms and partly for the thighs. At the same time, proper temperature distribution was not achieved on the head, chest and back, i.e. at the measurement points which are vital from the point of view of thermal clothing modelling.
4. Considering the mean temperature for particular segments, the best correspondence was achieved again at an ambient temperature equivalent to 20 °C. However, in this case the result achieved should not be considered satisfactory. The statistical correspondence was 5 out of 17 segments/parts of the body.

On the basis of the tests conducted it is possible to determine future directions for the further development of thermal manikins towards a more accurate mapping of human skin temperature. First of all, a thermal manikin control system should allow for the thermoregulatory processes taking place in a human body, i.e. in a cold environment - vasoconstriction and shivering, and in a hot environment - vasodilatation and sweating [32].

The tests results point to the biggest problem occurring at an ambient temperature equivalent to 15 °C. In the case of the semi-nude volunteers exposed to such a relatively low ambient temperature, thermal processes, i.e. vasoconstriction and shivering were triggered, resulting in an increase in skin temperature. Thermal manikins are usually not equipped with software which allows for this additional heat production. Consequently the manikin surface temperature was lower. In a thermally neutral environment (20 and 25 °C) and in a hot climate (30 °C), the software controlling the thermal manikin was sufficient to obtain a decent correspondence between the temperature distribution on the manikin surface and the temperature of the volunteer's skin. It can be forecast, however, that in a hot climate (above 30 °C for semi-nude volunteers) the temperature on the volunteer's skin would be lower than that on the surface of the thermal manikin. Thus a relevant lowering of the surface temperature should be allowed for in new software.

Thermal numeric models of a human being have been developed for years [25 - 28]. They take into consideration both physical processes of a heat exchange as well as the functioning of the thermoregulatory system. In addition, a part of those models is realised by software based on the computational fluid dynamic (CFD) method, which takes into account anthropometric geometric data of a human being as well as the acclimatisation, distribution and adhesion of clothes to the body surface [29, 30]. There also exists a thermal manikin whose functioning is based on computational software - the thermal numeric model [31].

The functioning of the manikin was verified in a moderate climate. A change in the software system controlling the functioning of the manikin can solve the problem, i.e. unsatisfactory accuracy of the temperature measurements obtained on the surface. It should also be noted that the software currently used is sufficiently precise to map skin temperature distribution in a moderate climate. Given that the classification of a thermal environment in an area of a hot, moderate or cold climate depends on the human metabolism, clothing insulation and the parameters of the environment [25, 33], a moderate climate for semi-nude volunteers was defined within the 20 - 30 °C temperature bracket. In the case of clothed volunteers and a thermal manikin attired in clothes of higher thermal insulation, a moderate climate will range between different ambient temperature limits.

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