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Estimating the Effect of Torso Clothing Insulation on Body Skin and Clothing Temperatures in a Cold Environment Using Infrared Thermography

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Abstract
The study presents experiments, conducted with human subjects in an artificial cold chamber, assessing the influence of a cold environment on the temperature of the human body. Infrared thermography was applied as a non-invasive, contactless method for direct measurement of the temperature distribution of both clothed and uncovered parts of the body. Two subzero temperatures were applied and clothing ensembles with two different clothing insulation values were used to assess the effect of the clothing insulation of the torso on the temperature of clothed and uncovered parts of the body of the participants. The average temperature of the chest, back, upper arms, face and middle finger is presented and discussed in relation to the cold exposure duration and clothing insulation used. The results obtained showed the strong influence of the clothing insulation over the torso on skin and clothing temperatures of the body and overall cooling of the body in subzero temperatures.

Key words: *clothing temperature, skin temperature, cold environment, infrared thermography, thermophysiological comfort.*

Introduction

Thermophysiological comfort of the human body is related to the balance between heat production and heat losses from the body to the environment [1]. In a cold environment the temperature gradient between the body and the surrounding air is much higher than in a hot environment; the heat transfer is additionally complicated by the fact that the greater part of the body's surface is covered by several clothing layers, while the face and hands mostly remain uncovered [2]. The heat transfer rate from the body to the environment through the clothed areas is smaller than that from the skin surfaces, and depends strongly on the thermal insulation of the clothing ensemble. The uncovered body parts are substantial sources of heat losses from the skin surface to the environment [3, 4].

Infrared thermography has the advantage of measuring instantaneously and contactlessly the surface temperature of both covered and uncovered parts of the body, thus giving room for analysis of the thermal insulation of textile garments and thermophysiological reactions of the body in particular environment. Gasi & Bittencourt [3] used infrared thermography to assess the thermal efficiency of high-tech sportswear during physical activity. They found that a small variation in the temperature field of the clothing surface was a sign of better garment insulation. Matusiak [5] proposed the Thermal Comfort Index to assess the insulation abilities of textile materials, developed on the basis of infrared camera thermograms. The study showed the advantage of infrared thermography in assessing the insulation capability of all textile layers composing clothing, together with all air layers between them and between the skin surface and clothing. In [6] infrared thermography was successfully applied to estimate the core body temperature of persons with wildland firefighter protective clothing. Thermograms were used in [7] to assess the individual thermal comfort of a person in a sleeping posture and established a corealation between subjective evaluation of the participants and the results from infrared thermography.

Recently an algorithm was developed for determining clothing thermal insulation on the basis of infrared thermography [8]. The Finite Volume Method and infrared thermography were used to test multi-layer systems with potential application in protective clothing for firefighters [9]. Both infrared thermography and a theoretical model based on the thin plate theory were used to study the temperature distribution on a double layered fleece textile [10].

In a cold environment, the general cooling of the body and local cooling of the uncovered parts influence working abilities and performance. Even during limited exposure to subzero temperatures, cold related problems like thermal discomfort, pain sensation in the extremities, low efficiency and hampered finer finger movements may appear [11, 12]. It was proposed in [13] that the hand temperature be used for prediction of the thermal comfort of people indoors. De Oliveira & Moreau [14] made a measurement of local skin temperature to assess the thermal environment sensation of inhabitants of different environments with fluctuating air flow. Measurement of the skin temperature of uncovered parts of the body in a cold environment might be used not only for assessing the thermal comfort of people but also for evaluation of thermophysiological reactions, as the process of temperature decrement of face and hand skin starts before the process of vasoconstriction of the peripheral blood vessels.

In this study infrared thermography was used as a method for non-invasive, contactless measurement of the temperature of both covered and uncovered parts of the human body at two different subzero temperatures (-1 and -11 °C). The measurements were performed in an artificial cold chamber with two levels of clothing insulation. The aim of the investigation was to use the temperature distribution over the body as a token for an in-depth understanding of the relationship between the cooling of clothed parts of the body (back, chest, upper arms, thighs) and the body's uncovered parts (face, hands). At the same time, the investigation aimed to study the effect of the clothing insulation of the torso on the clothing and skin temperature of other parts of the body in different cold environments. The practical result of the research can be found in the information about how the insulation of the torso can influence the cooling of other body parts, which can be used in the designing process of ensembles for cold protection. Finally the study was used to lay the foundation for a larger-scale investigation of thermophysiological comfort in an artificial cold environment, based on infrared thermography.

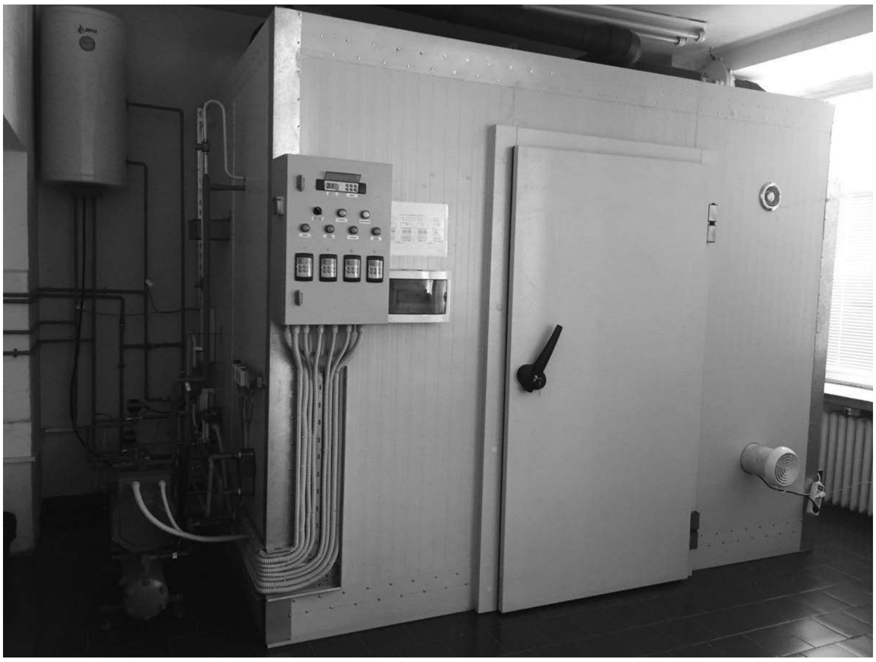

Figure 1. View of the artificial cold chamber.

Materials and methods

Subjects

Three young female subjects were volunteers in these experiments. Statistical data for their age, height and body mass were as follows: 29.6 years (SD 3.05), 1.60 m (SD 0.006), 52.7 kg (SD 3.05). The participants declared they had no diseases that require systematic use of drugs, including hormonal pills, which can change the responses of the thermoregulatory system, according to the findings in [15, 16]. Participants gave signed, informed consent for their participation in each protocol. All protocols conformed to the guidelines contained within the Declaration of Helsinki.

Clothing and ambient conditions

The clothing ensemble of each subject included personal underwear (0.04 clo), socks (0.05 clo, 100% cotton), ankle shoes (0.02 clo), denim trousers (0.15 clo, 100% cotton, size S), a blouse with long sleeves (0.25 clo, 100% cotton, size S), a sweatshirt from polyester microfibres (0.39 clo, size M), and outerwear: jackets with different thermal insulation (0.63 clo and 1.07 clo, size M). The clo-values of the clothing items were determined following ISO 9920 [17], except for the jackets, whose thermal resistance was measured using a Permatest instrument, which simulates human skin [18]. Thus two clothing ensembles with a total thermal insulation of 1.53 clo and 1.97 clo were used. This difference was due to the insulation over the torso only, with the different insulation abilities of the outerwear jackets. The hands and head remained uncovered. All subjects had long hair.

The experiments were performed in an artificial cold chamber (***Figure 1***), with dimensions 3 × 2 × 2.20 m. Two different subzero air temperatures were applied (-1 and -11 °C), and the chamber authomatically supported the cold environment in a temperature interval of -1 ± 1 °C and -11 ± 1 °C . During the experiments, the air temperature and relative humidity in the chamber were continuously recorded with a time step of 10 s.

Measurements

Remote recording of the surface temperature of the body (clothed and uncovered) was done using an infrared thermal camera, model FLIR E6 (FLIR Systems Inc., Wilsonville, OR, US) with the following parameters: IR 19200 pixels resolution (160×120), thermal sensitivity < 0.06 °C, temperature range from -20 to 250 °C, 3 measurement modes, multi-spectral dynamic imaging resolution 320×240, adjustment of radiation from 0.1 to 1.

Ambient data were measured inside the artificial cold chamber with a PS33 IAQ (Indoor Air Quality) monitor.

Experimental protocol

The study consisted of two phases, where one and the same protocol was used. In Phase One the participants were exposed to the impact of an ambient temperature of -11 °C. Phase Two took place 48 hours after the first one, and the exposure temperature was -1 °C. The same schedule was applied during the two phases to avoid possible circadian effects on the body temperature.

The subjects were exposed to the cold environment twice during each phase with the clothing ensemble with lower (1.53 clo) and greater insulation (1.97 clo), corresponding to the use of jackets with 0.63 and 1.07 clo insulation. The stay in the artificial cold chamber lasted 30 ± 5 min. Between the two exposures in the chamber per phase, each individual rested in an air-conditioned laboratory (temperature 22 °C, 65% relative humidity) for 65 ± 5 min.

The day before the measurements, participants were asked to stop eating and not to consume alcohol after 8:00 PM. On the day of the measurements the participants did not consume coffee, tea or energy drinks. One of the participants was a smoker, who was asked not to smoke before the measurements and during the breaks.

The protocol of the measurements included the following sequence:

1. Arrival of participants, dressing into matching outfits.
2. Acclimatisation in an air-conditioned laboratory (23 °C, 65% RH) for 30 minutes.

Figure 2. *Thermograms of individual 2, Phase One: a) chest, b) back, c) thighs.*

3. Move to the laboratory with the artificial cold chamber. Dressing of the first subject with extra clothing: a sweatshirt and jacket. Stay for 3 min, and then enter the chamber.
4. Exposure of the subject to the cold environment for 30 ± 5 minutes in a sitting posture (on a wooden chair).
5. Leave the chamber and stay in an air-conditioned room till the next exposure. Each participant was exposed twice to the cold during each phase.

Results and discussions

Ambient data

The average temperature in Phase One was -11.64 °C (SD 0.23 °C) and the average relative humidity 61.32% (SD 3.44%). The average temperature in Phase Two was -1.15 °C (SD 0.37 °C) and the average relative humidity 57.28% (SD 4.56%).

Clothing temperature

The temperature of the following clothed parts of the body were measured:

- back: at the level of the scapulas;
- chest: between the lines of the chest and neck;
- upper arms: between the elbow and shoulder – left and right upper arms;
- thighs in a sitting position – left and right thighs.

The average temperature on the clothing surface per every clothed part was determined using FLIR Tools software. The level of radiation on different surfaces was set following the information from [19].

Figure 2 shows exemplary thermograms of the chest, back and thighs of individual 2, captured within Phase One.

Figure 3 presents the change in the average clothing temperature in the zone of the chest at -11 °C. Analysis of the change in the clothing surface temperature showed that in the case of the jacket with lower thermal insulation, the surface temperature increased with time (***Figure 3a***), while the surface temperature of the jacket with higher insulation decreased (***Figure 3b***). Explanation of

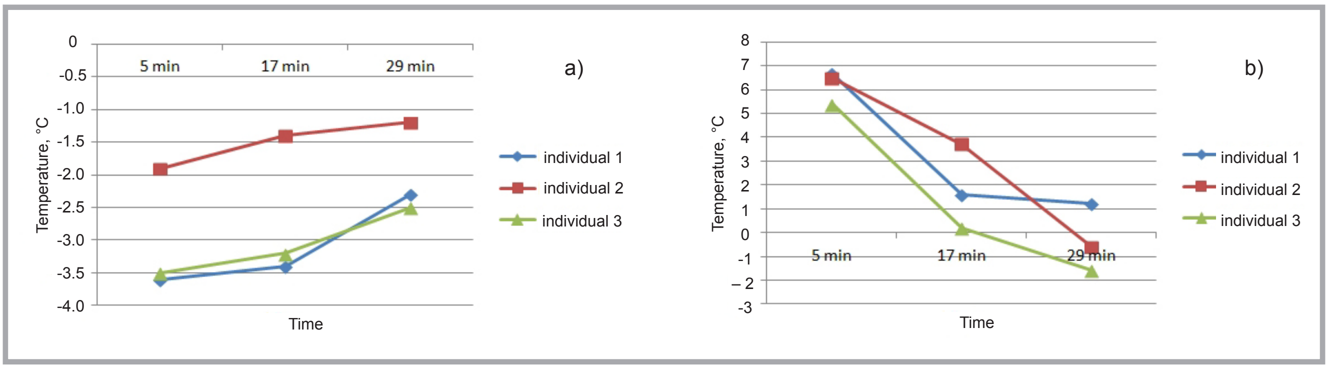

Figure 3. *Clothing temperature in the zone of the chest, Phase One, temperature -11 °C: a) clothing insulation 1.53 clo, b) clothing insulation 1.97 clo.*

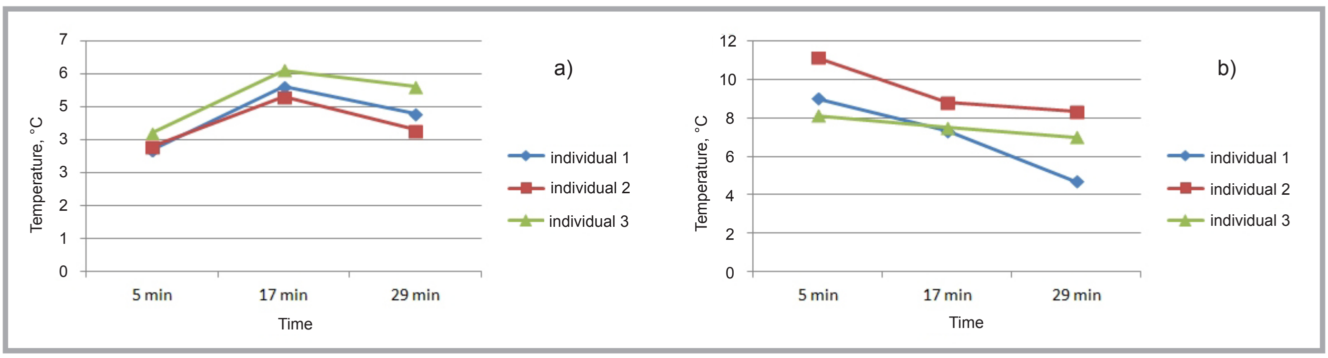

Figure 4. *Clothing temperature in the zone of the chest, Phase Two, temperature -1 °C: a) clothing insulation 1.53 clo, b) clothing insulation 1.97 clo.*

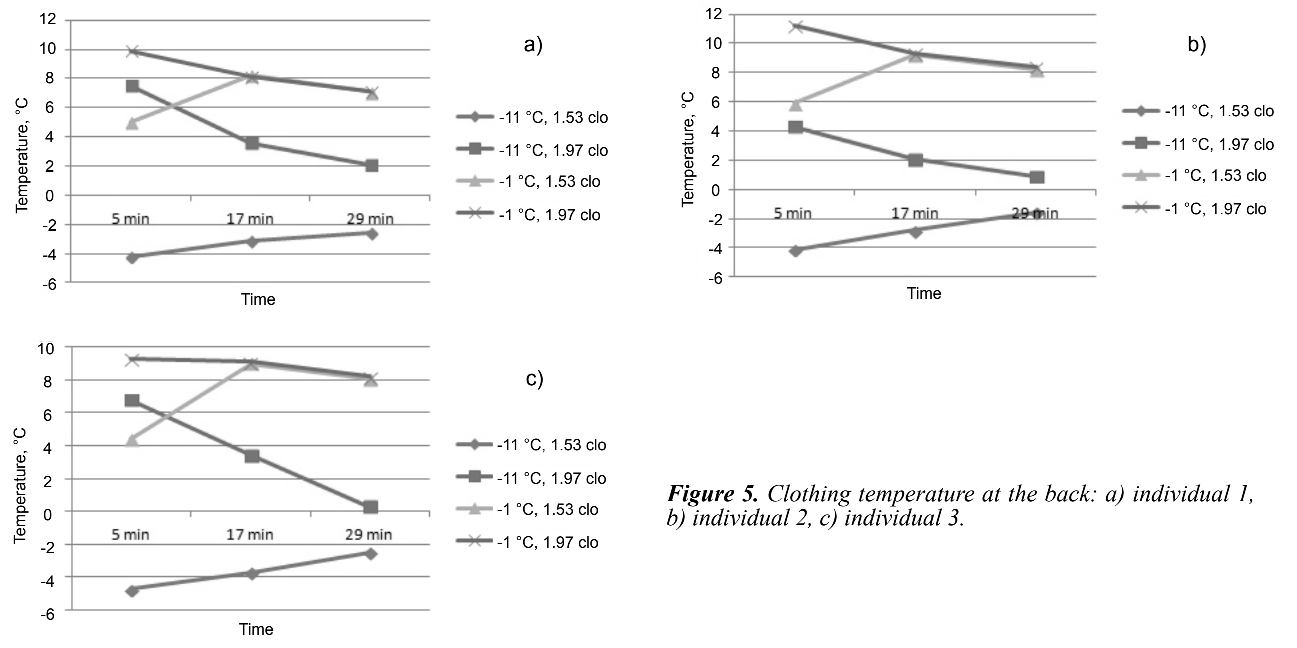

Figure 5. *Clothing temperature at the back: a) individual 1, b) individual 2, c) individual 3.*

this fact can be found in the mechanism of heat exchange between the body and the environment. The jacket surface temperature in ***Figure 3a*** is growing due to it being heated by the body, which supposes that a process of cooling of the body appears over time. The change in the jacket surface temperature in ***Figure 3b*** is due to the cooling effect of the surrounding cold air. It could be assumed, however, that the body temperature has decreased to a lesser degree than in ***Figure 3a***.

Similar results can be visualised for the temperature of the jacket surface in the zone of the chest during Phase Two (air temperature -1 °C): ***Figure 4***.

The lower thermal gradient between the body temperature and the temperature of the environment compared to Phase One led to the appearance of a different character of temperature change of the surface of the jacket with lower thermal insulation (***Figure 4a***). At the beginning of the exposure, the jacket was warmed on the account of the transmission of heat from the body, similar to ***Figure 3a***. Later on the surface temperature decreased due to the impact of the cold surrounding air. The temperature of the jacket with higher thermal insulation (***Figure 4b***) in the chest area decreased all the time, cooled by the ambient air. The cooling process was lighter compared with that in ***Figure 3b***, which was preconditioned by the higher ambient temperature. Obviously the two jackets provided better protection of the body at -1 °C than at -11 °C.

The field studies with real subjects require an analysis with respect to the effect of individuals on the results. Comparison of the graphs in ***Figures 3*** and ***4*** shows that the trends for all three individuals are similar, although variation in the values are observed.

Figures 5 present results for the temperature of the clothing surface on the back of the subjects, grouped as per individual.

Analysis of the results shows that there are clear trends for the combined effect of the parameters studied for all three subjects. At a temperature of -11 °C, the temperature in the back area increased in the case of the jacket with thermal insulation of 0.63 clo and decreased in the case of the jacket with thermal insulation of 1.07 clo. The increment was due to the transfer of heat ‘from the inside out’, at the expense of the body temperature, which proceeded more slowly. The faster temperature decrement in the case of the higher clothing insulation (the curves are steeper for all individuals) appeared because the process of cooling of the outer surface of the jackets was due to contact with the surrounding cold air. Within the period of cold exposure (approx. 30 min), the jacket with 1.07 clo clothing insulation managed to insulate the body from the cold environment.

At an ambient temperature of -1 °C, the trends are different (***Figures 5***): at the beginning of the exposure (5 min), there is a clear distinction in the back temperature of the jackets with different insulations. In the middle of the exposure (17 min), however, the temperature on the surface of the two jackets is equal for all three individuals. In the case of the jacket with thermal insulation 0.63 clo, the temperature rose due to the warming of the garment by the body. In the case of the jacket with thermal insulation 1.07 clo, the temperature decreased due to the cooling ‘from the outside in’. In the second half of the exposure till the end, the surface temperature of the two jackets decreased at the expense of the cooling effect of the surrounding air.

These results show that the ambient temperature has a significant effect on the behaviour of the clothing garments for protection from cold. The thermal insulation of the particular ensembles was essential in the colder environment (-11 °C), while at higher temperature (-1 °C) the outwear garments with different thermal insulations studied had similar surface temperatures over time.

Figure 6 (page 116) present results for the temperature of the clothing surface in the zone of the sleeves for each of the participants. The temperature of the sleeves was measured in front of the arm above the elbow, and was averaged for the left and right sleeve.

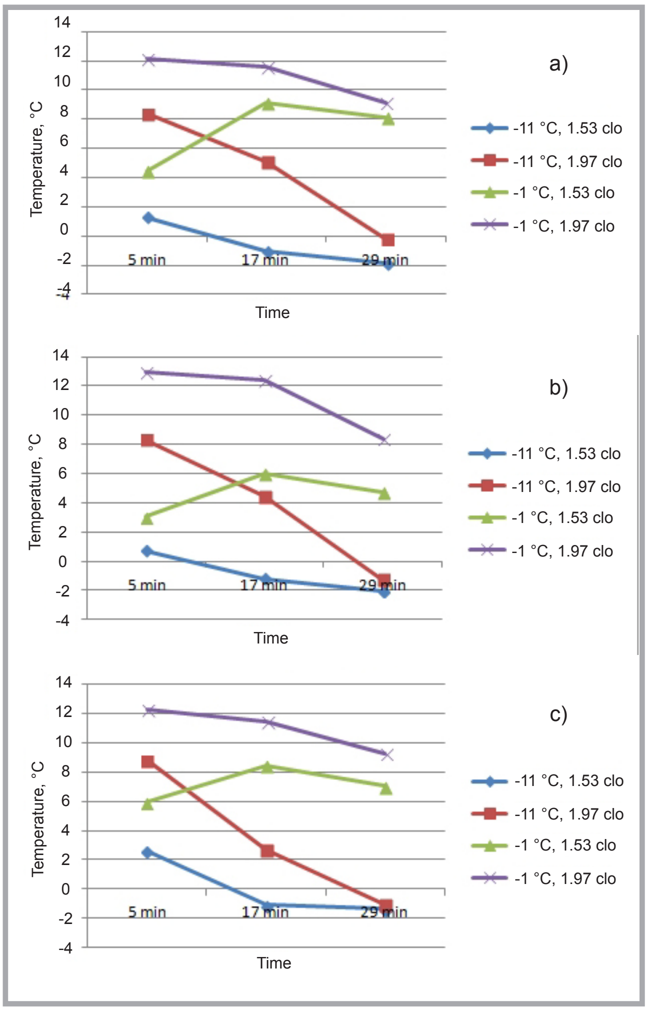

***Figure 6**. Clothing temperature at the sleeve: a) individual 1, b) individual 2, c) individual 3.*

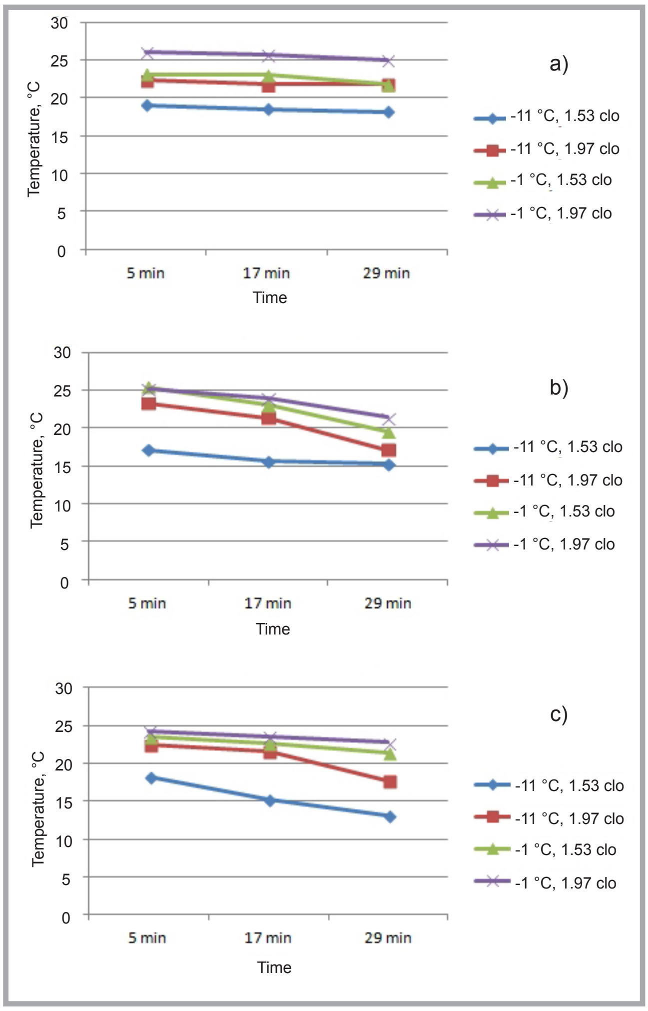

***Figure 7**. Clothing temperature at the thighs: a) individual 1, b) individual 2, c) individual 3.*

The results from the measurements show that in most cases the temperature in the area of the sleeves is the highest one, if compared with the clothing temperature of the chest and back. The trends in temperature change over time were similar, with one exception: at -11 °C the temperature of the sleeves of the jacket with clothing insulation of 0.63 clo decreased continuously during the exposure, in contrast to the temperature of the chest and back surface, which gradually increased. A possible explanation of this result can be found in the smaller surface area of the arms compared to that of the torso and in their inability to heat the surface of the clothing layers as the torso does. Proof of this explanation is the fact that the temperature of the jacket surface is at its highest in the zone of the sleeves: obviously the transfer of heat from the body to the environment (direction from inside to outside) is greatest. Another realistic reason for the results is the smaller thickness of the air layers in the sleeves as compared with that of the torso (due to the folded elbows in the sitting position).

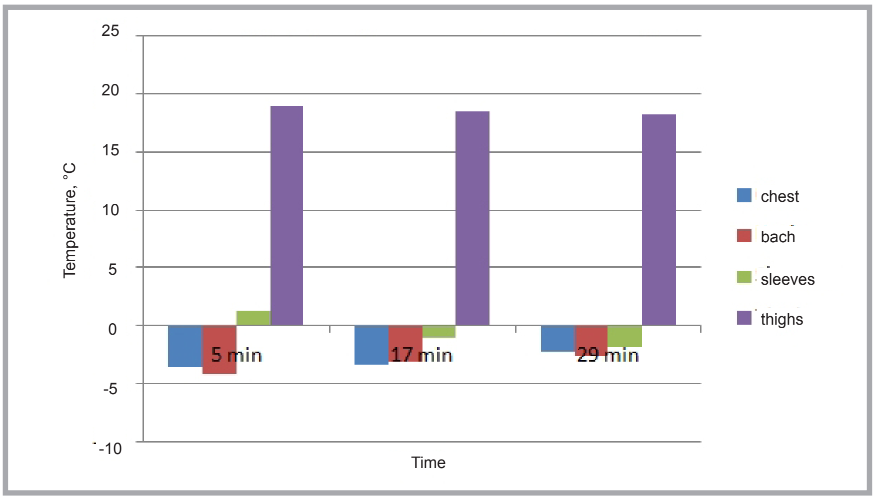

***Figure 14.** Temperature of clothed parts of the body: Individual 1, -11 ^{o}C, jacket 0.63 clo.*

One of the specific tasks of the study was to prove or to reject the effect of the clothing insulation of an outerwear garment with a length up to the line of the hips on the temperature of other parts of the body not covered by the outerwear. Apart from the hands and face, these are the thighs, protected from the cold with denim trousers only (as many people in urban areas are dressed in winter time).

The results for the temperature on the clothing surface in the area of the thighs are shown in ***Figure** 7* for all cases and individuals.

It is obvious that the temperature on the surface of the trousers at the thighs is higher than the surface temperature of any of the jackets. ***Figure 8*** shows a comparison between the different clothed parts of the body of individual 1. The highest temperature on the trouser surface shows that the cooling of the body from the surface of the lower limbs is much greater in comparison with that of the torso.

The comparison between the cases in each figure indicates that the clothing temperature at the thighs is influenced not only by the ambient temperature but also by the insulation of the jackets. The temperature of the thighs of all three subjects is higher when the torso is clothed with better insulating outerwear (1.07 clo). The temperature of the thighs is also higher for all cases with an ambient temperature of -1 °C. The analysis also shows that the difference in temperature of the thighs when jackets with different clothing insulation are used is lower at -1 °C and greater at -11 °C.

Skin temperature

Thermograms of the uncovered parts of the body were taken during the experiments as follows:

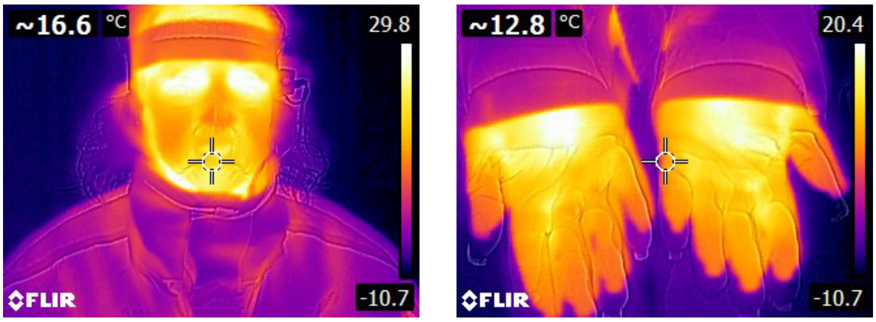

***Figure 9**. Thermograms of individual 3, Phase One: a) face; b) hands.*

- Face;
- Last (distal) phalanx of the middle finger.

The average temperature on the face and hands was determined using FLIR Tools software.

Figure 9 presents two sample thermograms of the face (***Figure 9.a***) and the palmar side of the hands (***Figure 9.b***).

Figures 10 and ***11*** summarise the results of the face temperature measured for all cases. The temperature of the face in the cold air decreased constantly over time. The graphs in ***Figure 10*** show that the face temperature for all participants was in the range of 19-25 °C with clothing insulation 1.53 clo (***Figure 10.a***) and in the range of 22-34 °C with clothing insulation 1.97 clo (***Figure 10.b***).

Obviously the decrement of the skin temperature was greater when using the jacket with lower clothing insulation (0.63 clo).

The higher ambient air temperature (-1 °C) led to smaller changes in the skin temperature – ***Figure 11***, remained in the interval of 24 – 30 °C for the two clothing insulations. The results allow to conclude that the use of outerwear clothing with two different insulating abilities had no particular effect on the skin temperature of the uncovered face.

To assess the difference between the cases studied, the results for the face temperature measured are grouped for each participant: ***Figures 12*** (page 118).

The lowest temperature of the face skin was measured in the coldest environment

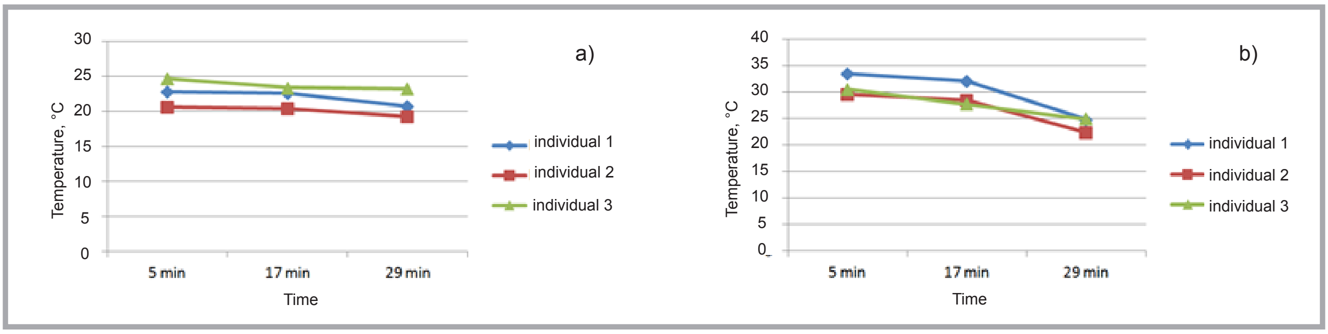

***Figure 10.** Face temperature, Phase One, temperature -11 °C: a) clothing insulation 1.53 clo, b) clothing insulation.*

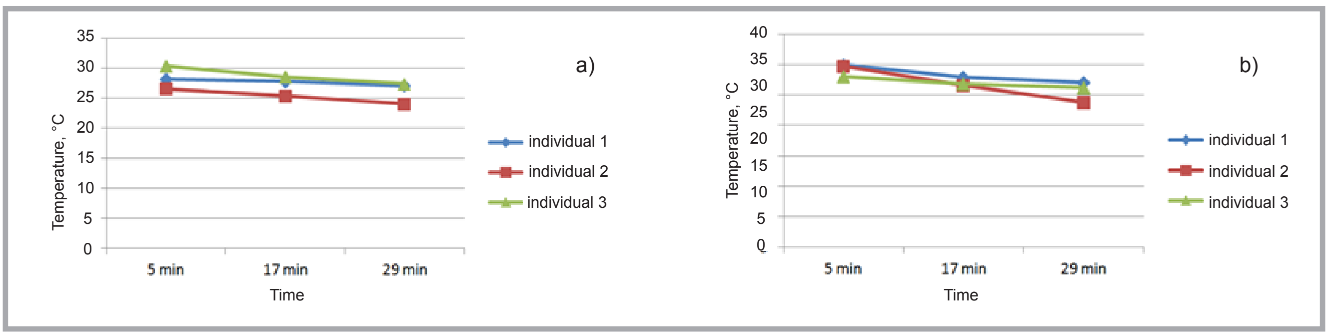

***Figure 11.** Face temperature, Phase One, temperature -1 °C: a) clothing insulation 1.53 clo, b) clothing insulation.*

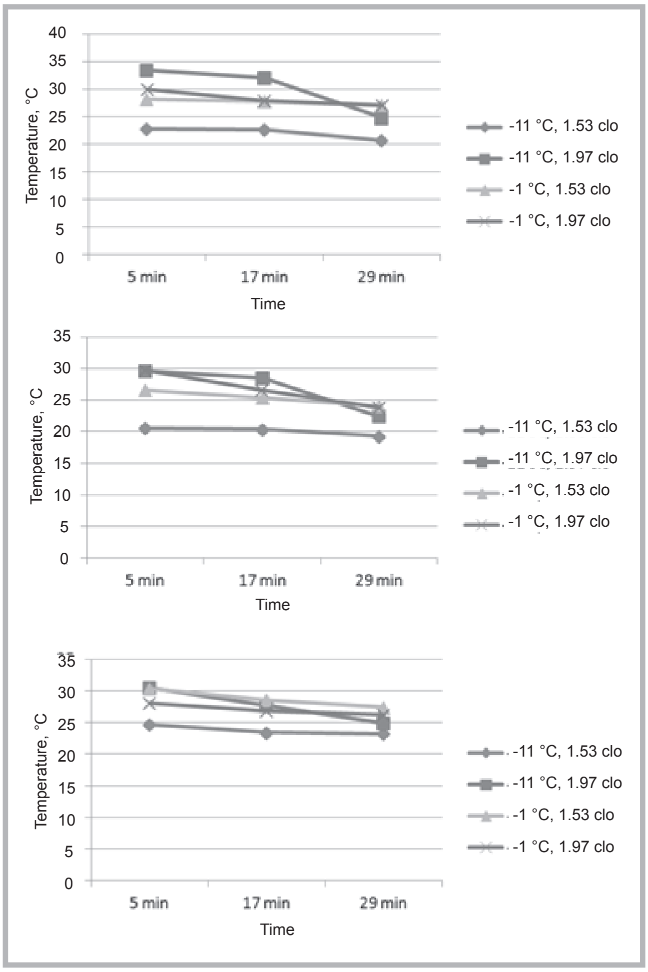

Figure 12. *Face temperature: a) individual 1, b) individual 2, c) individual 3.*

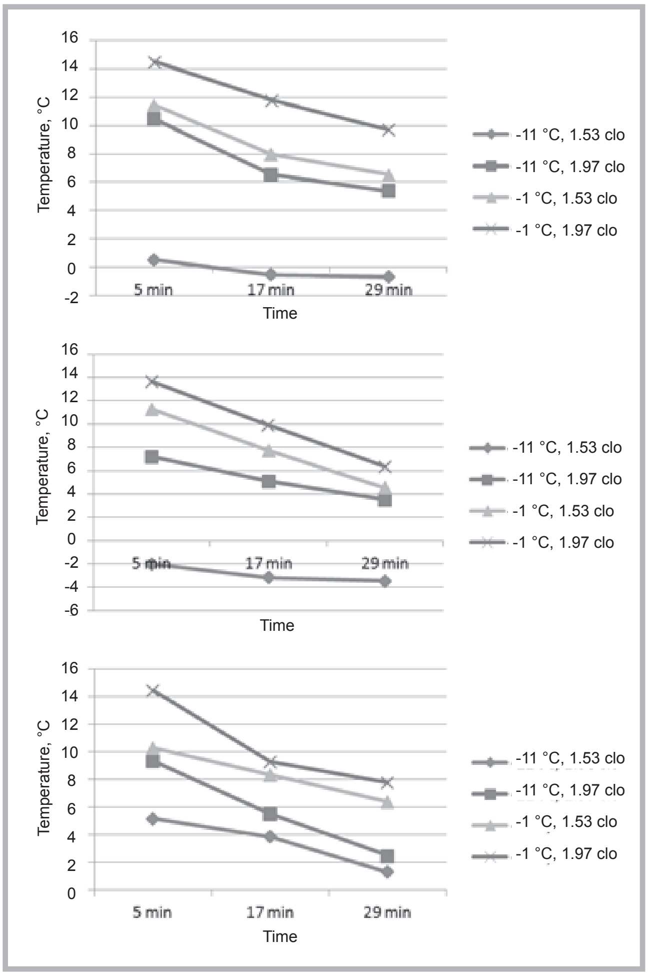

Figure 13. *Temperature of the distal phalanx of the middle finger: a) individual 1, b) individual 2, c) individual 3.*

(-11 °C) when the subjects were dressed in ensembles with lower clothing insulation (1.53 clo). The highest face temperature of individual 1 (***Figure 12.a***) was measured in the case of clothing insulation of 1.97 clo and air temperature -11 °C; but at the end of the exposure the face temperature decreased, becoming comparable to the face temperature during the exposure at -1 °C. The face temperature of individual 2 (***Figure 12.b***) and individual 3 (***Figure 12.c***) when clothed in an ensemble of 1.97 clo at -11 °C was comparable to the face temperature at -1 °C for almost the entire period of exposure.

In addition, analysis of the results shows that for all participants the face temperature sharply decreased in the second half of the cold exposure at -11 °C with clothing insulation of 1.97 clo. This gives reason to conclude that the higher thermal insulation of the clothing (in the case of the jacket) allowed the higher temperature of the face to be maintained for a fixed time interval, then the subzero ambient temperature provoked an increment in heat losses from the face to the environment.

The measurement of the temperature of the distal phalanx of the middle finger gives information about the effect of the vasoconstriction of the blood vessels in the extremities (particularly in the hands). ***Figure 13*** summarise the results (averaged for left and right hand) for each participant in the study.

The comparison between the temperatures of the face (***Figure 12***) and hands (***Figure 13***) clearly demonstrates the response of the thermoregulatory system in a cold environment: the temperature of the middle finger is much lower than face temperature, due to the process of vasoconstriction. Analysis of the graphs shows that the cases investigated had a substantial effect on the temperature of the fingers: it decreased with both lowering the temperature of the air and reduction of the clothing thermal insulation. The temperature of the middle finger decreased with the duration of the exposure as well. The lowest temperature of the middle finger was measured at an ambient temperature of -11 °C with the clothing ensemble of lower insulation (1.53 clo). For individual 2 (***Figure 13.b***) even a negative temperature of the fingers was registered, and for individual 1 (***Figure 13.a***) the finger temperature became negative during the exposure.

Obviously the higher thermal insulation of the clothing ensemble (or outerwear) affected the heat losses from the uncovered hands, as in the case of the face.

Conclusions

In this study infrared thermography was successfully applied as a method for contactless, real time measurement of the temperature of the surface of a clothing ensemble and uncovered parts of the human body at two different subzero temperatures (-1 °C and -11 °C), using two levels of clothing insulation (1.53 clo and 1.97 clo).

The analysis of the thermograms of the clothed parts of the body allowed to draw the following conclusions:

- The temperature of the clothed body parts falls under the influence of the thermal insulation of the clothing ensemble: the higher the clothing insulation, the lower the surface temperature of clothing, which is a sign of arduous heat transfer from the body to the environment ('from inside out').
- The surface of an outerwear garnment with smaller clothing insulation warms faster than that of clothing with higher thermal insulation, at the expense of body cooling.
- The temperature on the surface of the outerwear clothing varies in different zones, which corresponds to the intensity of the cooling of the body: in the sitting posture of the participants tested, where the process of cooling of the upper arms was faster, followed by the chest and back.
- There is evidence that the temperature of body parts not covered by the outerwear garnment is strongly affected by clothing insulation on the torso. This influence is greater the lower the ambient temperature is. The higher thermal insulation of the outerwear on the torso decreases the level of cooling from the thighs.

The analysis of thermograms of the unprotected parts of the body led to the following inferences:

- The temperature of the uncovered parts of the body changes in correspondence with the mechanisms of the body's thermoregulation, and particularly with the constriction of blood vessels at the extremities.
- The temperature of the uncovered parts of the body is affected by the clothing insulation and particularly that of the torso: the higher the insulation , the higher the temperature of the face and hands. This influence is greater the lower the subzero temperature is.

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