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**Research Paper**

# Infrared Thermography for Assessment of Human Thermo physiological Reactions: Hands and Feet Temperature Responses to Fast Cooling

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***ABSTRACT:-*** *Results from a pilot study on the thermophysiological reactions of human subjects, exposed to natural cold environment with bare feet and hands, having a contact with a cold surface, are presented. Infrared thermography was used to record and analyze the changes in skin temperature. Nine topographical regions of interest were considered and the changes in their temperature over time were presented. Differences in temperature of dorsal and palmar side of hands, left and right hand, left and right foot and between the tested subjects, were established.*

***Keywords:-*** *infrared thermography, thermophysiological comfort, fast cooling, clothing insulation, subzero environment*

## I. INTRODUCTION

Human thermophysiological comfort is defined as a neutral state, when the heat, generated by the body is equal to the heat losses from the body to the environment, or the body heat storage is equal to zero [1, 2]. The process is complex as the transfer of heat and fluids between the skin and the environment is done through one or more textile layers. Clothing can protect the body from the negative influence of the weather conditions, especially in cold environment. The clothing insulation, enough to protect the body from cold, can be modelled and predict theoretically, using the Required Clothing Insulation (IREQ index) that is part of ISO 11079:2007 [3-5].

In the cold environment, however, part of the body surface remains uncovered: usually face, rarely hands and never on common situations – the feet. Hands and face are a big source of heat losses in cold environment [6]. Though covered, fingers and toes are of greatest risk for cold related injuries [7, 8]. Actually, cold related injuries of hands and feet can happen not only to alpinists and mountaineers, but also to common people in countries with cold and snowy winters: Harirchi et al. [7] reported that one third (37%) of alpinists suffer from cold injuries per year; at the same time Hassi and Mäkinen [9] communicated that 44% to 68% of young Finish man have suffered from frostbite.

Rapid cooling of hands and feet influences the thermoregulation system [10]. Bouzida et al. [6] reported the appearance of periodic wave profiles of the temperature of the cold stimulated hand. The temperature decreased and increased in a cycling manner, though the trend was towards constant cooling. The same was communicated in [10] and explained with a stimulation of the sympathetic system; this fact was used also for investigation of the warming process after cold exposure [8].

The results of Bouzida et al. [6] demonstrated the fast cooling of the dorsal side of the hand under cold stimulation within 250 s. Similar were the observations in [11]: the reported graphs showed that the drop in the temperature of toes and fingers in the first 60-150 s were maximal, while the cooling after 5 min reached kind of plateau, that barely changed till the end of exposure (30 min). Detailed observations and analysis of the temperature change in bare hands and feet in real cold environment is missing, however.

The aim of the present study was to measure the temperature changes in unprotected (bare) hands and feet, subject to fast cooling (60 s of exposure) in natural cold environment. The rest of the body was accordingly dressed so as to ensure the thermophysiological comfort for the time of exposure. IREQ index was applied to

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predict the required clothing insulation. Infrared thermography (IRT) was used to scan the extremities, to take pictures and to be used as a source of both temperature and temperature distribution over the fields of interest.

## II. THEORETICAL BACKGROUND

The effective clothing insulation is defined as the difference between the mean skin temperature $\bar{t}_{sk}$, $^{o}$C and the mean clothing temperature $\bar{t}_{cl}$, $^{o}$C, divided by the heat losses per square meter of the skin, W/m$^2$, namely [12, 13]:

$$I_{cl} = \frac{\bar{t}_{sk} - \bar{t}_{cl}}{H}, \ \frac{^{o}C\,m^2}{W} \tag{1}$$

The uncovered parts of the body increase extremely the heat losses per square meter of the skin, thus decreasing the effectiveness of the clothing as thermal insulation barrier between the body and the environment.

The Required Clothing Insulation (IREQ index) is predicted as [3, 4]:

$$IREQ = \frac{\bar{t}_{sk} - t_{cl}}{R + C}, \text{clo} \tag{2}$$

where R is the radiative heat exchange, W/m$^2$; C is the convective heat exchange, W/m$^2$.

IRT is a noninvasive technique for temperature measurements, including measurements of the human body. It is based on the electromagnetic radiation, emitted from every object, which temperature is above 0 K (-273.15 $^{o}$C). IRT is the most appropriate method for measurement of the skin temperature and assessment of the skin temperature distribution [6, 8, 14, 15].

## III. PROTOCOL

The protocol of the study was in conformity with the Declaration of Helsinki guidelines. The participants signed an informed consent before measurements. Due to severe conditions of the testing only two persons were involved: one male and one female. The participants were selected to be non-smokers; they did not take any kind of medicines and were requested not to consume caffeine and alcohol before measurements and the day before, after 8 PM.

The testing was performed in outdoor conditions (natural cold environment) with a temperature of -10 $^{o}$C, relative humidity 72% and wind speed 1 m/s. The IREQ index for these environmental conditions was simulated, using a code, based on the mathematical model of [5] and presented in [16].

Before testing the subjects were dressed properly and the resulting clothing insulation was calculated to be 2.1 clo: underwear (0.04 clo); T-shirt (0.12 clo); long-sleeve-cotton shirt with collar (0.33 clo); wool cardigan (0.36 clo); denim trousers, loose (0.24 clo); highly insulated winter jacket (1 clo) [13].

The IREQ index was simulated for the given environemntal conditions and available clothing insulation, as well as for 80 W/m$^2$ metabolic rate (standing position). The results obtained showed that a person has to be dressed in a clothing ensemble with 4.06 clo thermal insulation value to be sure in his/her thermophysiological comfort. The minimal value of the clothing insulation was predicted to be 3.71 clo. It was also calculated that the duration of exposure with the available clothing insulation (2.1 clo) had to be from 0.62 h (37 min) to 0.73 h (43 min). Therefore the foreseen exposure of approx. 1 min was far beyond the limits. Certainly, the exposure of bare feet and hands could not be taken into account by the predicted values of IREQ index and duration of limited exposure.

The participnats were exposed to cold twice: with bare feet (Protocol 1) and bare hands (Protocol 2):

- ***Protocol 1.*** Before the exposure the participants stayed dressed for 5 min in a conditioned room (22 $^{o}$C, 65% relative humidity) and then went out. They sat down on a chair to remove their shoes and socks and stood, stepping with bare feet on ceramic tale flooring with a surface temperature -9 $^{o}$C. The measurements continued for 60 s and a picture of the dorsal part of the feet were taken every 5 s.
- ***Protocol 2.*** Before the exposure the participants stayed dressed for 5 min in a conditioned room (22 $^{o}$C, 65% relative humidity) and then went out. In a standing position they placed their hands on ceramic tales (border of a wall) with a surface temperature -9 $^{o}$C. The measurements continue for 60 s and a picture of the palmar or the dorsal side of the hands was taken every 5 s (the side of the hands in contact with the cold tales changed after each picture from palmar to dorsal, and vice versa).

The skin temperature of hands and feet was measured using IRT camera (E6 FLIR camera, FLIR Systems Inc., Wilsonville, OR, US) with the following features: IR pixel resolution 19200(160x120); thermal sensitivity < 0.06 $^{o}$C; temperature range from -20 $^{o}$C to 250 $^{o}$C; 3 measurement modes; Multi-Spectral Dynamic Imaging (MSX) resolution (320x240); emissivity correction from 0.1 to 1.

## IV. RESULTS AND DISCUSSION

The participants were able to tolerate the cold exposure, though they reported feeling of pain in the feet. They were asked to rate the thermal discomfort, felt in feet, palmar and dorsal sides of the hands. The answers showed that the discomfort in the bare feet was greatest, followed by the dorsal side of the hands and the palmar side of the hands.

The skin temperature readings were performed using FLIR Tools software. Four topographical regions of interest were measured in each foot: dorsal side of feet, toes (phalanges mediae and proximales of the long, middle and ring toes), big toe (phalanges distales and proximales) and the edge of the nail bed – Fig. 1. Five topographical regions of interest were measured in each hand: dorsal side of fingers, dorsal side of hands (Fig. 2), palmar side of fingers, palmar side of hand and distal phalange of the middle finger (Fig. 3). Minimum, maximum and average temperature values were obtained for each region. Average temperature changes over the time were presented graphically for each participant.

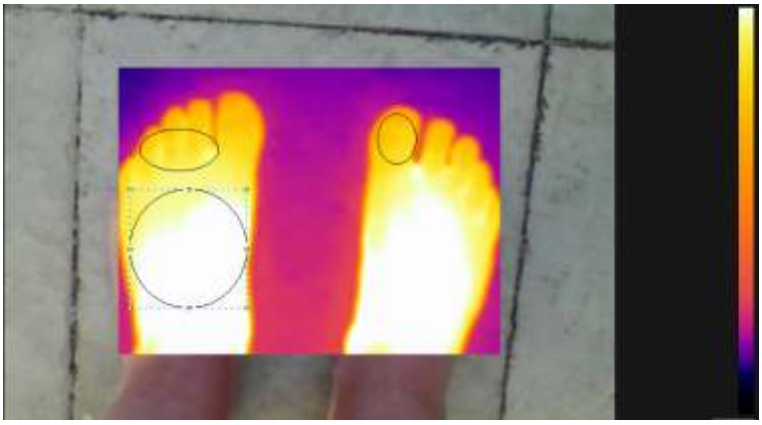
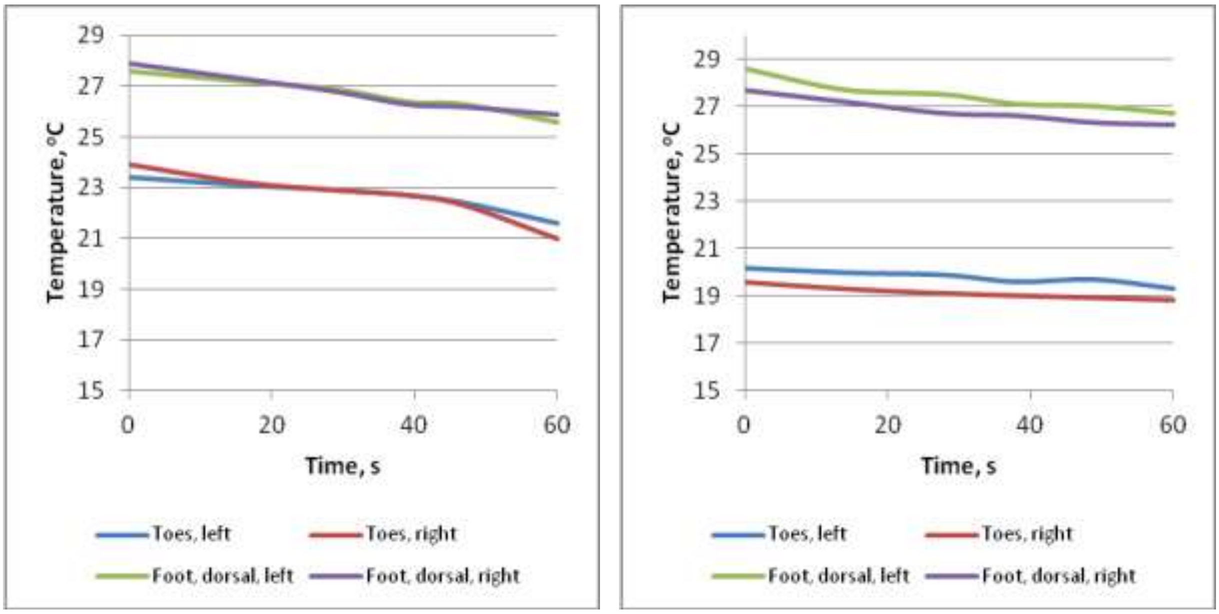


**Figure 1.** Topographical regions of interest in the feet: picture in picture view with the testing cold surface.

**Figure 2.** Topographical regions of interest in the hand dorsum.

Figure 4 shows the comparison between the results from the IRT of the feet: temperature of the dorsal part of the left foot (LF) and right foot (RF) and temperature of the toes, for the female (Fig. 4a) and the male subject (Fig. 4b) during the fast cooling period. The results indicated that in the particular cold environment the temperature of the foot dorsum decreased with 2 $^{o}$C in 60 s for both legs of the female subject (LF: from 27.6 to 25.6 $^{o}$C; RF: from 27.9 to 25.9 $^{o}$C). The temperature decrement for the male subject was a bit smaller: 1.9 $^{o}$C for LF (from 28.6 to 26.7 $^{o}$C) and 1.5 $^{o}$C for RF (from 27.7 $^{o}$C to 26.2 $^{o}$C). The difference between the temperature of the foot dorsum for LF and RF was noticeable for the male subject (maximum difference: 0.9 $^{o}$C at the beginning of the experiment; minimum difference: 0.5 $^{o}$C at the end of the experiment), while the temperatures of the foot dorsum for LF and RF of the female subject were almost identical (maximum difference: 0.3 $^{o}$C at the beginning and the end of the experiment; minimum difference: 0.1 $^{o}$C within the rest of the time).

**Figure 3.** Topographical regions of interest in the hand palmar side.




a/ b/

**Figure 4.** Toes and feet temperature: a/ female subject; b/ male subject.

The temperature of the toes was quite lower, compared with the temperature of the dorsal parts of the feet. This difference was lower for the female (average value 4 $^{o}$C) than for the male subject (average value 7.7 $^{o}$C). As a whole, the toes temperature of the male subject was lower than that of the female subject. The comparison between the average values of the toes temperature for 60 s period showed that the male subject had 19.8 $^{o}$C (LF) and 19.1 $^{o}$C (RF) temperature of the toes, while the temperature of the toes of the female subject was 21.6 $^{o}$C (LF) and 21 $^{o}$C (RF).

The results obtained clearly showed that the sex could influence the temperature of feet in fast cooling. The differences between the temperatures of the two feet (LF and RF) of each subject could be a warning that measurements of one foot (leg) only, when thermophysiological reactions are assessed (like in [11]) may not be enough.

Figure 5 presents the results from the IRT of the big toes and the big toe nail beds. The selection of the edge of the nail bed was suggested in [11], based on the results of [17], instead of the finger pad. According to the findings in [17] the nail bed responded better to cold exposure and vasoconstriction induced by the thermoregulatory system, than the nail pad.

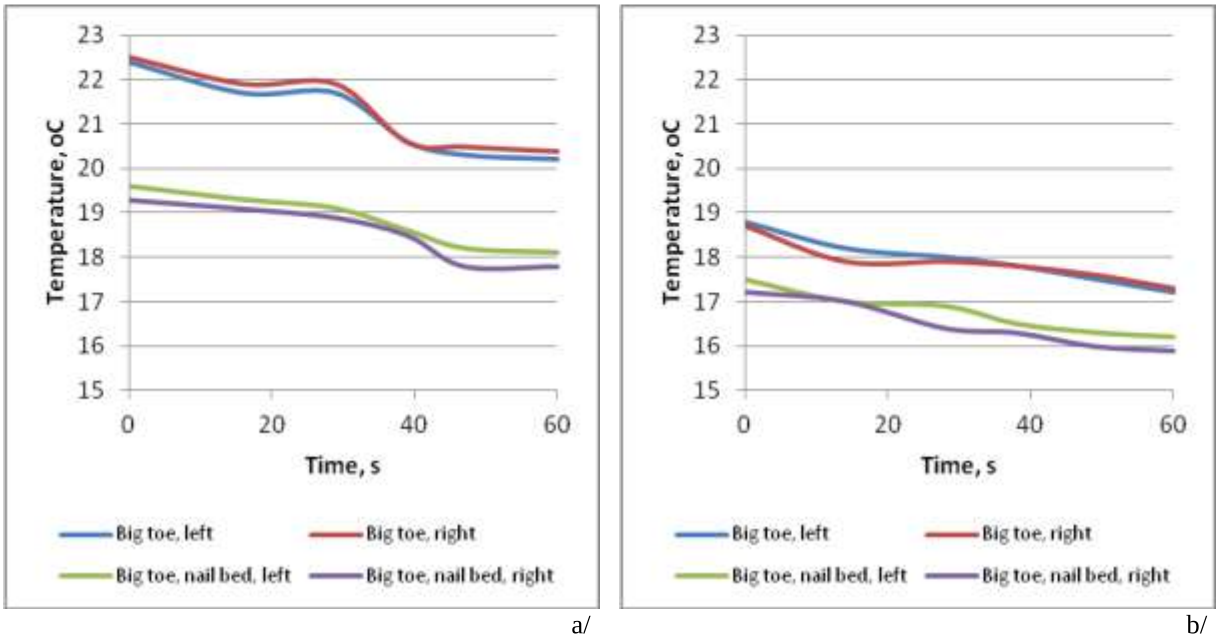



**Figure 5.** Big toes temperature at dorsal side and nail bed: a/ female subject; b/ male subject.

The change in the big toe temperature for 60 s was 2.2 $^{o}$C (LF) and 2.1 $^{o}$C (RF) for the female participant; and 1.6 $^{o}$C (LF) and 1.4 $^{o}$C (RF) for the male participant. As a whole, the temperature of the big toe of the female participant was higher (average value for LF and RF): from 22.45 $^{o}$C at the beginning to 20.3 $^{o}$C at the end of the exposure (Fig. 5a), compared to the respective values for the male participants: from 18.75 $^{o}$C at the beginning to 17.25 $^{o}$C at the end of the exposure (Fig. 5b). The big toe temperature drop for the LF and RF for each participant was quite similar: the maximum difference for the female participant was 0.2 $^{o}$C (Fig. 5a), and for the male participant: 0.3 $^{o}$C.

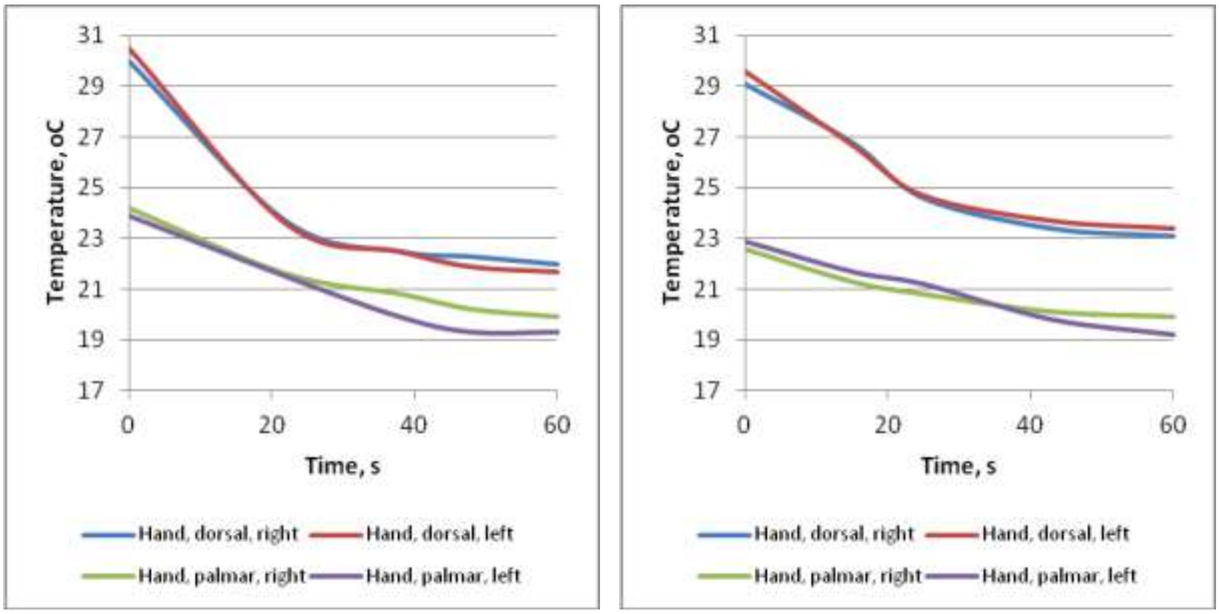
The big toe temperature, measured at the nail bed only was lower than the averaged temperature over the big toe whole area. The difference in the averaged values for the whole exposure (60 s) was 1.9 $^{o}$C (LF) and 2.7 $^{o}$C (RF) for the female subject and 1.18 (LF) and 1.4 $^{o}$C (RF) for the male subject. The temperature of the nail bed showed faster cooling of the tissues around the phalanges distales compared with the other phalanges and the tissue of the feet, and could be the main reason for cold induced injuries of toes.

The change in the temperature of the nail bed of the big toe was 1.5 $^{o}$C for both LF and RF of the female subject; and 1.3 $^{o}$C for both LF and RF of the male subject. Though only two subjects were tested, the results showed that the nail bed temperature could be very appropriate for assessment of the thermophysiological reactions in the feet. As a whole, the temperature of the big toe of the female participant was higher (average value for LF and RF): from 19.45 $^{o}$C at the beginning to 17.95 $^{o}$C at the end of the exposure (Fig. 5a), compared to the respective values for the male participants: from 17.35 $^{o}$C at the beginning to 16.05 $^{o}$C at the end of the exposure (Fig. 5b).

Figure 6 shows the results from the IRT of the hands: a comparison between the temperature change in the dorsal and the palmar side of the hands for the female (Fig. 6a) and the male subject (Fig. 6b). As a whole, the palmar side had lower temperature than the dorsal side of the hands. The difference in the temperature of the dorsal part of the right hand (RH) and the left hand (LH) of the female participant (Fig. 6a) was 0.5 $^{o}$C (maximum) at the beginning of the exposure and 0 $^{o}$C (minimum) at the 40 s of the exposure. For the male participant (Fig. 6b) these values were 0.5 $^{o}$C (maximum) at the beginning of the exposure and 0.1 $^{o}$C (minimum) at the middle and the end of the exposure. The difference in the temperature of the palmar part of RH and LH of the female subject (Fig. 6a) was 0.8 $^{o}$C (maximum) at the 40 s of the exposure and 0.1 $^{o}$C (minimum) at the 20s of the exposure. For the male participants (Fig. 6b) these values were 0.7 $^{o}$C (maximum) at the 25 s to 45 s of the exposure and 0.3 $^{o}$C (minimum) at the 15 s of the exposure. Obviously, the temperature fluctuations of the palmar side of the hands were greater than these of the hand dorsum. The graphs showed as well, that the temperature drop of the hand dorsum was abrupt during the first 20-25s of the exposure, and then the temperature decrement was smoother. Steady decrement of the temperature of the palmar side was observed during the whole period.

The results from the IRT of the fingers are shown in Fig. 7. The diminution of the temperature of the fingers for the LH and RH (averaged values for both hands) was 4.65 $^{o}$C for the dorsal and 2.5 $^{o}$C for the palmar side of the fingers of the female subject (Fig. 7a). The respective values for the male subject (Fig. 7b) were 3.2

$^{o}$C for the dorsal side of the fingers and 3.3 $^{o}$C for the palmar side. At the same time the temperature difference between both sides of the fingers was smaller for the female than for the male subject.




a/ b/

**Figure 6.** Hands temperature: a/ female subject; b/ male subject.

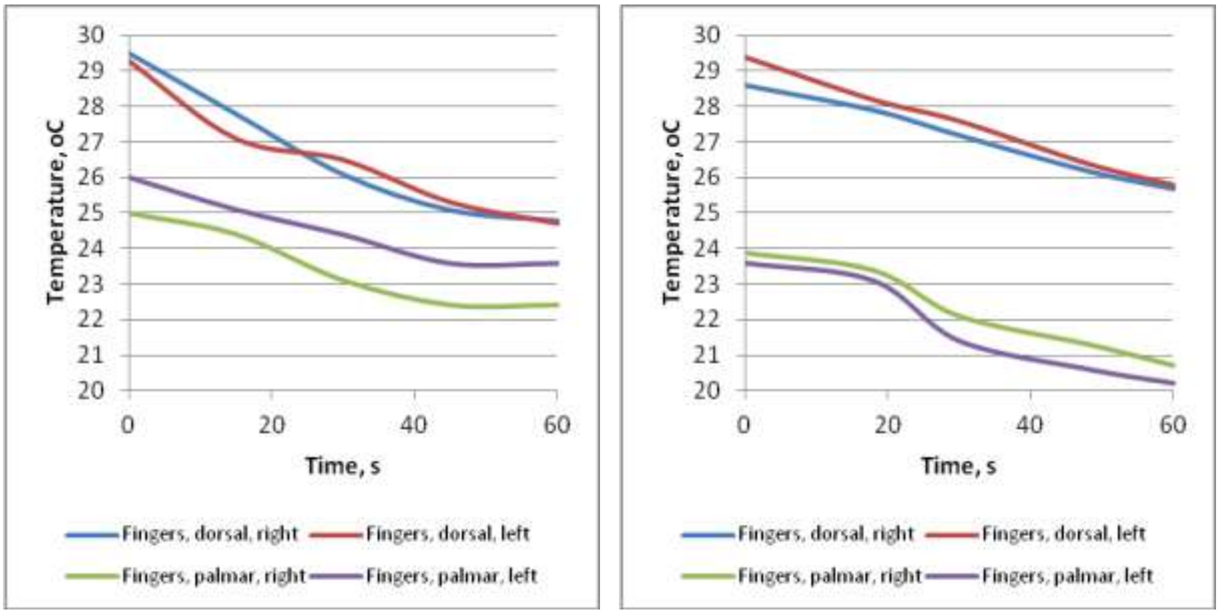



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**Figure 7.** Fingers temperature: a/ female subject; b/ male subject.

The difference in temperature of LH and RH was also greater for the female subject. This difference was noticeable for the palmar side of the fingers, which was measured at the 0 s of the exposure (1 $^{o}$C difference between LH and RH) and was kept till the end of the exposure (1.2 $^{o}$C at 60 s) (Fig. 7a). The same values for the male subject were 0.3 $^{o}$C at the beginning and 0.5 $^{o}$C at the end of the exposure (Fig. 7b). Concerning the fingers dorsum, the temperature difference between LH and RH was smaller: 0.7 $^{o}$C (maximum) at 15 s of the exposure for the female subject (Fig. 7a) and 0.8 $^{o}$C (maximum) at the beginning of the exposure for the male subject (Fig. 7b).

## V. CONCLUSION

The study reported results from the exposure of female and male subject to natural cold environment (-10 $^{o}$C, 72% RH and wind 1 m/s) with bare feet and hands for 60 s, assuring contact with a surface with a temperature of -9 °C. Infrared thermography was used to scan the extremities of the participants and to assess the thermophysiological changes in 9 topographical regions of interest all together: 4 on each foot and 5 on each hand. The results obtained showed temperature changes over the time of the exposure and allow to assess the thermophysiological reactions, related with temperature changes in the extremities for each subject, hands and feet, left and right hand, left and right foot, dorsal and palmar side of hands.

The main advantage of the reported study is the exposure of real subjects in extreme cold conditions with bare feet and hands, which are in contact with cold surface for 60 s. Another advantage is the application of IRT to record the fast changes in skin temperature of different zones of the extremities. The IRT allowed as well the measurements to be done in a very short period of time, thus ensuring constant weather conditions. A limitation of the study is related with the number of participants and the lack of statistical analysis. However, having the results from the pilot study, our future plans are to repeat the experiment with more subjects – both male and female. Certainly, the exposure in artificial climatic chamber will be necessary so as to ensure unchangeable environmental conditions for all subjects during the field experiment.

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