THERMAL AND UTILITY PROPERTIES OF SOCKS

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Abstract: *The aim of this paper was to evaluate the thermal and utility properties of sock goods. The sock assortment had a different material composition and knitted structure. Material analyses were performed on samples of socks before of measuring properties. The basis of the research was the determination of thermal insulation properties by using of a thermal imaging camera. To do this, it was necessary to know the changes in length and weight before and after wearing the socks. It has been proven that the temperature of the foot is different in the monitored parts and the composition of the textile material and change dimensions and weight does not significantly influence the thermal insulation properties of the evaluated assortment.*

Keywords*: knitting structures, socks, thermal insulation, thermogram.*

1 INTRODUCTION

Socks are an important part of the wearer's feet protection. The quality of the socks assortment currently influenced by its thermal and aesthetic-fashionable properties, antibacterial and antimycotic effects, structure, surface, and color. The socks are composed of a toe, a foot, a heel, and a hem [1]. They usually have a doubled hem in the upper part, into which a rubber strip is inserted, or elastic yarns. Some types of socks are folded into a cuff at the top. In the shape of a sock, they are produced by knitting technology, for example on single - cylinder three - system automatic knitting machines (Ange 15 - universal Lonaty GK 616, etc.) [2]. The following structures knitted fabrics are used: plain, ribbed, terry and velour. The preparation of the sock pattern itself consists of the following operations:

- design of a graphic pattern,
- design of a program for knitting socks,
- transfer of the pattern to a specific program and type of sock knitting machine,
- knitting of model socks,
- verification of sock dimensions, stretch and adjustment,
- modification of the graphic pattern resp. adjust the number of chains and lines.

Then the socks are adjusted to the final shape by operations such as: forming, ironing, sorting, sewing labels, strapping, and packaging. The following types of socks are known (Figure 1):

a) invisible socks - they reveal the whole instep, covering only the heel,
b) sneaker socks - leave the ankle exposed, the hem ends just below the ankle,
c) ankle socks - cover the ankle,
d) high socks - reaching up to the calf muscle,
e) socks with a hem - these are high socks, the upper part folds and creates a cuff in the ankle part,
f) knee socks - ending below the knee,
g) socks above the knees - reaching above the knees,
h) loose socks - are wide, worn lowered and gathered to knee height,
i) tabi socks - characterized by their separate big toe,
j) toe socks - have a place for each toe separately [1].

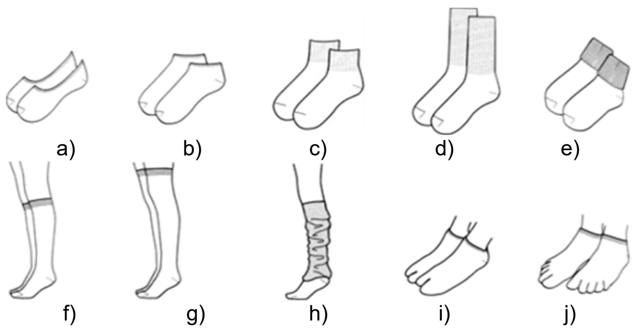

Figure1 Types of socks

Socks of different shapes made of different materials can be inappropriately shaped and prevent the transfer of residual heat and moisture during wearing. From the point of view of thermal comfort, it is therefore most important to maintain the optimal temperature between the foot, the sock and the shoes during the transfer of heat and moisture, especially by convection and conduction [3]. Human temperature is typically around 37°C, a known fact. However, the skin surface has a lower temperature, in the range of approximately 33.5 to 36.9°C.

Warmer spots are in the muscle areas, but the tendons and bones, as well as the feet, are colder [4]. It is important to ensure optimal temperature and humidity in this area of the body to achieve comfort when wearing socks. Moving and pressing the foot on the sock and shoes increases or decreases the generation of heat and moisture in this area. The most important is the dynamics of the spread of moisture and heat in this part of the body, which affects the ability to wick sweat from the body surface through the sock into the environment (or through shoes into the environment) [5]. In case of insufficient moisture wicking, the body overheats, and moisture liquefies and accumulates between the skin and the socks [6]. When the feet meet with the sock and the shoe, this process slows down significantly compared to other parts of the body, even though the surroundings can absorb sweat. Based on the above information, the basis of the paper was:

- temperature measurement using a thermal imaging camera at selected points of the foot (measurement was performed at certain time intervals before and during the wearing of the sock),
- changes in the distance of the socks before and after wearing, since changes in temperature can also be caused by the shape instability of the socks,
- -the observed properties may also be related to the weight of the sock, therefore the change in the weight of the sock due to wear was also evaluated.

Based on the measurements, the most suitable material composition and knitted structure for thermal properties of the sock were chosen. The differences in temperature due to the wearing of socks were also evaluated. The presented measurement of temperature differences represents only a qualitative evaluation of a certain estimate of the degree of thermal insulation of different socks. The work is informative rather than research. These measurements were preceded by a detailed analysis of the material composition of the examined range of socks.

2 EXPERIMENTAL PART

2.1 Materials

Natural materials such as cotton and its combinations with polyester, polyamide and Lycra are mainly used to produce socks. Table 1 shows the base materials (yarns used) in a wide range of combinations. Figure 2 shows electron microscope images. These are longitudinal and transverse views of the fibers and longitudinal views of the yarns that have been used in the range of socks. Twisted combed mercerized cotton yarns with a fineness of 14.5 tex are used to improve strength, affinity for dyes and smoothness. The yarn made of cellulose fibers provides good antibacterial properties. Instead of 100% cotton yarn, a single blended yarn of 29.5 tex with 60% cotton and 40% polyester is used. Polyester fiber gives the yarn greater strength and longer life. They retain their shape well even when repeatedly washed and worn. Polyester is less absorbent than cotton, but also forms less stains. One of the special materials is the profile polyester fiber Coolmax®, the main feature of which is the increased specific surface. The fiber wicks sweat away from the body faster and thus speeds up its drying. Polypropylene fibers Prolen® with Siltex treatment prevent the multiplication of bacteria, fungi and molds. The reason is that additives based on biogenic silver ions were used in the production of the material. Resistex® Carbon yarn has similar effects. It contains 34% of polyamide 6, which has been cast on the surface with conductive carbon and coated with 66% of structured polyamide 6.6. The fibers ensure that no electrostatic charge is generated.

Table 1 Material composition of yarns

Sample no.	Material composition of yarns
1.	33% wool, 19% polyamide,46% polyester, 2% elastane
2.	98% cotton, 2% Lycra
3.	93% cotton, 5% polyamide, 2% elastane
4.	47% cotton, 47% viscose, 4% polyamide, 2% elastane
5.	65% cotton, 23% polypropylene, 10% polyamide, 2% elastane
6.	98% cotton, 2% elastane
7.	98% cotton, 2% elastane
8.	83% wool, 15% cotton, 2% elastane
9.	100% cotton
10.	33% cotton, 19% polyamide, 48% polyester

2.2 Methods

The research process mainly involved temperature measurements. Related are measurements of the change in weight and length of a sock. These properties were measured before and during the wearing of socks.

2.2.1 Weight of socks

The socks absorbed moisture, sweat and dust while wearing them. This support bacterial growth and weight gain. It is a sign of reduced comfort when wearing socks. For these reasons, it was necessary to detect a change in the weight of the socks during wearing. Samples were weighed before and after use on the proband. The time interval for wearing socks was 12 hours.

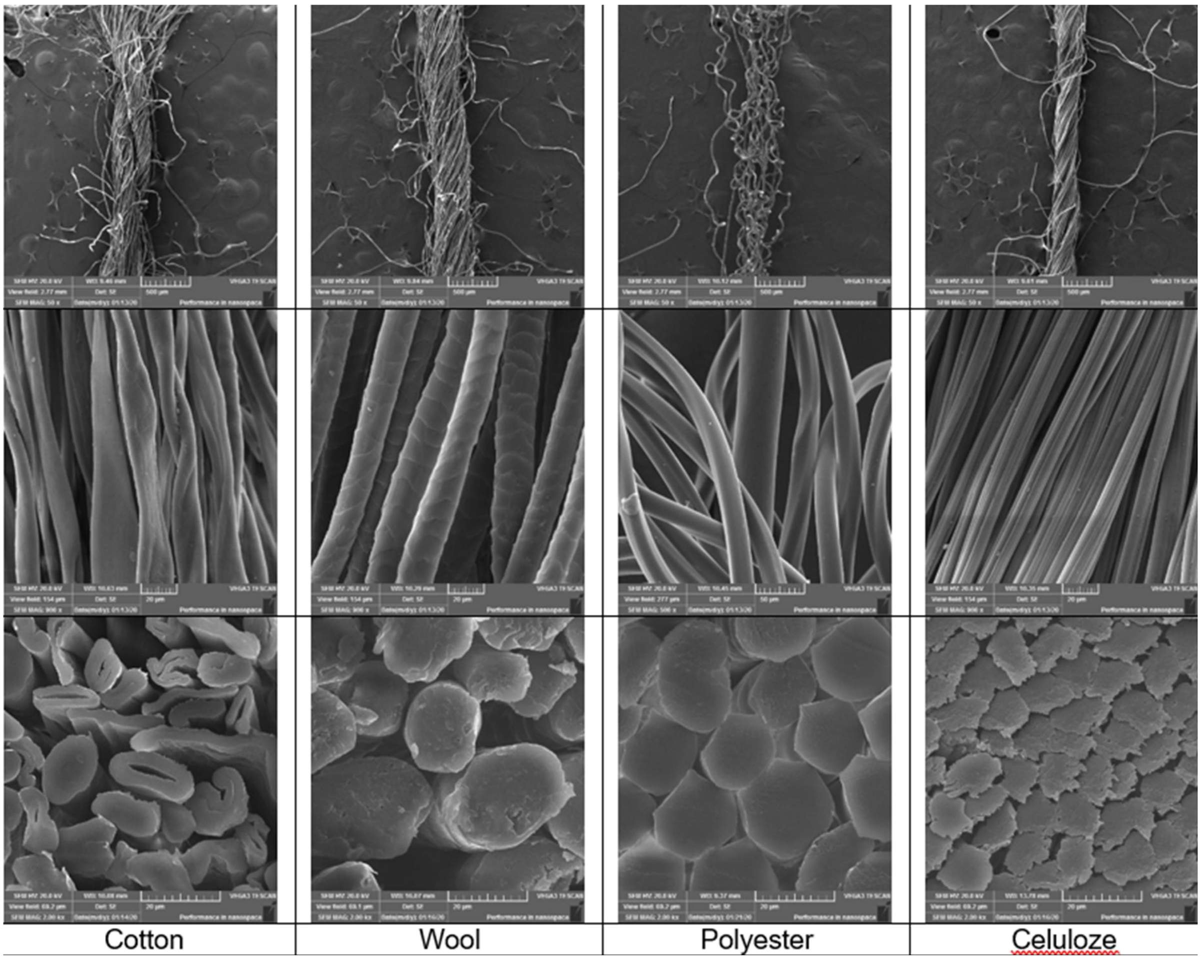

Figure 2 Types and shape of yarns and fibers

2.2.2 Length of socks

The shape deformation of the sock mainly leads to a change in its distance. This fact causes problems during wearing the sock and can influence the measured temperature of the sock. Changes in the shape of socks are mainly influenced by the material composition and the knitting structure used. Therefore, it was the sock length was measured before and after wearing. The distance in the part of the foot was measured from of the heel to the toe (Figure 3). The sock was fixed in position on the pad during the experiment.

2.2.3 The temperature measurement using a thermal imaging camera

Thermo Vision can be called a technology that detects temperature differences between the environment and objects in the foreground of the image. It uses infrared imaging techniques for this purpose. It deals with the capture, processing, analysis, display of a thermal radiation [7]. The result is infrared images called thermograms. It is a graphical representation of the heat [8]. The temperature of the head and foot in real conditions in a dressed person is clearly visible on the thermogram.

The clothing area usually radiates less heat than the naked skin. The more layers or thicker the clothing the body have, the lower the temperature measured from the outside.

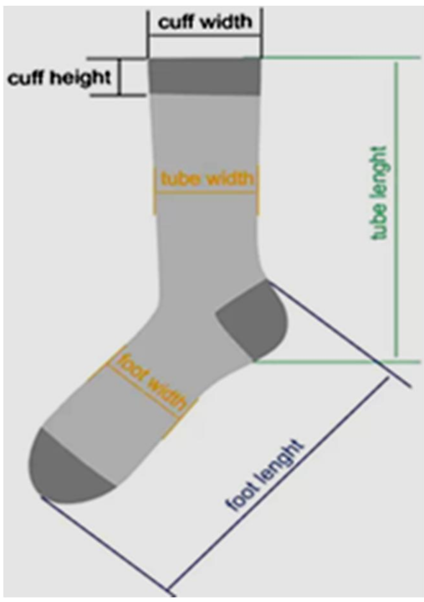

Figure 3 Measurement of the length of the sock

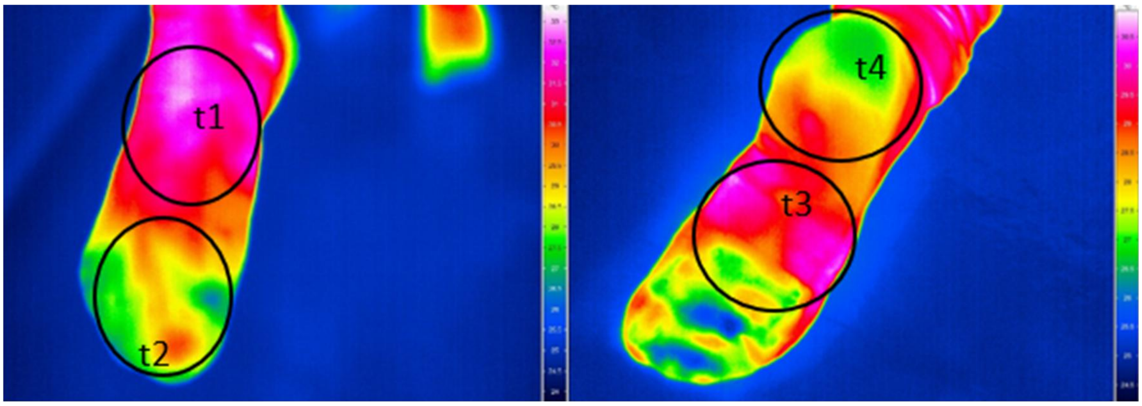

Figure 4 Thermal images of the upper and lower part of the bare foot

The infrared thermal imaging camera measured the surface temperature of the end of the wearer foot, which was at first without a sock and then covered by a sock. The thermal energy that a body receives, or transfers was measured. In this experiment a thermal imaging camera Jenoptik Vario CAM (serial no. 10381) was used with following settings:

- resolution 2048x1536 pixels,
- detector resolution 1024x768 pixels,
- temperature range -40°C to +1200°C,
- detector: uncooled FPA microbolometer, 17 μm, 7.5 μm to 14 μm [9].

Measurements performed by a thermal imaging camera and subsequent assessment of thermal properties are performed according to the standard STN EN 13187 [10]. The thermal imaging camera enabled the setting of the emissivity coefficient in the range of values 0.1 - 1 and the value was set to 0.85. The captured data was recorded in the form of digital images (thermograms) on a storage medium and further evaluation.

In the study, the bottom of the foot was monitored under light load. The experiment procedure consisted of the following steps:

- the foot was placed stationary on the stand,
- the distance of the foot from the thermal imaging camera was length 1 m and height 0.4 m,
- measurement of the temperature of the foot without the sock (before the measurement, the foot was bare for 15 minutes to acclimatize in the laboratory),
- the measurement of the temperature of the foot with the sock after 30 minutes of wearing the sock with loose bedroom slippers.

Environment conditions in the laboratory were set at a temperature of 20°C and relative humidity 60%. It was also important to prevent heat radiation and air flow on the measured probant. In selected areas of temperature fields, minimum, maximum as well as mean values of surface temperatures were identified on all analyzed thermograms. After the actual sensing of the temperature field, it was necessary to sort these fields. The knowledge of the anatomy of the foot was used here. The points of temperature changes were selected from the record (Figure 4), where is the temperature t_1 on the instep, t_2 on the toe, t_3 in the middle of the foot and t_4 on the heel.

3 RESULTS AND DISCUSSION

3.1 Change in the weight of socks

Measurements of the weight were taken before and after wearing the socks. The weight was measured using an analytical balance. It was assumed that due to the material composition of the socks, there would be larger weight gains for those samples that contained a higher percentage of cotton and wool. This assumption was not confirmed by measurements and weight changes due to wear were minimal (Figure 5).

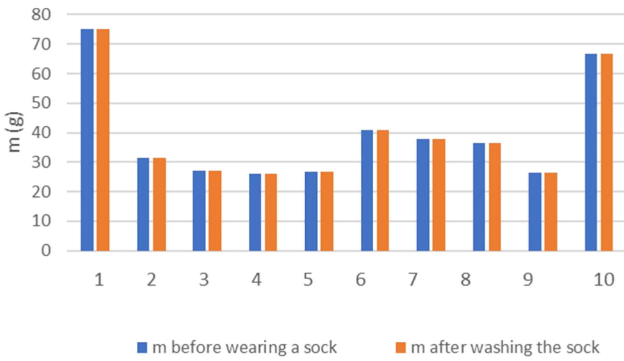

Figure 5 Weight m [g] of the socks before and after washing

3.2 Change in the length of socks

The measurement of the distance of the socks was focused on the length before and after wearing the proband. The results in Figure 6 show that the length of the socks was reduced by 3 to 16% of the original length. Samples without elastane no. 9 and 10 can be deformed the most.

This assumption was not confirmed by measurement. However, socks containing a wool component were the most deformed (samples no. 8 and 1). It is also not possible to determine from the measurement results which material composition of the socks will have the lowest shape change due to wear.

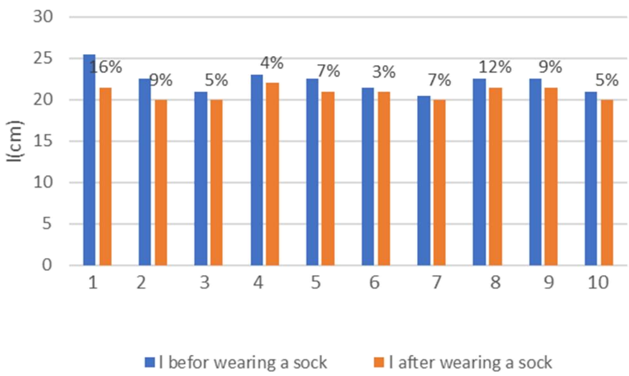

Figure 6 Length *l* [cm] of the sock before and after wearing

3.3 *Temperature sensing using a thermal imaging camera*

The surface temperature distribution on the sample was measured using a thermal imaging camera. Five images were taken from the upper (instep area) and the lower (heel area) of the foot. Measurements were performed at short time intervals. Figure 7 shows selected images of a foot with a sock. The temperature of the foot with the sock was variable, which results from a visual analysis of all images.

However, it is not possible to determine exactly which material composition will be the best heat insulator from the results of thermograms.

When evaluating the thermal images, the detection was performed with different data, which in our case represent the temperature in the parts of the foot. Minimum, maximum, as well as mean values of surface temperatures were identified on all analyzed thermograms [11]. The average results of their analysis and elementary statistical processing in this system are given in the Table 2, where t_{min} is the minimum temperature in the heel area (t_4 on the heel), t_{max} is the maximum temperature in the instep area (t_1 is on the instep), $t_{average}$ mean temperature in the monitored areas and s is standard deviation of temperatures. The high temperature variability of the foot with the sock was confirmed from all measurement results.

Table 2 Results of thermograms analysis

sample no.	t_{max} [°C]	t_{min} [°C]	$t_{average}$ [°C]	s [°C]
1	33.0	24.0	28.5	2.50
2	32.5	27.0	29.75	1.49
3	32.5	27.5	30.0	1.32
4	32.0	25.0	28.5	2.14
5	32.0	25.0	28.5	1.65
6	32.5	25.0	28.75	2.35
7	31.5	27.0	29.25	0.95
8	32.5	25.0	28.75	2.46
9	32.0	27.5	29.75	1.38
10	33.0	25.0	29.0	2.27

Figure 8 shows a mean temperature of specific foot parts. In all measurements, it was found uniformly that the highest temperature is reached by the foot in the instep (t_1) and the lowest temperature in the heel (t_2). The foot temperature is similar in the area from the center of the foot to the toe (t_2, t_3). Next experiment containing outputs from thermograms was a comparison of the average temperature of the bare foot and the foot with the sock. From the results in Figure 9 it follows that within 30 min wearing the foot did not retain its temperature. In all cases, there was a slight decrease in foot temperature with a sock ranging from 0.25 to 1.5°C.

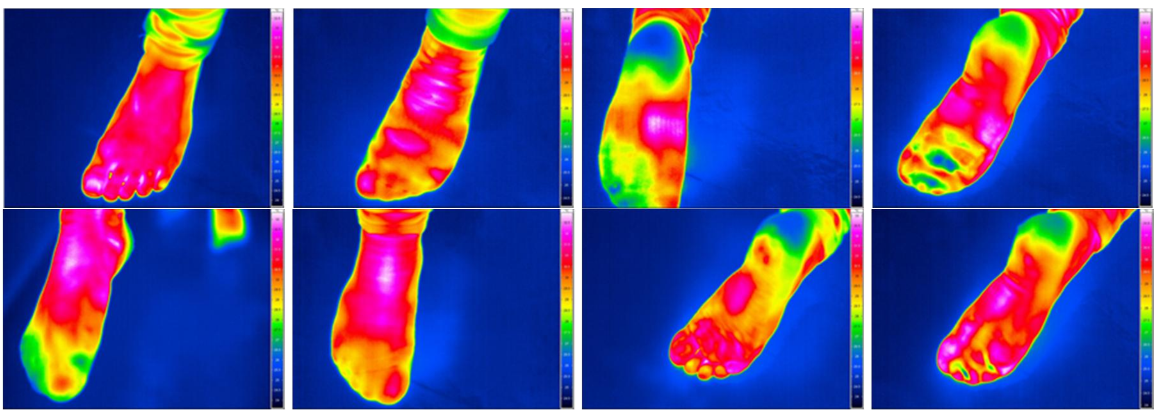

Figure 7 Selected images of thermograms front and back of the foot

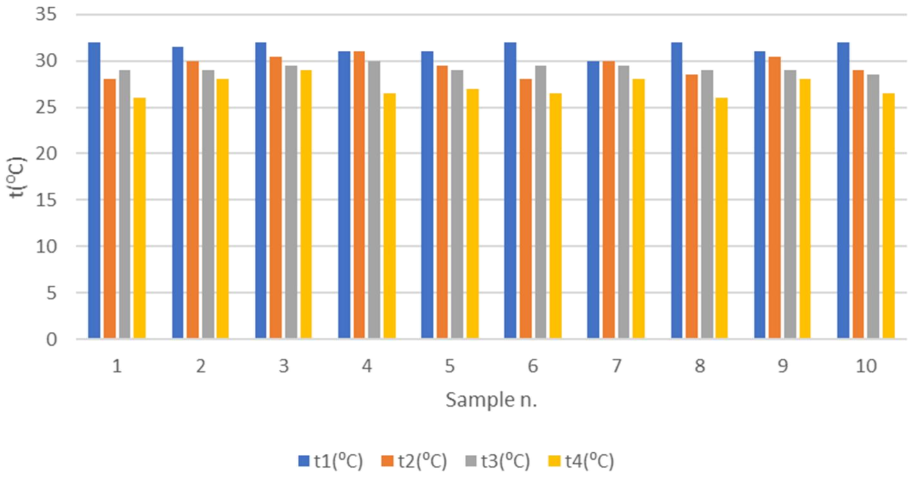

Figure 8 Foot temperature where t_1 is on the instep, t_2 on the toe, t_3 in the middle of the foot and t_4 on the heel

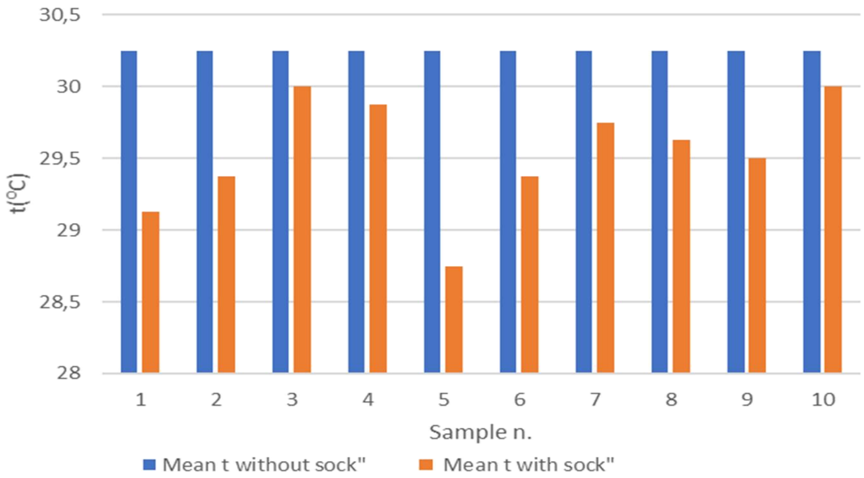

Figure 9 Mean temperature without and with the sock

4 CONCLUSIONS

The main aim of the work was to measure and evaluate temperature changes in parts of the foot and sock and to determine the change in length and weight of socks due to wearing.

From the measured results, it was found that changes in the weight of the socks due to wearing and maintenance are minimal. This means that the change in the weight of the socks will not affect the measured temperature fields.

The length of the socks was reduced by 5% to 16%. The content of elastane in the mixture did not significantly affect this distance. Its main role is to maintain the shape of the sock on the foot during wearing. Samples no. 1 and 8 had the worst dimensional stability. The reason may be the content of the wool component or the knitted structure.

The composition of the material shown in Figure 2 was for information only. A detailed analysis of the influence of the structure of linear textiles on the thermal insulation properties of socks will be the subject of further articles.

Temperature measurements were performed using a thermal imaging camera on a bare foot and on a foot with a sock at a proband during a time interval of 30 minutes of wearing. The result was thermographic images in the instep and foot part. Specific temperatures t_1, t_2, t_3, t_4 in these parts of the foot were selected. Based on them, it was found that the temperature of the foot with the sock is different in parts of the foot. In places where the skin is coarsest and the blood supply is lowest (the heel t_4), the temperature was lowest. The temperature was highest in the upper instep (t_1). It has also been shown that the temperature of the bare foot is higher than the temperature of the foot with the sock in the range from 0.25 to 1.5°C (Figure 9). However, from the results of the thermal imaging camera, it is not possible to conclusively determine which material composition of the sock is best heat insulation.

In the part of the sock where a denser knitted structure or terry and filler weave structures was used, it is possible to improve the insulating and mechanical properties [13]. The used method of temperature measurements on foot skin and a sock based on infrared camera may suffer for very low measurement precision. The temperature detected by infrared thermometers depend strongly on the surface emissivity of the measured object, and on the radiation energy penetrating from the background of the measured object (here human skin).

For knitted fabric structures, the penetration coefficient may reach 10%. Regretfully, the emissivity of a skin differs from emissivity of textiles. Moreover, emissivity of a skin depends on the skin moisture level. Therefore, the use of this method in the textile area is limited. Strictly scientifically, the measured knitted fabric surface temperatures will also depend on boundary condition on free surface, namely on the free convection heat transfer coefficient.

Moreover, temperature measurements on bare and dressed foot do not bring the information about thermal resistance of socks which also involves the effect of thermal resistance of the air gaps. Thus, the temperature difference data should be accompanied by thermal resistance data of the socks plus the knowledge of the average level of the air gaps.

These inaccuracies in thermal imaging camera measurements can be specified using thermal resistance and porosity measuring instruments. The main benefit of the paper is the evaluation of temperature variability in different parts of the foot, while its inaccuracies are also justified.

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