

The influence of knitting structures of men's socks on thermophysiological comfort in dynamic conditions

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ABSTRACT – REZUMAT

The influence of knitting structures of men's socks on thermophysiological comfort in dynamic conditions

The influence of environmental conditions on the thermophysiological comfort of men's socks with different knitting structures was investigated using an objective evaluation of comfort in dynamic conditions. Men's socks made in three knitting structures – R22, R31 and R71 rib constructions with the same raw material composition were used: bamboo yarn, filament polyamide yarn and wrapped elastomeric yarn for the sock welt. The influence of climate factors artificially generated in the climate chamber was analysed by measuring three physiological parameters: skin temperature, relative humidity on the skin's surface and temperature of the microclimate between socks and shoes. The results of the research indicate that the knitting structures of socks have a significant impact on their thermophysiological comfort. For an ambient temperature of 20°C and a relative humidity of 50% (autumn and spring conditions), preference is given to socks with R22 construction.

Keywords: socks, thermal properties, rib constructions, physiological properties, comfort

Influența structurilor de tricot ale șosetelor pentru bărbați asupra confortului termofiziologic în condiții dinamice

Influența condițiilor de mediu asupra confortului termofiziologic al șosetelor pentru bărbați cu diferite structuri de tricot a fost investigată folosind o evaluare obiectivă a confortului în condiții dinamice. S-au folosit șosete pentru bărbați realizate în trei structuri de tricot – patent R22, R31 și R71 cu aceeași compoziție a materiei prime: fire din bambus, fire filametare din poliamidă și fire elastomerice înfășurate pentru partea superioară a șosetei. Influența factorilor climatici generați artificial în camera climatică a fost analizată prin măsurarea a trei parametri fiziologici: temperatura pielii, umiditatea relativă la suprafața pielii și temperatura microclimatului dintre șosete și încălțăminte. Rezultatele cercetării arată că structurile de tricot ale șosetelor au un impact asupra confortului termofiziologic al șosetelor. Pentru o temperatură ambientală de 20°C și o umiditate relativă de 50% (condiții de toamnă și primăvară), se preferă șosetele cu structura R22.

Cuvinte-cheie: șosete, proprietăți termice, tricot patent, proprietăți fiziologice, confort

INTRODUCTION

The thermal comfort or comfort when wearing clothing made of different knitted fabrics is defined on the basis of objective analysis in the field of clothing physiology, structural and thermal properties of textile materials, microclimate, dry and wet heat flow, etc. The thermal comfort of clothing is a subjective evaluation by which a person expresses their satisfaction with their thermal environment. It is a psychological phenomenon related to the physical environment or physiological state, and it is difficult to determine exactly whether or not users are satisfied with thermal comfort (warmth, freshness, satisfaction, etc.). Socks are one of the most popular knitted products, made by knitting staple or filament yarns of different raw material composition (cotton, wool, bamboo, polyamide, polyacrylic, etc.). Cotton socks, for example, are soft, absorb sweat and water vapour well, are easy to care for and are very durable (especially mercerised cotton). Wool socks provide excellent thermal

insulation and have an excellent ability to absorb moisture and sweat. Socks made of bamboo fibres are quite thick and soft; they not only absorb moisture but also odours, so the feet stay fresh all day, and the person feels comfortable. They have antibacterial properties, a very soft texture and are ideal for sensitive skin. They are characterised by good air exchange; the disadvantages are the high cost of producing these fibres, and the products have a low level of strength and tear quickly [1–3].

The knit structure of the socks affects the thermophysiological properties of the product, which is directly reflected in the knitted fabric's ability to allow air and water vapour to pass through, wick sweat away from the feet, achieve thermal resistance and conductivity, etc. The raw material composition and the structure of the yarn, the density, thickness, bulk density or porosity of the knitted fabric are also important structural factors that determine the properties and comfort of socks [4, 5].

Numerous studies have shown the influence of materials and knitted construction on the comfort of socks [6–8]. In Ozdil's research [6], the thermal comfort properties of socks knitted from popular fibres in the field, such as wool, acrylic, cotton and PA, were investigated. Thermal resistance, thermal absorption, thermal conductivity, water vapour permeability and air permeability were analysed. The results show that the thermal conductivity values of woollen socks are lower than those of acrylic ones. The thermal resistance values of wool-acrylic socks are higher than 100% acrylic socks and give a feeling of warmth at first contact. Socks containing PA fibres provide high values of thermal conductivity and thermal absorption.

The effect of the fibre mix on the comfort of the socks is interesting [7]. Socks are knitted from traditional fibres such as cotton, bamboo and viscose and new types of regenerated fibres such as Modal, Promodal, Micromodal, Linen-Modal, and Lyocell. According to the air conductivity test, socks knitted from cotton had the lowest results, and Modal socks had the highest. According to the percentage of water vapour, the Micromodal sample had the lowest score, and the Modal sample had the highest score. In water resistance, the Modal sample had the worst result, and the bamboo had the highest value. The higher the thermal conductivity, the higher the heat transfer from the skin to the fabric. The viscose sample gave the highest values, and the Micromodal sample had the lowest values. The increase in thermal absorption of textile materials leads to a feeling of coldness at the first touch; the cotton sample gave the lowest, and the viscose the highest. Cotton proved to be the most suitable material for the production of socks, while Modal, Promodal and viscose are unsuitable, but at the same time suitable for the production of inner and outer parts of socks. In terms of moisture transfer, viscose, Promodal, bamboo and lyocell scored similarly and were not considered suitable sock materials. Micromodal and cotton are more suitable for use in socks.

Skin-to-fabric friction and other characteristics of some sock fabrics produced from cotton and regenerated cellulose fibres were investigated by surface friction, tear resistance, pilling and abrasion tests [8]. According to the results, cotton and its blend with Modal had better performance for burst strength, and cotton/Modal had better performance for pilling and abrasion resistance. Skin-to-fabric friction is lower for viscose among cellulose fibres, allowing for a smoother surface for leather garments. The breaking strength of the fabric is correlated not with the strength of the yarn, but with the breaking work. Cotton/Modal blend can be suggested for daily or functional socks.

This article describes investigations into the thermo-physiological properties of socks with the same raw material composition and different knit structures under dynamic conditions – when walking in shoes. The results of heat exchange and sweat, as well as

the temperature of the microclimate under the conditions of movement, make it possible to obtain information about which type of knit construction of socks is best suited for wearing under certain climatic conditions.

MATERIAL AND METHOD

Material and test methods

Short men's socks made of the same yarn type in three different rib constructions were used for the test. A bamboo fibre yarn (30.75 tex) with a nominal content of 77% was used as the base yarn. In addition, a filament yarn made of PA 6.6 (4.4/13 tex × 2) with a nominal content of 22% and finally, at the beginning of the sock, the cuff, an elastomer yarn (100 tex), which is wrapped with PA yarns (78 dtex) in two layers, with a nominal content of 1%.

The socks are made in three knitted structures (rib constructions), with the following labelling: R22, R31 and R71. A "Lonati Bravo 856" two-cylinder hosiery machine with a cylinder diameter of 95 mm and 168 needles was used to make the socks.

The measurements of the most important properties of the socks were carried out using suitable standards or tests:

- Thickness of the socks, according to the SRPS EN ISO 5084:2013 standard [9].
- The porosity (P) is calculated according to the equation: $P = (1 - m/\rho \times h) \times 100$; where m is the mass per unit area (g/cm^2), h is the thickness of the knitted fabric (mm), and ρ is the fibre density (g/cm^3) [10].
- Water vapour transmission of materials, according to the ASTM E96 [11].
- Air permeability, according to the SPRS EN ISO 9237:2010 [12].

The basic characteristics and the same thermo-physiological performances of the socks are listed in table 1.

Test protocol

In the experiment, the influence of three identical models of socks in size number 11.5 (43–44) with different knitting structures and the same raw material composition was monitored on the thermal-physiological comfort when walking in shoes. All of the wear trial tests were performed under artificially designed ambient conditions in a computer-controlled climatic chamber. During the wear tests, the temperature of the skin, the relative humidity of the skin and the temperature of the microclimate (the space between socks and shoes) were measured at various points on the foot using the MSR 12 Modular Signal Recorder.

The test subjects (three male participants) took part in the study, always dressed in the same way and in the same wardrobe and wearing leather shoes, with the upper part and the inner sole of the shoe made of 100% natural leather. This testing was conducted as a preliminary or pilot study, aimed at identifying

MORE IMPORTANT INDICATORS OF SOCKS FOR THE THERMOPHYSIOLOGY OF THE PRODUCT						
Rib construction	Thickness (mm)	Horizontal density (1/cm)	Vertical density (1/cm)	Porosity (%)	Water vapour transmission (g/m ² /24h)	Air permeability (m ³ /m ² /min)
R22 	1.886±0.04	12.83±0.4	10.66±0.2	85.50±1.1	4703.61±45.5	57.48±1.3
R31 	1.710±0.1	10.50±1.2	11.00±1.1	87.65±1.8	5246.34±58.3	65.40±1.5
R71 	1.877±0.08	10.00±1.0	11.50±1.1	89.61±1.7	6331.79±51.4	56.40±1.7

trends and assessing the feasibility of the testing protocol. While the data collected provides useful insights, we recognise that a larger and more diverse sample is necessary to obtain physiologically relevant and statistically valid results. Future testing will be expanded to include a greater number of participants in accordance with scientific and methodological standards.

Selection of participants

The selection of participants took place in such a way that the test person was observed while standing, so that disorders of the longitudinal arch of the foot, flat feet or high feet could be observed. Then the feet were examined from behind while the respondent stood on the toes; muscle contraction, the degree of heel inversion, the height of the arch of the foot and the degree of lateral symmetry were evaluated. Also,

discolouration of parts of the feet, swelling, or deformities were observed. After the examination, respondents with very similar feet, without deformities, were selected to participate in the experiment.

Physiological parameters monitored for the study

The following physiological parameters (temperature and relative humidity of the skin, microclimate temperature) in the climatic chamber were monitored using the MSR Modular Signal Recorder from MSR Electronics GmbH.

Sensors for measuring the temperature (T61, T62, T63, T68, T69, T161) and relative humidity (RH1, RH2, RH4, RH5) are placed directly on the skin of the feet, while microclimate temperature sensors (T67, T162) are placed on the socks, under the shoes (figure 1).



Fig. 1. Positions of the sensors for measuring the temperature and relative humidity on the feet and the temperature of the microclimate on the socks

Thermo-physiological test protocol

The test subjects performed two treadmill exercises while wearing normal clothing and leather shoes under warm environmental conditions (ambient temperature 20°C, relative humidity 50%, and air velocity 0.5 m/s). The test subjects performed the activity in the following order:

- Acclimatisation under the same testing conditions: 30 minutes
- The first phase: Exercise I (subject walking on the treadmill in the test climate chamber at a speed of 2.5 km/h on the flat in the direction of the wind): 30 minutes
- Rest period: 20 minutes
- The second phase: Exercise II (subject walking on the treadmill in the test climate chamber at a speed of 3.5 km/h on the flat in the direction of the wind): 30 minutes
- Rest period: 5 minutes.

The test period after each phase will allow the test subject to complete a questionnaire on comfort.

RESULTS AND DISCUSSION

Some indicators of socks

Table 1 shows data on the most important indicators of socks, which are decisive for the thermophysiological state of the sock during use. Numerous values of the statistical parameter standard deviation are also shown in table 1 (mean \pm standard deviation). The thickness of the sock varies depending on the knitting structures, given the same composition and type of yarn [13]. The socks in the R22 construction have a slightly greater thickness, which is connected to the method of production and the change of loops on the upper and lower cylinders. The thickness of the knitted fabric, as a rule, affects the thermophysiological properties of socks, because the thickness of the socks affects the porosity of the product, which in turn affects the permeability of water vapour and air. Relations are not always directly proportional, as can be seen from table 1, the type of knitting structure has a visible influence, in this case.

According to table 1, R71 rib knitted socks dominate when it comes to water vapour permeability, while R22 rib knitted socks have the highest thickness and lowest porosity. R31 rib knitted socks are characterised by the smallest thickness and the highest air permeability. All these properties determine the behaviour of socks on the feet when walking in shoes; they affect the exchange of heat and moisture, i.e., the comfort of socks and feet in dynamic conditions. It should be added that the socks worn on the feet with shoes are in a tensioned state with pressure from the shoes, while all the properties in table 1 were measured in a relaxed or resting state of the socks without any external pressure. For this reason, the results from table 1 must be taken conditionally when used to predict the behaviour of socks under dynamic conditions of movement in tension and compression.

Skin temperature of the feet while wearing socks

The results of the skin temperature of the feet wearing socks and shoes during the stay in the climate chamber, under dynamic conditions, are shown in figures 2 to 4. In each graph, there are 6 dependencies (curved lines) from 6 sensors that measure the temperature change on the skin of both feet during the 80 min stay in the air conditioning chamber. Certain regularities are noticeable in the curves in the graphs of figures 2 to 4 from the sensors that measure the temperature of the skin of the feet. Namely, at sensors T61 (upper part of the right foot, next to the toes), T62 (arch of the right foot), T68 (upper part of the left foot, next to the toes) and T69 (arch of the left foot), in all cases, a higher temperature was recorded in relation to the temperatures of sensors T63 (above the ankle of the right foot) and T161 (above the ankle of the left foot).

According to the curves from the graphs of these figures, all knitting structures give similar but not identical temperature curve flows from the sensors placed on the skin of the feet. All individual curves follow a certain order of appearance on the graphs, i.e. temperature sensors T62 and T69 have the highest positions on the graphs, i.e. register the highest temperature of the skin of the feet in socks and shoes. Next are the temperature sensors T61 and T68, whose curves are placed a little lower on the graphs, and finally, with the lowest position and thus the lowest temperature, come the curves from the temperature sensors T63 and T161, which are placed above the ankles of both feet and below the socks.

According to figure 2 (R22 construction), the curves of the temperature sensors T61, T62, T68 and T69 have a similar flow. Until about 2000 s, they show a constant increase in temperature, followed by a drop until about 3000 s, and then the temperature increases continuously until the end of the test. The other sensors, T63 and T161, have an initial mild increase in skin temperature in the graph with a partial decrease between 2000 and 2500 s (rest in the climate chamber). In the case of R31 construction, figure 3, a similar phenomenon occurs, the initial rise in temperature occurs up to about 2000 s, followed by a drop or stagnation (sensor T68) up to about 3000 s with a subsequent rise. In the R71 construction, the temperature curves in the graph of figure 4 appear differently. Namely, here only the temperature sensors T62 and T69 have a similar appearance to the other constructions, pronounced initial growth up to 2000 s and then a drop up to 3000 s with subsequent continuous growth. Sensors T61, T68 and T161, with an initial slight increase up to 2000 s, show a short drop and stagnation up to 3000 s, then there is a continuous rise until the end of the experiment. The T63 sensor (figure 4) completely deviates from the usual flow observed with other socks. Namely, here a continuous increase in the flow of the curve was observed until 3000 s, when a sharp drop in the flow of the curve followed until about 3300 s, with a subsequent increase until the end of the graph. These

differences in the appearance of the curves from individual temperature sensors are expected; however, it is a matter of different knitting structures of socks with expected different behaviour in practical use.

In general, the lowest temperature range of the feet's skin during the entire experiment was registered with the R71 rib knitted socks, while the R22 rib knitted socks had the highest temperature range of the feet's skin, regardless of the sensor.

The temperature curves of the T63 and T161 sensors, mostly for all socks, run almost parallel to the x-axis, with slight, rhythmic variations during testing in the climate chamber. As expected, on the part of the leg just above the ankle, which is covered only by the sock, the temperature of the skin is lower than the temperature of the other parts of the foot covered by shoes. This is connected to the fact that this part of the sensor is covered only by a sock and not by a shoe, so there is better ventilation, and there is also the influence of the movement of the surrounding air (0.5 m/s). Of course, in all this, the knitting structure of socks has a decisive influence.

Regardless of the knitting structures, if the influence of the activity in the climate chamber is observed, the highest temperature of the skin of the feet in socks and shoes was registered in all samples, during fast walking („walking II“, 3.5 km/h) in the last 20 minutes of the test when the curves temperatures have a constant rise, reaching a maximum in the last minutes of the test.

For R22 construction, the temperatures from the sensors T62 and T69 (arch of the right and left feet) have

the highest numerical values during the activity „walking I“, 34°C and 35°C, which exceeds the limit of the comfort zone (average skin temperature from 31.4°C to 33°C). For other knitting structures, temperatures from the same sensors reach values of 33.5°C – 34.3°C, which are closer to the comfort zone. In this sense, from the aspect of thermal comfort, socks in the R71 construction turned out to be the best.

Relative humidity of the skin of the feet

Socks are expected to release water vapour or moisture quickly and dry quickly. Depending on the knitting structure, the fluid will be retained in the interstices of the fibres or absorbed by the fibres. Given that the selected samples of socks are of the same raw material composition, the differences will exist only due to the knitting structure that changes.

The results of testing the relative humidity of the skin of the feet, registered by sensors, when wearing the analysed socks, are shown in graphs in figures 5 to 7. Skin moisture was measured using 4 sensors, 2 on each foot, labelled as follows: RH1 (front of right foot next to toes), RH2 (arch of right foot), RH4 (front of left foot next to toes) and RH5 (arch of left foot).

The curves, which determine the change in the relative humidity of the skin over time in dynamic conditions, have a different flow from the beginning to the end of the test, during all 4800 s. The appearance of the curves from the graphs in these figures differs for different knitting structures of socks, as expected. On the other hand, the well-known higher swelling of

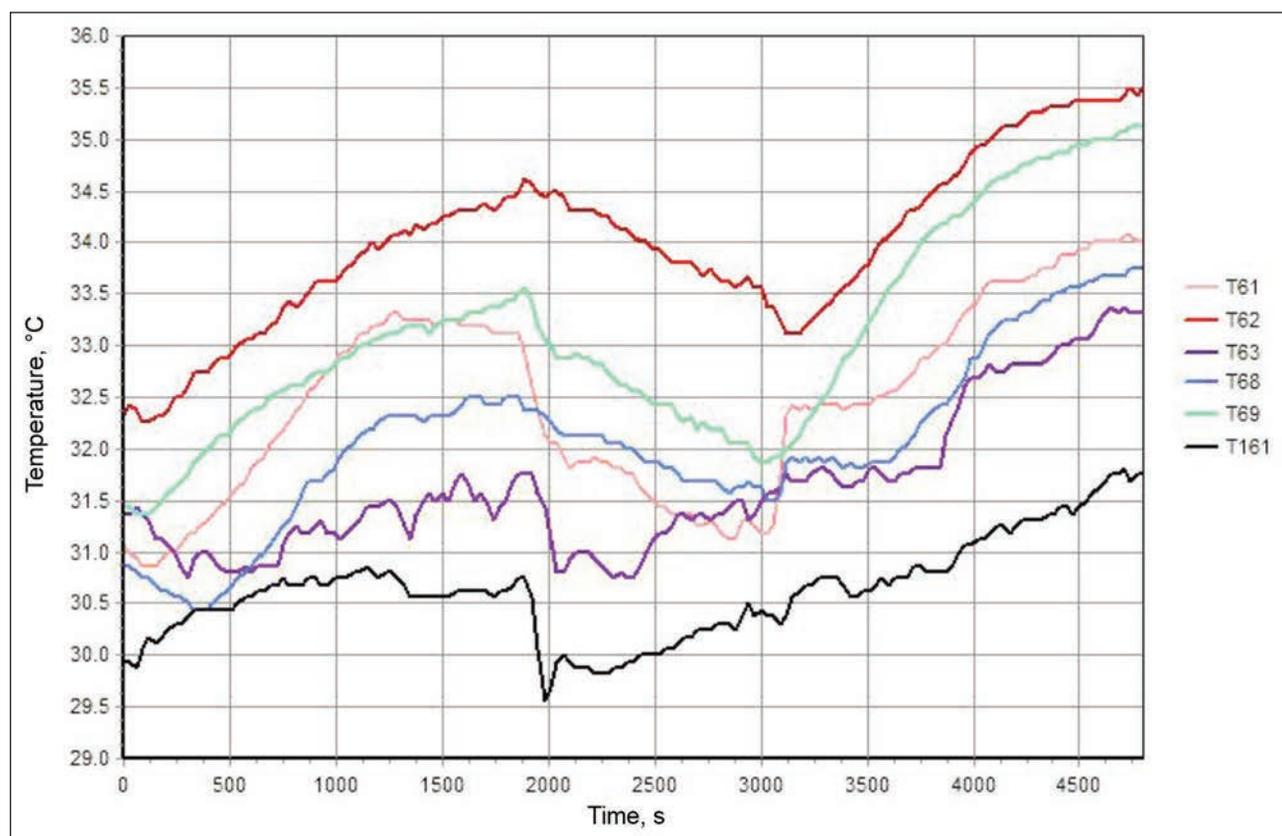


Fig. 2. Foot skin temperature when wearing R22 rib knitted socks during testing under dynamic conditions

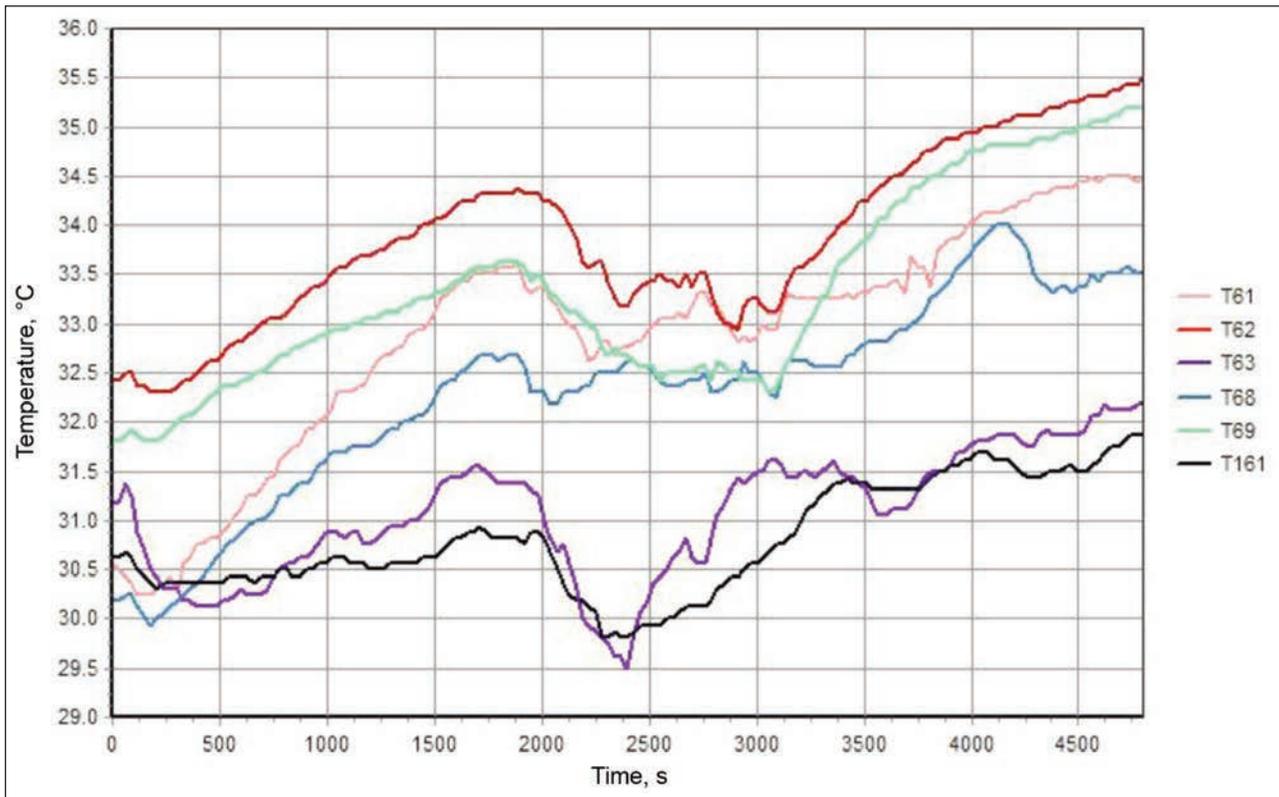


Fig. 3. Foot skin temperature when wearing R31 rib knitted socks during testing under dynamic conditions

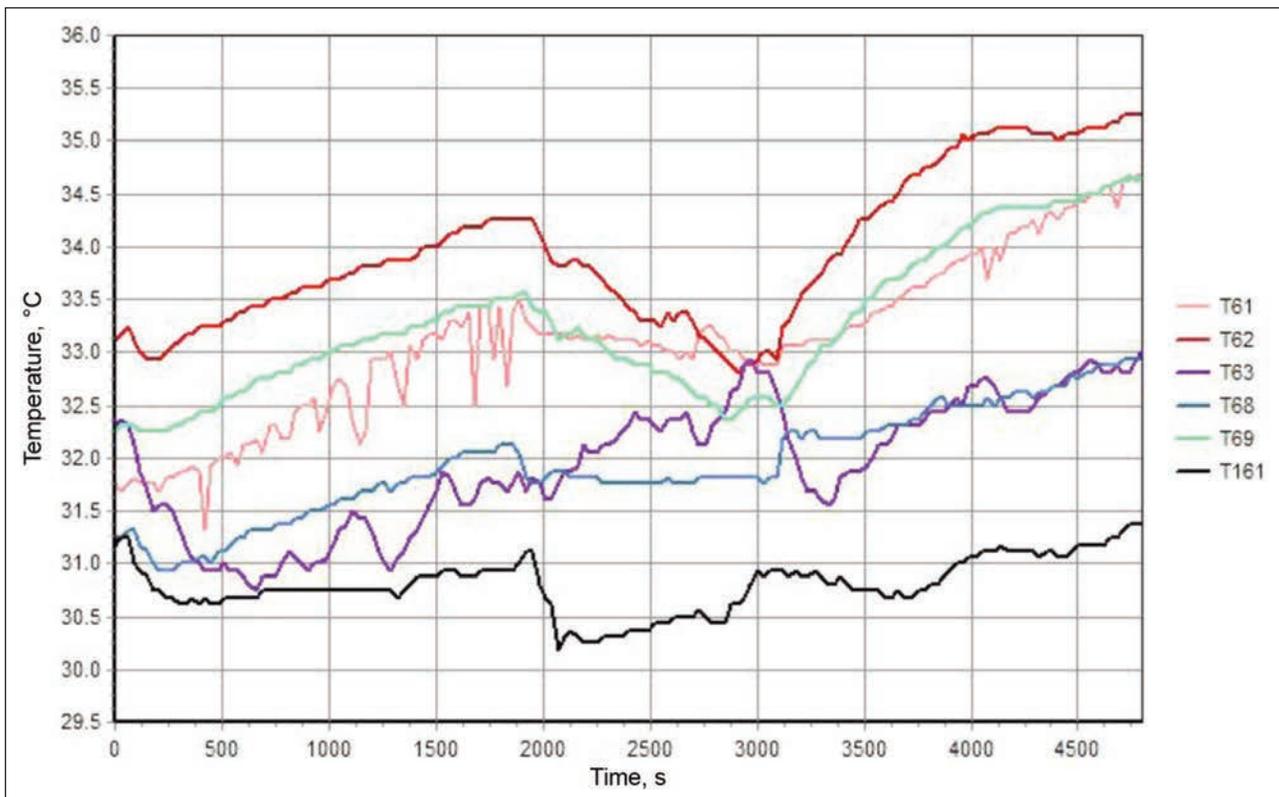


Fig. 4. Foot skin temperature when wearing R71 rib knitted socks during testing under dynamic conditions

bamboo fibres contributes to the retention of liquid in the fibres because the flow is slowed down, or even capillary closure may occur. The initial higher relative humidity of the foot skin in socks and shoes during acclimatisation before the

“walking I” phase in products with R71 construction confirms the fact that this rib construction does not allow a greater flow of moisture, i.e., heat (figure 7). For socks in R22 and R71 constructions, figures 5 and 7, the humidity curves from sensors RH1 and

RH5 have a similar appearance; the changes are more intense in the part between 1900 and 3000 s, where a strong drop in the flow of the humidity curve was observed, during the phase “rest”. In the case of R31 rib knitted socks, for humidity from the same sensors and in the same range, a milder growth and stagnation of humidity change or only a slight decrease during rest in the middle of the experiment, was observed. The sensors RH2 and RH4, for all knitting structures, identically register skin humidity; the curves are very similar. When it comes to the humidity sensor RH5, located under the left foot (arch of the foot), in the R31 construction, it gives a relative humidity signal that is significantly different from the same signal in the other rib constructions. Namely, this is an error during the measurement; the RH5 sensor has broken, so this curve from the graph in figure 6 should not be taken into consideration. Also, the curve from the moisture sensor RH4 should be conditionally taken for socks with R22 construction, because the very high beginning of the curve (81% moisture) and the appearance of the curve are not realistic enough.

The lowest initial relative humidity was registered with socks in R22 construction (58% from sensor RH5), while the highest was recorded with socks in R71 construction (74% from sensor RH4). The same applies to the end of the experiment, i.e., at the final stage “walking II”.

If you compare the appearance of the curves on the graphs for temperature and humidity (figures 2 to 7), a coincidence is noticed, i.e. with most sensors,

where the temperature is the highest, the humidity is the lowest and vice versa.

Physiological comfort is known to decrease if the value of average skin humidity is 30% or more. Values of over 60–70% humidity (sweat coverage) mean that the skin is already wet, so the feeling of comfort is unpleasant. Above this limit, the zone of intolerance begins with discomfort with impaired temperature regulation as a result of overheating. In the specific case, according to the results of the relative humidity of the skin on the foot, there is a partially impaired comfort when walking in bamboo socks, of different knitting structures, especially in the last phase of the experiment, “walking II”. The best product in this sense, in terms of physiological comfort during the entire experiment, was shown to be the R22 rib knitted socks.

In similar research with socks [14], the influence of textile, physiological and sensory parameters on the comfort of socks was analysed. Using sensors, foot temperature, fabric moisture and pain were measured. Significant correlations were found between physiological and sensory parameters, as well as between fabric friction and perceived comfort. Comfort depended on the fibre content of the socks and the humidity and temperature of the feet. The surface roughness and water content in the textile did not affect the comfort of the socks. Fabric friction and fibre content are relevant textile parameters for sock comfort. In subjective tests, socks with a high coefficient of friction were less comfortable than socks with a low coefficient of friction. Fibre content can affect

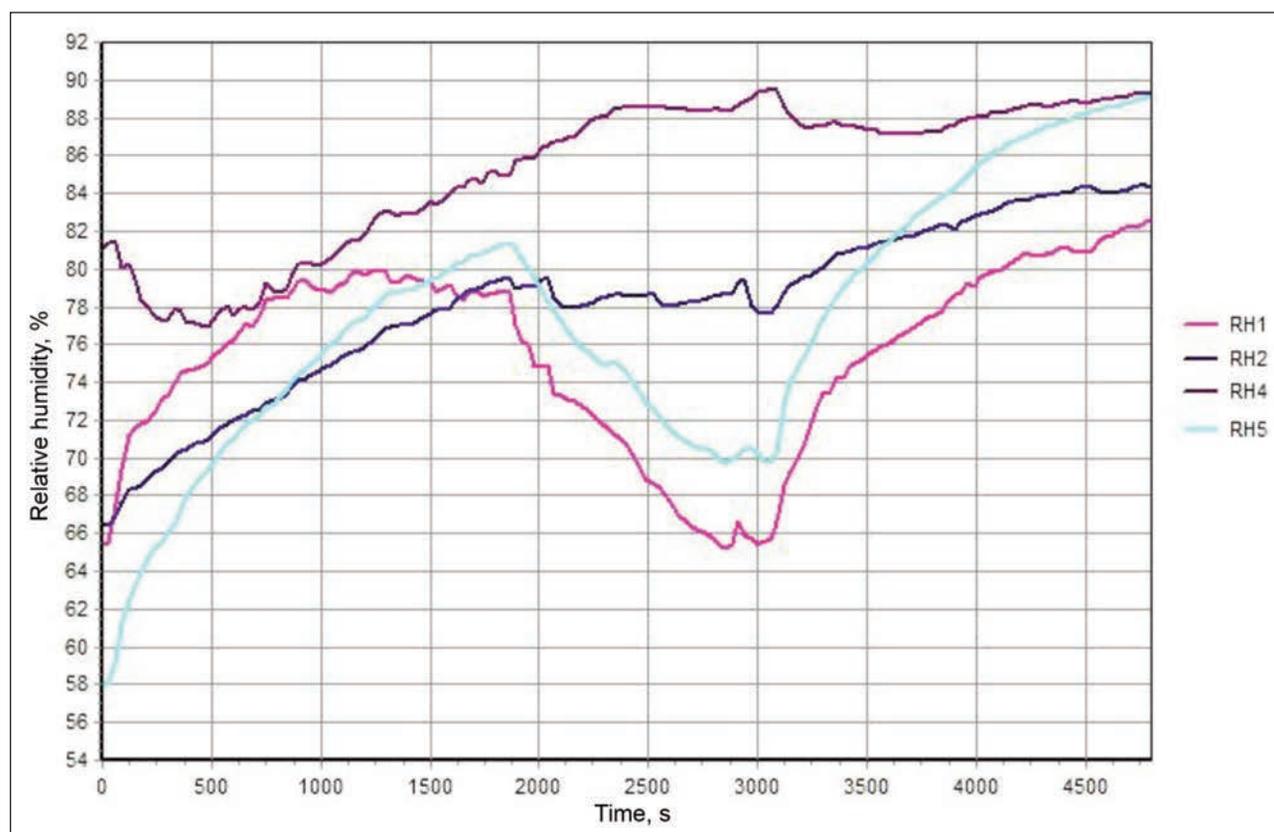


Fig. 5. Relative humidity of the foot skin when wearing R22 rib knitted socks during testing in dynamic conditions

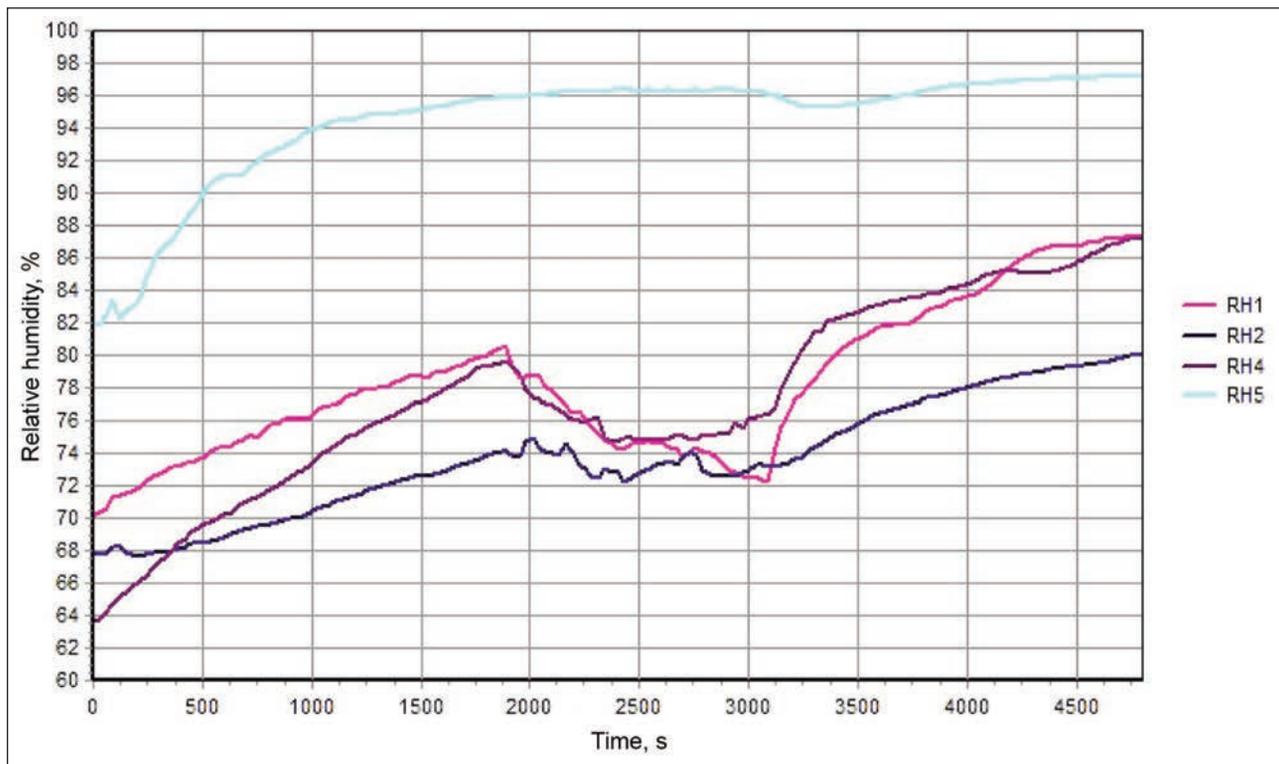


Fig. 6. Relative humidity of the foot skin when wearing R31 rib knitted socks during testing in dynamic conditions

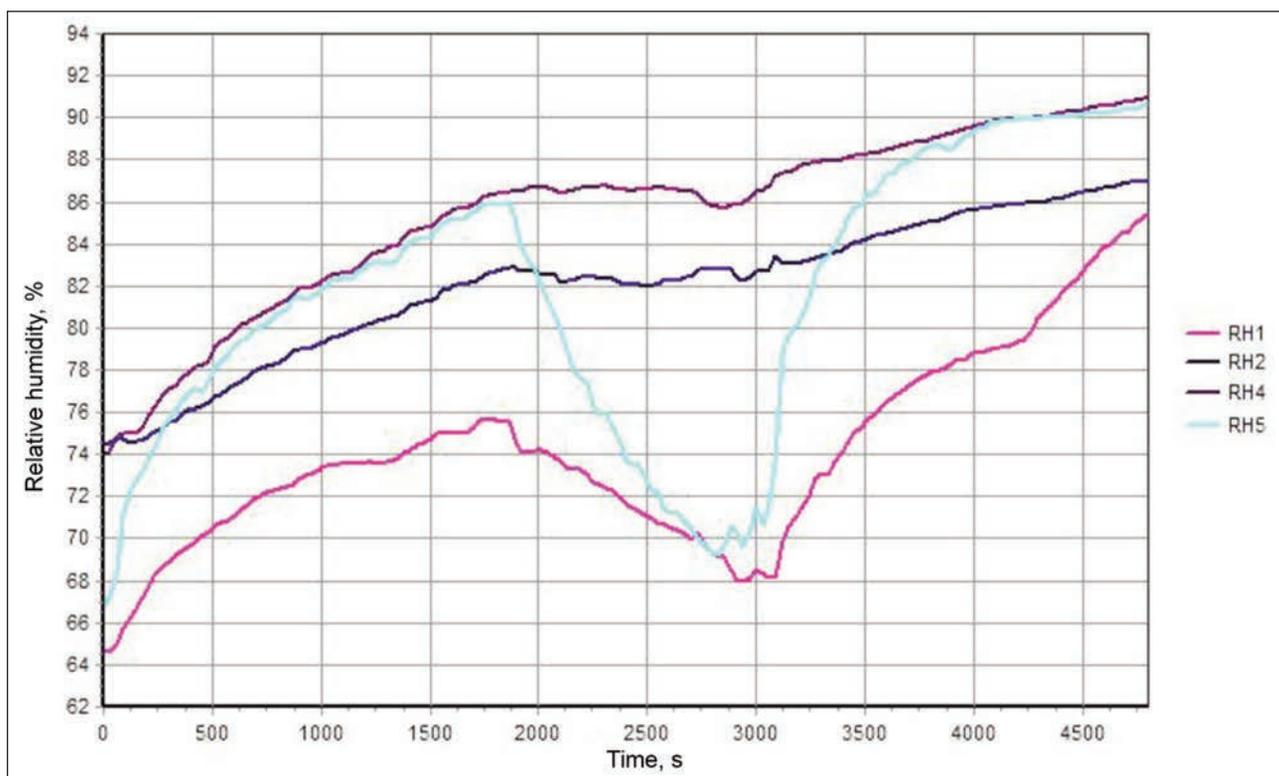


Fig. 7. Relative humidity of the foot skin when wearing R71 rib knitted socks during testing in dynamic conditions

comfort; socks containing cotton are less comfortable than synthetic socks. However, many consumers still prefer clothing that contains cotton. Comfort is related to sensory parameters such as temperature and humidity. Fibres that can transport sweat from the sock are needed to avoid high foot temperature and humidity. The respondents were 11 men aged

between 26 and 56 years. Participants wore the same shoes before each test. Before the start of the experiment, the subjects were conditioned for 15 minutes in the laboratory climate where the sports exercises took place. In order to measure physiological parameters, two sensors are integrated in each shoe, one in the area of the toes and one in the area

of the ankle. The placement of these sensors is carefully chosen to avoid pressure points and friction. One sensor is fixed above the toes on the inside of the shoe.

Socks are the subject of research in the following paper, where a study was conducted that evaluated the effect of socks (made of different fibres) and the effect of not wearing socks on the perception of thermal comfort in relation to changes in the temperature of the skin of the feet and the microclimate of the shoes (temperature and humidity) during rest and exercise [15]. Ten women participated in the trials on different occasions. Four socks were evaluated (cotton, wool, polyester, Coolmax), and one test was without socks. The tests were conducted at 23°C and 50% relative humidity, and consisted of rest (10 min, sitting), treadmill running (40 min, 7.5 km/h) and recovery (15 min, sitting). Foot skin temperature and shoe microclimate were measured at seven places on the right foot. Foot skin hydration was measured at nine places. Not wearing socks resulted in a greater perception of foot wetness, stickiness and discomfort. As the tactile interactions caused by foot movement inside the shoe are strong determinants of foot wetness perception, socks are important in reducing the tactile cues generated. The results of this study show similar thermophysiological and perceptual responses when socks composed of different types of fibres are worn during rest and exercise. Also, similar thermophysiological responses were observed when wearing socks (regardless of fibre type) compared to not wearing socks. Surprisingly, however, exercising without socks resulted in greater perceived foot wetness, stickiness, and thermal discomfort.

In addition to socks, other clothing items are the subject of thermal and moisture comfort research [16]. In a climate chamber experiment, quantitative research guides underwear development. The thermal and wet comfort of pure cotton underwear is worse than that of blended or knitted underwear, which is consistent with previous results that the thermal and wet comfort of multi-fibre fabrics is better than that of same-fibre fabrics. Half an hour before the experiment, participants entered a room with artificial climate with constant temperature and humidity: ambient temperature (25±2)°, relative humidity (65±5)% and wind speed ≤0.1 m/s. The test personnel wore only an undershirt and underpants for the experiment. The temperature and humidity of the chest, back, hips and thighs of the human body change with the change of the exercise state, and the results of the heat and humidity comfort of each part are different, while the heat and humidity of the chest and back change greatly. In addition, the results of the subjective assessment of thermal and wet comfort are basically consistent with the objective assessment results. The simulated values are in good agreement with the experimentally measured values.

Furthermore, in order to evaluate the thermophysiological comfort of men's workwear, an analysis was performed based on the evaluation of the clothing

system using test persons in a study simulating environmental conditions [17]. Analysis of the thermo-physiological comfort of men's business clothing based on wear tests shows that environmental conditions, activity levels and thermal properties of the clothing system have a significant impact on the physiological parameters of the subjects and the subjective assessment of thermal comfort in a cold environment. At an ambient temperature of 10°C, when the study participants wore a four-layer clothing system, the mean skin temperature averaged about 32.5°C while sitting and about 31.6°C while walking. Subjective assessment showed that study participants felt thermally comfortable despite lower mean skin temperatures. Subjective assessment showed that study participants felt somewhat uncomfortable while sitting, but felt thermally comfortable or slightly cool while walking. The research shows that different environmental conditions, activity levels and thermal properties of the clothing system have a significant impact on the physiological parameters of the subjects and the subjective assessment of thermal comfort in a cold environment.

Microclimate temperature

Figures 8 to 10 show Temperature/Time graphs for the microclimate in the space between wearing socks and wearing tied shoes during dynamic walking conditions in the climate chamber. These graphs have two curves each, one curve comes from the T162 sensor (left foot) and the other from the T67 sensor (right foot).

For bamboo socks in all rib constructions, the curves from both sensors generally follow each other, after an initial rise to 1500–1900 s ("walking I" phase), the curve begins to fall with one sharp jump (R31 and R71 constructions, right foot) to about 3000 s (rest at the end of phase "walking I"), after which the curves continue to grow continuously until the end of testing in the climate chamber (phase "walking II"). This more intense jump after 2000 s was not registered with the microclimate sensor on the left foot. The existence of rapid cyclical or rhythmic shifts of the temperature curve from the sensor on the right leg between 2300 s and 3000 s in the R31 construction or between 2600 s and 3000 s in the R71 construction can be related to the subjective error that occurred during the resting time period after the "walking I" phase, it is probably a reflex movement of the toes, i.e. the front part of the foot (toes curling, bending the foot in the shoe, etc.), which was reflected in the result.

The graphs in figures 8 and 9 represent the temperature of the microclimate of socks in R22 and R31 constructions, for both feet with shoes in dynamic walking conditions. The temperature curves from the space between the sock and the shoe, for the left (sensor T162) and right (sensor T67) legs, follow each other, i.e., the differences are minimal. With socks in the R71 construction, the situation is a little different; the curves from these sensors do not follow

each other. It is expected that there are real differences in the temperature of the microclimate of one foot and the other foot; it is unlikely that both feet give the same values of heat that accumulates in the space between shoes and socks. In addition to the knitting structures of the socks, this is also influenced by the pressure of the shoe, the strength of the laces, the shape of the foot, the fit of the shoe on the upper part of the foot, etc.

All these observations are related to the properties of the fibres from which the socks are made, as well as the structural, i.e., constructive characteristics of the knitted fabric from which the socks are made. As the composition and structural characteristics of the sock yarn are identical, the differences are attributed mainly to the differences in the knitting structures of the socks.

During the experiment in the climate chamber, the highest recorded values of skin temperature and microclimate are in the following sequence of rib constructions: R22>R31>R71. For foot skin moisture results, the order of rib constructions is as follows: R71>R31>R71. Socks with R22 construction generally have the highest skin temperature during the experiment, which at first glance leads to the thought that the product with this knitting structure is the greatest insulator; however, it is not so, on the contrary, this knitting structure is the most heat permeable. Namely, if it is considered that socks with R22 construction leave the least amount of moisture on the skin of the feet, this means that they transmit the most heat and water vapour, so they do not allow a large condensation of moisture on the skin.

Therefore, if these socks with R22 construction were the greatest insulator, they should simultaneously have the greatest condensation of water vapour, that is, show the greatest moisture of the skin (which does not happen). It turns out that socks with R71 construction and/or R31 construction (a small difference between them) are the greatest insulators, in this case, because they cause the greatest moisture in the skin of both feet, that is, they are the least permeable to water vapour and heat, which causes condensation and sweating of the feet. Socks in R22 construction have the highest temperature of the skin of the feet; this heat is transferred to the sock and then to the space between the sock and the shoe, so as expected, they also have the highest microclimate temperature. This is not the case with R31 and R71 rib knitted socks because they are better insulators, heat condenses into moisture-sweat, and they have a slightly lower microclimate temperature.

Considering that moisture is more uncomfortable than heat, then bamboo/polyamide, 77/22%, R22 rib knitted socks give the best results for foot comfort while walking in shoes at 20°C and 50% relative humidity.

Many authors point out that the microclimate parameters of footwear, especially humidity, have a decisive influence on the feeling of the user in relation to thermal comfort. Research on shoe microclimate [15] evaluates the effect of sock fibre type and the effect of not wearing socks on the perception of foot thermal comfort in relation to shoe microclimate. Results have similar thermophysiological responses when wearing socks (regardless of fibre type) compared to no socks during rest and exercise.

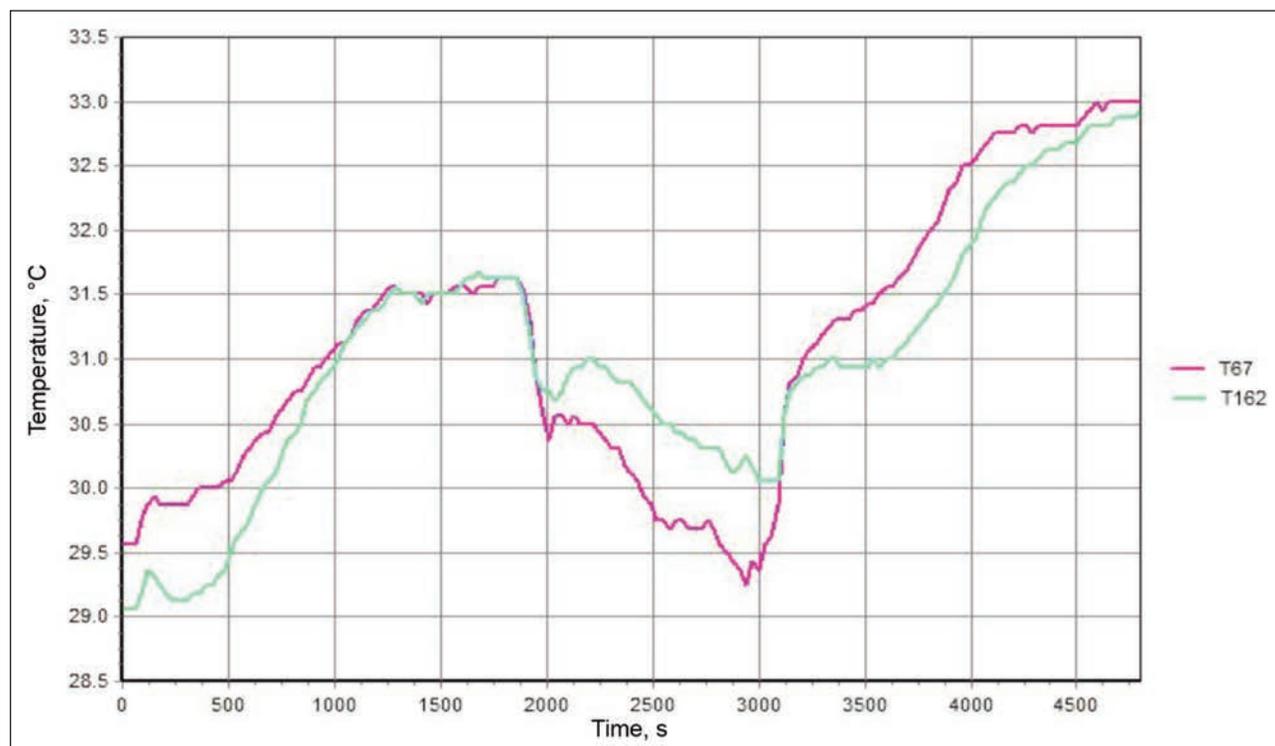


Fig. 8. Microclimate temperature in the space between R22 rib knitted socks and shoes during testing in dynamic conditions

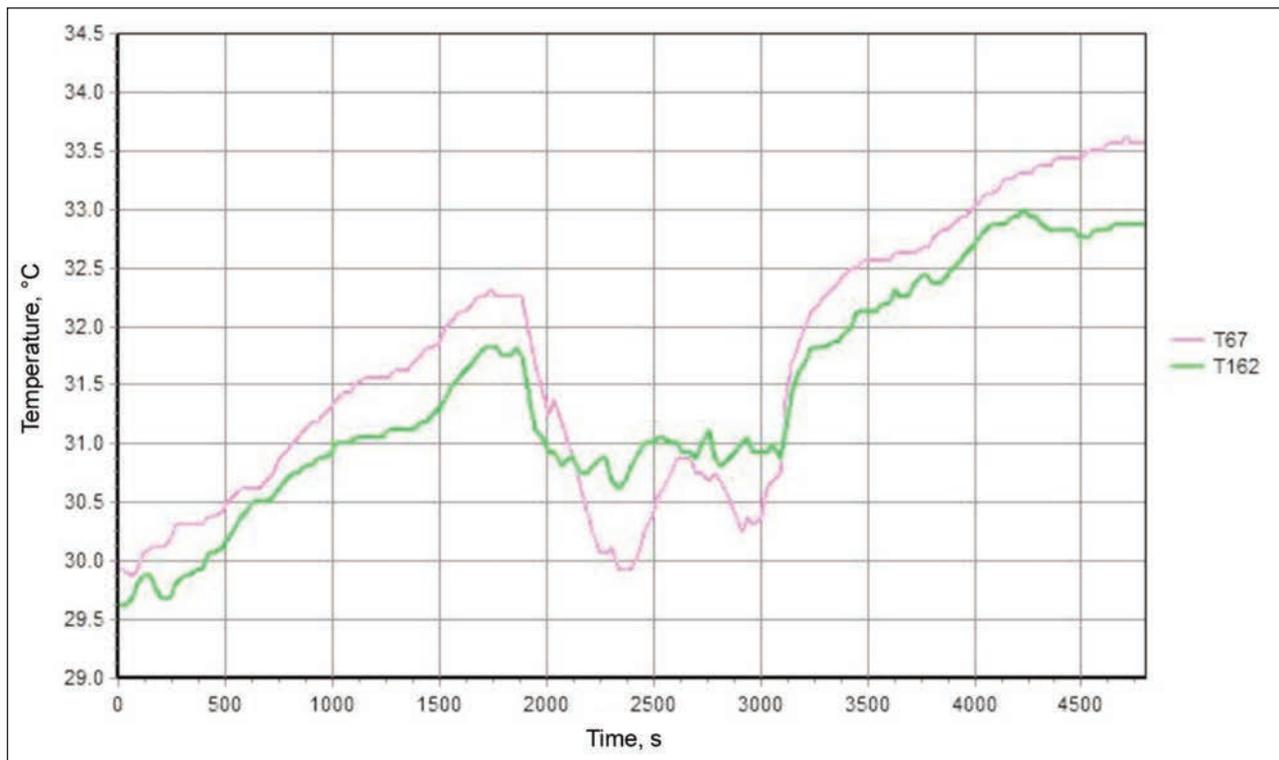


Fig. 9. Microclimate temperature in the space between the R31 rib knitted socks and shoes during testing in dynamic conditions

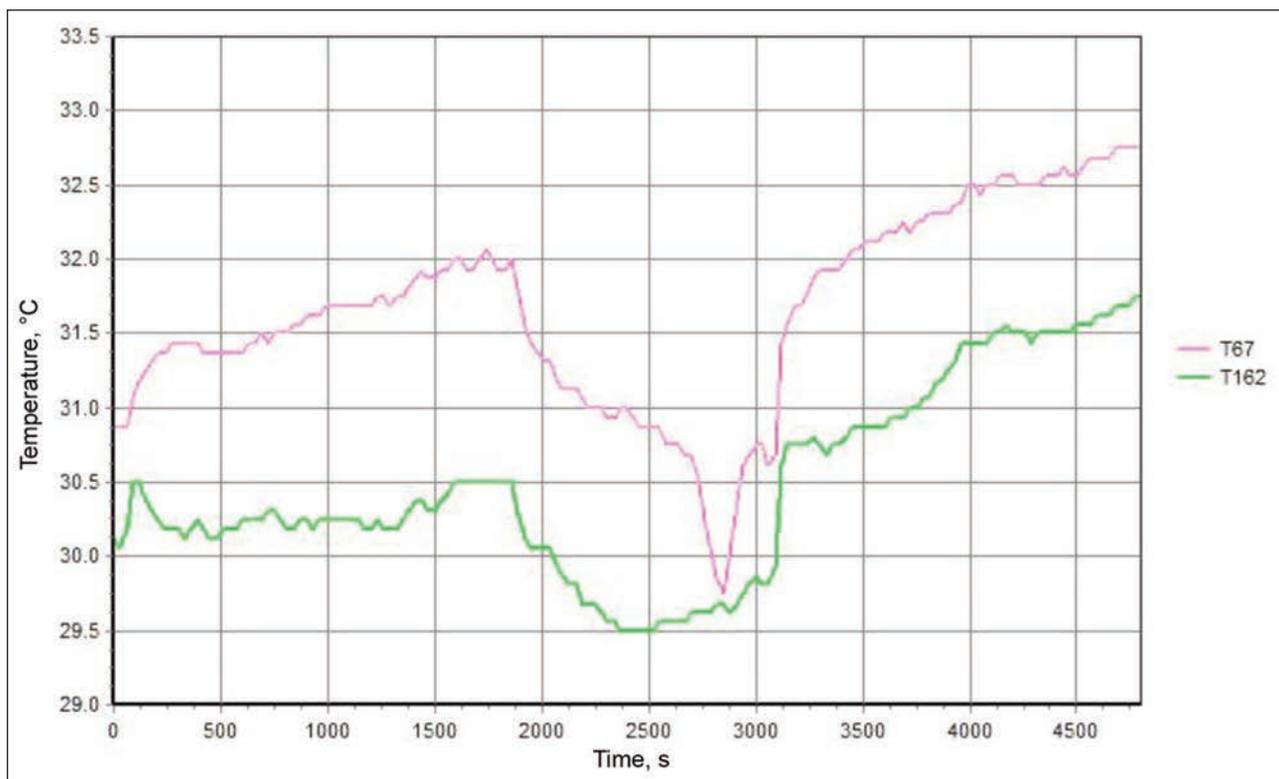


Fig. 10. Microclimate temperature in the space between the R71 rib knitted socks and shoes during testing in dynamic conditions

No differences were observed in foot temperature, shoe microclimate or foot skin hydration. Socks composed of different types of fibres were also shown to induce similar thermophysiological responses during rest and exercise, as no differences were observed in

foot temperature, shoe microclimate, or foot skin hydration.

The following research deals with a validation study for the already published thermal simulation of the clothing system and the human environment through wear testing [18]. Three test persons and a clothing

system were selected for this research. The temperature of the microclimate has a great influence on the temperature of the skin. Skin temperature has an almost similar pattern of variation on the microclimate temperature curve. For example, significant variations in microclimate temperature affect corresponding skin temperatures that show a similar pattern of temperature curves. Therefore, the occurrence of pumping in the air gaps between the clothes and the body causes not only a decrease in the temperature of the microclimate, but also the corresponding temperature of the skin. During the wear test, the subject has to perform various activities while walking on a treadmill, which causes forced convection on the moving parts of the body and also a pumping effect in the microclimate between the clothing and the body.

The indication of microclimatic conditions in footwear is also shown by the research of Irzanska et al. [19], which points out that the accumulation of heat leads to an increase in the temperature of the skin of the feet and an increased humidity of the microclimate inside the footwear, to the point of saturation. These conditions cause an intense production of sweat, which again cannot evaporate and accumulates on the skin and inside the textile structure, which increases the user's discomfort. By analogy with the treadmill test, three characteristic phases of the development of the microclimate inside the footwear can be distinguished: the first phase – increased heat transfer to the skin and the beginning of intensive sweat production; the second stage – evaporation of produced moisture; and the third stage – local condensation of water vapour. Unfavourable microclimatic conditions inside rubber protective footwear disrupt thermoregulatory processes associated with blood flow in the lower extremities. This can subsequently disrupt the functioning of the entire human body. Therefore, it is crucial to control this microclimate. These changes in the internal microclimate seem to be influenced by the moisture sorption and desorption characteristics of the materials used in the interior of the footwear.

The respondents in this pilot study were always dressed in the same wardrobe; the models of socks on the feet changed, depending on the rib constructions. Three different respondents answered individually during the interview according to the international standard ISO10551 2019. Each of the respondents, during a test of subjective perception in laboratory conditions, wore one model of socks (a total of 3 models) and answered the questions 3 times (after a certain time spent in the air conditioning chamber). Detention in the climate chamber lasted a total of 110 min with acclimatisation. Results are recorded throughout the entire testing process.

The questions, before the air conditioning chamber, were: how was the previous night, how was the sleep, what was the last meal and the way to the institution where the measurement is performed, as well as the general feeling before the examination in the air conditioning chamber. During their stay in the

climate chamber, the respondents were interviewed 3 times at certain intervals. Answers were given to questions about the subjective assessment of the thermal comfort of the feet in socks and shoes. The questions were about the feeling of heat, thermal comfort, desired thermal state, acceptability of the current thermal conditions, assessment of one's personal thermal tolerance of the environment and the degree of skin moisture.

For example, on the question "Feeling heat" in the feet, the subjective ratings were as follows:

- At the beginning of the research (after 28 min): for sock models R31 and R71, the answer is "Neutral" (in two respondents) and "A little warm" (in one respondent), while for the sock model marked R22, the answer is "Neutral" (for all respondents).
- In the middle of the research (after 48 min): for all models of socks, the answer is "Neutral" (for all respondents).
- At the end of the research (after 108 min): for the R31 sock model, the answer is "A little warm" (in two respondents) and "Warm" (in one respondent), while for the R71 and R22 sock models, the answer is "Warm" (for all respondents).

Or:

Answers to the question, "How moist is your skin?" on the foot:

- At the beginning of the research (after 28 min): for all models of socks, the answer is "Slightly moist" (the part under the foot and above the toes), by all respondents.
- In the middle of the research (after 48 min): for the sock model R31, the answer is "Dry" (the part under the foot and above the toes), for all respondents, for the sock model R71 and R22, the answer is "Slightly moist" (the part under the foot and above the toes) in two subjects, while the answer is "Dry" (the part under the foot and above the toes) in one subject.
- At the end of the research (after 108 min): for all models of socks, the answer is "Slightly moist" (the part under the foot and above the toes), by all respondents.

CONCLUSIONS

According to the results of testing the parameters that define comfort when wearing socks, obtained based on dynamic experiments, under simulated climatic conditions, the following conclusions can be drawn:

- Regardless of the knitting structures of the socks, the temperature of the skin of both feet in the socks is always the highest during walking ("walking I and II") and the lowest during the "resting" phase, i.e., at rest between two phases of walking.
- The lowest value of foot skin temperature in socks and shoes, during the entire experiment, was determined with socks in R71 and R31 constructions, while the highest temperature was registered with socks in R22 construction.
- The tested sock models are not completely suitable in terms of thermal comfort during the stay in the air

- conditioning chamber during the “walking II” phase. Socks in the R71 construction are closer to the comfort zone than socks in other rib constructions.
- According to the results for foot skin moisture, there is a partially impaired physiological comfort when walking in socks, especially in the last phase of the experiment, “walking II”. The best product in this sense was the R22 rib knitted socks.
 - The microclimate temperature when wearing socks with basic bamboo yarn in R22 construction is slightly higher (on average 0.5–1 °C) in the whole range compared to the microclimate temperature of socks with other rib constructions.
 - Socks in R22 construction, which have the highest thickness and lowest porosity in a relaxed state (at rest), are also better conductors of heat when walking in shoes. At the same time, socks in R32 and R71 constructions, which have the highest porosity, permeability of water vapor and air in a state of rest, show the property of lower heat conductivity in dynamic conditions (movement).
 - In general, the combination of man-made and synthetic fibres in socks in the R22 construction, bamboo/polyamide composition, 77/22%, gives the best results for the comfort of the feet during walking in shoes, in specific conditions, 20 °C and 50% relative humidity.
 - The objective measurement results in this pilot study, the subjective perception and prediction of the thermophysiological comfort of the test subjects in laboratory conditions, wearing the made sock models is also significant.
- Considering the obtained results of the research on the influence of the construction of socks on the thermal-physiological comfort during practical use, the performed research represents a contribution in the area of comfort and convenience when walking.

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