THE INFLUENCE OF THE RAW MATERIAL COMPOSITION OF MEN'S SOCKS ON THERMO-PHYSIOLOGICAL COMFORT UNDER DYNAMIC CONDITIONS

Predrag Tasić[1*], Dušan Trajković[2], Jelka Geršak[3], Svetomir Golubović[4]

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[1]"Vunil" d.o.o., Leskovac, Serbia
[2]University of Niš, Faculty of Technology, Leskovac, Serbia
[3]University of Maribor, Faculty of Mechanical Engineering, Research and Innovation Centre for Design and Clothing Science, Maribor, Slovenia
[4]Academy of Vocational Studies Southern Serbia, Department of Technological Art Studies, Leskovac, Serbia

The influence of environmental conditions on the thermo-physiological comfort of men's socks was investigated using an objective assessment of comfort under dynamic conditions. Men's socks made in a 3:1 rib construction from three types of basic yarns (77%) were used: bamboo, cotton, and a cotton/polyester blend. The remaining composition of the socks is identical: filament polyamide yarn (22%) and wrapped rubber thread (1%) for the welt. The influence of climate factors artificially created in the climate chamber was analyzed by measuring three physiological parameters: skin temperature, relative humidity of the skin, and microclimate in the space between the sock and the shoe on both feet. The research results show that the raw material composition of the base yarn used in the manufacture of men's socks has a significant impact on thermo-physiological comfort when wearing socks. Under artificially created conditions in the climate chamber, an ambient temperature of 20 °C and relative humidity of 50% (autumn and spring conditions), socks with basic yarn made of a cotton/polyester blend are preferred, then with a base yarn made of cotton, and finally socks with a base yarn made of bamboo. The data from the study provide valuable information for the clothing industry in designing and defining the choice of base yarn to produce socks, depending on the conditions of use.

Keywords: thermal properties, physiological properties, comfort, MSR measuring instrument.

Introduction

The comfort of wearing socks is one of the key factors when choosing clothes and a decisive factor in assessing quality. The importance of the comfort factor when wearing socks can be represented by the heat exchange between the body and its environment. Modern demands on the comfort of socks are far greater than in the past [1, 2].

Socks are one of the basic clothing items used in everyday life and are one of the most common products made by knitting. As an article of clothing for the feet, they serve to absorb and remove moisture and sweat, preventing a few consequences that can occur in a humid environment. Today's socks can adapt to the shape of the feet and legs and are thermo-physiologically comfortable and economically beneficial [3, 4].

The properties of fibers and yarns used in the production of socks affect the properties of the knitted fabrics, which directly affects air permeability, water vapor permeability, sweat removal from the feet, thermal resistance, thermal conductivity, and so on. The raw material composition of the yarn, density, thickness, volumetric mass and porosity of the knitted fabric are the main structural factors that determine the properties and comfort of socks [5, 6].

This paper presents research related to the thermo-physiological properties of socks made in the same stitch design, but from different raw material compositions under dynamic wearing conditions. In dynamic conditions, the exchange of heat and sweat and the microclimate provide information based on which it is possible to assume which type of raw material composition of socks is the most appropriate for wearing in the given climatic conditions.

Material and methods

Short men's socks are made of different types of yarn. Three types of yarn (100% bamboo yarn, 100% cotton yarn, and 60/40% cotton/polyester blend yarn) were used for the basic yarn, which is interlaced into each

*__Author address__: Predrag Tasić, Vunil" d.o.o., Viljema Pušmana 19, 16000 Leskovac, Srbija Leskovac, Serbia
E-mail: predrag.vunil@gmail.com
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row along the entire length of the socks and accounts for 77% ± 3% part in manufactured socks.

The socks are made in the same rib construction (the face of the sock is knitted on the lower cylinder and the back on the upper cylinder), with 3 loops on the face, and 1 loop on the back (R3:1). A double-cylinder hosiery machine of the company "Lonati Bravo 856", with a cylinder diameter of 95 mm (33/4 inches) and 168 needles, was used to make the socks, while for the closing of the toes of the socks a special sewing device - "Rosso 025 full tronic" was used.

Together with the basic yarn, a filament yarn of PA 6.6, a linear density of 4.4/13×2 tex with a percentage of 22% ± 3%, is knitted in all samples. At the beginning of the sock, the welt, all samples contain a third type of yarn, wrapped rubber yarn with a linear density of 100 tex, with a proportion of 1% ± 3%. Therefore, all types of sock samples have the same percentage of polyamide and rubber, they differ only in the type of fibers that make up the basic yarn of the same percentage composition.

Table 1 shows data on raw material composition and basic physical properties of sock yarn.

Table 1. The raw material composition of the tested sock and basic structural characteristics of the yarn used

Composition of the sock	Linear density, T_t (tex)	Breaking tenacity, σ_b (cN/tex)	Elongation at the break, ε_b (%)	Number of turns, T_m (m^{-1})
Bamboo	30.7	416.0	15.1	772Z
Polyamide	4.4×2	378.5	32.4	90S
Wrapped rubber wire	100	607.0	283.0	-
Cotton	30.1	435.0	4.8	746Z
Polyamide	4.4×2	378.5	32.4	90S
Wrapped rubber wire	100	607.0	283.0	-
Cotton/Polyester 60/40%	29.7	418.9	6.0	696Z
Polyamide	4.4×2	378.5	32.4	90S
Wrapped rubber wire	100	607.0	283.0	-

Research protocol

The study of the thermo-physiological properties of socks on wearing comfort was conducted under artificially generated climatic conditions in a climate chamber. A male subject, medically examined and always dressed in the same way and in the same wardrobe (undershirt, shorts, shirt, pants, jacket, socks, shoes) participated in the test.

The wear tests were performed in a computer-controlled climate chamber under the following ambient conditions: ambient temperature: T_a = 25 °C, constant relative humidity: *RH* = 50%, airflow velocity: v = 0.5 m/s.

The weight of the test person without clothes was measured, as well as the mass of all mentioned articles of clothing, before and after the test in the climate chamber. Special attention was paid to measuring the mass of socks in the same interlacement - rib construction 3:1, with different basic yarns in the raw composition of the socks: 100% bamboo, 100% cotton and 60/40 % cotton/polyester.

The effect of three types of socks with the same interlacement and different raw material composition on thermal-physiological comfort, when worn under dynamic conditions was investigated. Three physiological parameters monitored by sensors were analyzed: skin temperature, skin relative humidity and microclimate temperature (the space between the stocking on the foot and the shoe).

The examination of physiological parameters was carried out using a measuring device MSR 12 (MSR Electronics GmbH, Switzerland). The MSR 12 is a modular unit for measuring, displaying, and recording various physical measurement parameters, such as skin temperature and skin relative humidity (microclimatic humidity).

Skin temperatures during the defined exercise test were measured at three measurement points on each foot (measurement points T61, T62, T63; T68, T69, T161), and relative skin moisture was measured at two measurement points (measurement points RH1, RH2; RH4, RH5), as shown in Figure 1. In addition, the temperature of the microclimate was also measured, in the area between the sock and the shoe (sensor placed directly on the sock under the shoe; measurement points T67; T162) (Figure 1).

Sensors for measuring skin temperature operate on the principle of resistance change. Sensors for measuring the relative humidity of the skin are capacitive sensors with a measuring range from 0% to 100%.

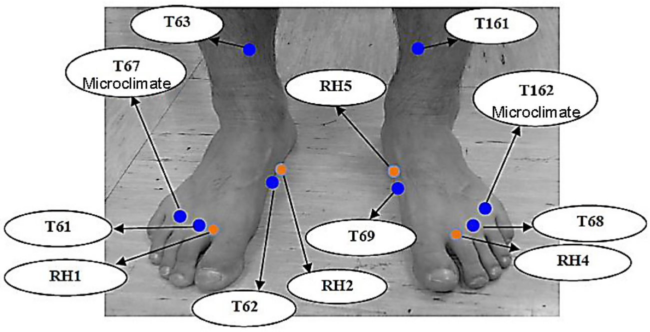

Figure 1. Positions of foot sensors for temperature and relative humidity

The test subject in each test performed the same physical activities in the following order:

- 30 minutes: acclimatization to the testing conditions;
- 30 minutes: load I (walking speed of 2.5 km/h on a flat surface in the direction of the wind);
- 20 minutes: rest, without movement;
- 30 minutes: load II (walking speed of 3.5 km/h on a flat surface in the direction of the wind).

Walking was carried out on a treadmill workstation Jaeger LE 200 (h/p/cosmos sports & medical GmHh, Germany), which was installed in the climate chamber.

Results and discussion

Given that all types of socks are composed of the same percentage of polyamide and rubber thread, these yarns in the composition of the socks were not taken as relevant in the discussion of the results. Also, an identical percentage of participation in the composition of socks and very similar results for other properties of basic yarns, according to Table 1, determined the discussion and presentation of results that primarily refer to the influence of the type of basic yarn on the thermo-physiological properties of socks during use.

The results of foot skin temperature when wearing socks are shown in Figures 2-4. In each graph in these Figures, there are 6 mathematical dependencies (curved lines) from 6 sensors that measure the temperature change on the skin of both feet over time.

According to the dependence curves with the graphs of these Figures, the test subject has the lowest temperature of the skin of the feet during the entire experiment when he wears socks in a rib construction 3:1 with a cotton base yarn, while the highest temperature is registered with socks in the same interlacement, made of bamboo and then with cotton/polyester mixed socks.

All the dependence curves in the graphs of Figures 2-4 have a similar flow, up to 2000 s, they show a constant increase in temperature, followed by a drop until 3000 s, and then a continuous increase in temperature begins again until the end of the test. This is especially pronounced in socks made of bamboo and a mixture of fibers, and somewhat weaker in cotton socks.

Also, certain regularities are noticeable in the dependence curves on the graphs 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 with the temperatures of sensors T63 (above the ankle of the right foot) and T161 (above the ankle of the left foot).

For sensors T63 and T161, for cotton fiber socks, the dependence curves run almost parallel to the x-axis, with slight, rhythmic variations over time when tested in a climate chamber. As expected, on the part of the leg directly above the ankle, which is covered by the sock, the skin temperature is lower than the measurements on the other parts of the foot, and here, there are no major variations over time. This relates to the fact that this part of the sensor is covered only by a sock but not by a shoe, so there is good ventilation and the influence of the movement of the surrounding air (0.5 m/s) is also important. Of course, the raw material composition of the socks has a decisive influence. With socks made of chemical fiber - bamboo and natural fiber - cotton, there is a difference, namely here the sensors on the right foot give a slightly higher temperature. For mixed fiber socks, the temperature curves for sensors T63 and T161 almost coincide.

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 (load II, 3.5 km/h) in the last 30 minutes of the test when the temperature curves have constant growth, peaking in the final seconds of testing. A slightly larger deviation in the comparison of the temperature curves from the graphs in Figures 2-4 was observed in the case of cotton socks and the case of sensors T68 and T63. Namely, the first sensor, placed on the upper part of the left foot, next to the toes, has a lower temperature by 1 to 1.5 °C than socks made of bamboo or a mixture of fibers, while the second sensor, placed above the ankle of the right foot, shows a temperature jump in the part between 2100 to 3100 s (load I, walking at a speed of 2.5 km/h) which was not observed in bamboo or mixed fiber socks. This is related to the properties of cotton, polyester and bamboo fibers, but also the way the test person walks with the left and right foot on the treadmill, the tightness of the shoelaces and the physical condition of the left and right feet.

For bamboo socks, it is shown that the skin temperature values are mostly above 33 °C after 3000 s (three sensors) and 3700 s (one sensor) of the experiment which exceeds the limit of the comfort zone (average skin temperature from 31.4 °C to 33 °C). For cotton socks (after 3400 s, three sensors) and mixed fibers, the situation is similar (after 3200 s, 1 sensor, after 3400 s, 1 sensor, and after 4000 s, 2 sensors) but generally with slightly lower maximum temperature values in that range.

In general, considering the results for the temperature of the skin of the feet, the tested sock models are not suitable in terms of clothing comfort under the mentioned climatic conditions during the stay in the climate chamber and faster walking in the second part of the test (load II). In this context, from the aspect of comfort and convenience while walking in shoes, socks made of a mixture of cotton and polyester proved to be a slightly better product.

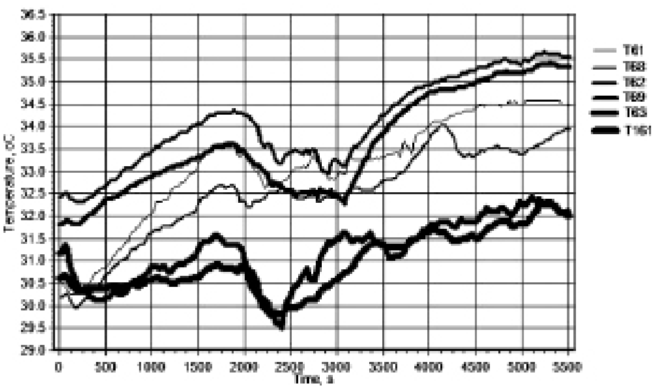

Figure 2. Foot skin temperature when wearing bamboo socks during testing under dynamic conditions

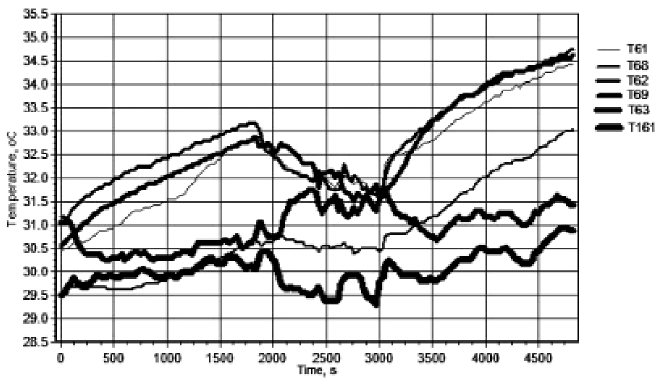

Figure 3. Foot skin temperature when wearing cotton socks during testing under dynamic conditions

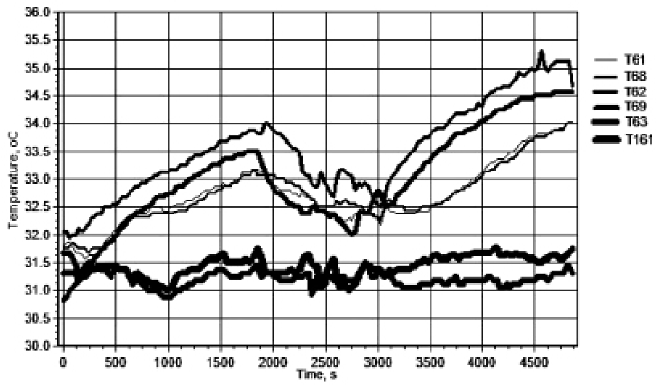

Figure 4. Foot skin temperature when wearing cotton-polyester mixed socks during testing under dynamic conditions

Socks are expected to release moisture quickly and dry quickly. Depending on the type of fiber, the liquid will be retained in the interstices of the fibers or absorbed by the fibers. Unlike synthetic fibers (polyester), natural or artificial chemical fibers (cotton, bamboo) are hydrophilic and absorb liquid. These fibers in conditions of high humidity can change the shape and structure of the yarn and affect the behavior of liquids, i.e. the movement or retention of liquids in the material [7, 8].

The results of testing the relative humidity of the skin of the feet when wearing the analyzed socks are shown in graphs in Figures 5-7. Skin moisture was measured using 4 sensors, 2 on both feet with the following markings: RH1 (front part of the right foot next to the toes), RH2 (arch of the right foot), RH4 (front part of the left foot next to the toes) and RH5 (arch of the left foot).

The dependence curves, which determine the change in the relative humidity of the skin over time in dynamic conditions, have a different course from the beginning to the end of the test, during all 5500 s. In the case of bamboo socks, the RH5 sensor is not installed for technical reasons, so there are no recorded humidity measurements for the arch of the left foot.

The appearance of the curves for measuring the skin humidity of all models of socks differ, as expected, very similar curves for all humidity sensors have feet with socks made of cotton and cotton/polyester blends. Greater swelling of bamboo fibers contributes to the retention of liquid in the fiber because the flow of liquid slows down, or even the capillaries may close. This is one of the reasons for the generally higher amount of relative moisture on the skin of the feet in bamboo socks. With cotton or mixed fiber socks, the appearance of the dependence curves is different, here the changes are more intense, especially in the part between 2000 and 3000 s, where there is a strong drop in the humidity curve, much more pronounced than with bamboo socks. Also, in the case of socks made of cotton or a mixture of fibers, Fig. 5 and 7, humidity sensors RH1 and RH5 have a very similar flow of curves, and sensors RH2 and RH4 also behave similarly, throughout the entire measurement range.

If you compare the appearance of the dependence curves on the graphs for temperature and humidity, you notice a coincidence, i.e. with most sensors, where the temperature is the highest, the humidity is the highest, and vice versa, where the temperature is the lowest, the humidity is the lowest.

Physiological comfort decreases if the value of average skin humidity is 30% or more. Furthermore, values of over 60-70% humidity (sweat coverage) mean that the skin is already very wet, so the feeling of comfort is unpleasant. Above this limit, the zone of intolerance begins with discomfort (which prevents quality physical activity) with disturbed temperature regulation as a result of overheating [6].

In the specific case, according to the results of the relative humidity of the skin on the foot, it is found that the comfort when walking in socks made of bamboo, cotton, or a mixture of fibers in the test chamber is partially impaired, especially in the last phase of the experiment, load II. The best product in this sense, in terms of physiological comfort, turned out to be a 60/40% cotton/polyester blend sock.

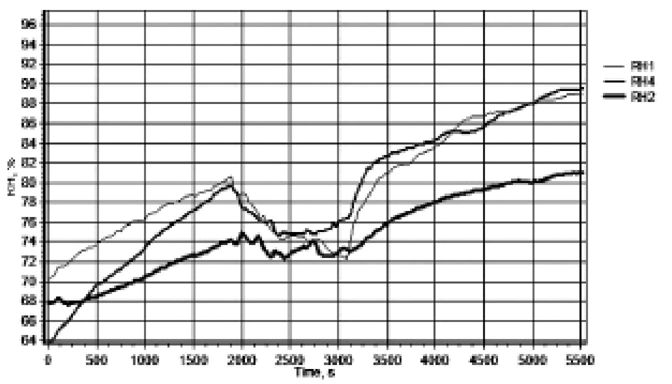

Figure 5. Foot skin relative humidity (RH) when wearing bamboo socks during testing under dynamic conditions

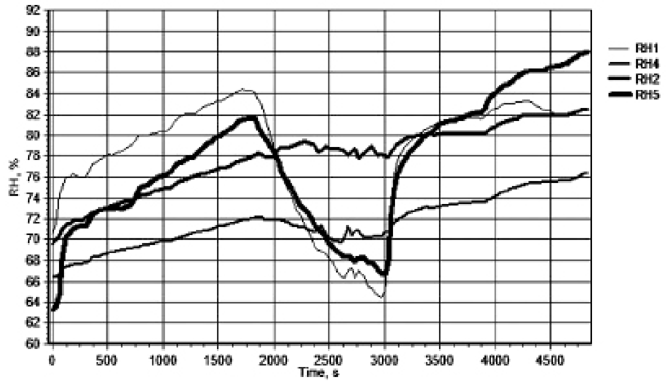

Figure 6. Foot skin relative humidity (RH) when wearing cotton socks during testing under dynamic conditions

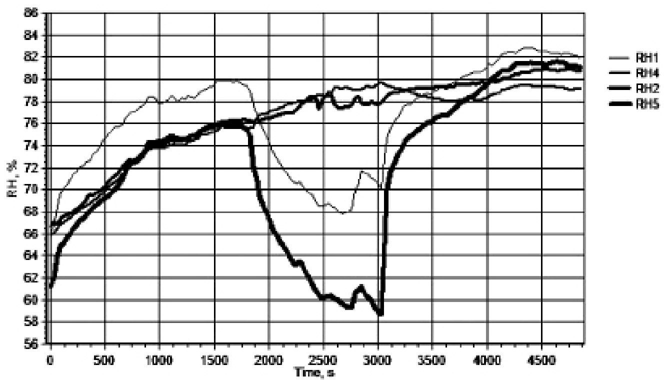

Figure 7. Foot skin relative humidity (RH) when wearing cotton-polyester mixed socks during testing under dynamic conditions

In Figures 8 - 10, the Temperature: Time graphs for the microclimate in the space between socks and shoes, tied shoes are given during the dynamic conditions performed in the climate chamber. These graphs have two dependence curves each, one curve refers to the left (sensor mark T162) and the other to the right (sensor mark T67) foot.

For bamboo socks, both dependence curves generally follow each other, after an initial rise to 1900 s (acclimatization and start of phase I load), the curve begins to decline with a single jump until 3100 s (rest after completion of phase I load), after which the curves continue to grow continuously until the end of the time spent in the climate chamber (phase load II). This jump after 2600 s was not registered by the microclimate sensor on the left foot. The microclimate of the mixed fiber sock has a very similar flow of temperature curves but with a narrower distribution of temperatures recorded throughout the experiment in the climate chamber.

In the case of cotton socks, the dependence curves for the left and right feet do not follow each other, i.e. the differences are more pronounced. These differences are associated with a subjective error on the left foot with a cotton sock, which occurred during the period of acclimatization and initial walking, probably due to the reflex movement of the toes, i.e. the front part of the foot (contraction-stretching), the weaker tightness of the laces on the shoe and air ventilation microclimate in the part between the sock and the shoe, which was reflected in the result. With a foot wearing a bamboo sock, the temperature is higher (about 1.5 °C) throughout the dynamic test range compared to the microclimate temperature of cotton or mixed fiber socks.

All these observations are related to the properties of the fibers from which the socks are made, primarily thermal conductivity and hygroscopicity of bamboo, cotton and polyester fibers. Bamboo absorbs more and faster than cotton fibers, which is usually considered an advantage of the material. In some cases, it can be a disadvantage. Namely, bamboo textile products are not the best option for permanent use in conditions of high humidity found in footwear, considering that the shoe partially retains and condenses the heat that evaporates from the feet while walking.

Given that the thermal conductivity of fibers similar to bamboo (about 0.230 W/(mK), cotton (0.464 W/(mK)) and polyester (0.141 W/(mK)) is higher than the value of the same parameter for air (0.026 W/(mK)) [9], it is obvious that the thermal conductivity of textiles will be higher with an increase in the proportion of fibers in the volume of the material or the use of fibers with higher thermal conductivity. As in this case, the thermal conductivity of cotton is almost twice or three times higher, it can be argued that the heat from the feet through socks and shoes will be conducted much faster with cotton products. Along with other parameters, the raw material composition has a greater influence on the thermal properties of socks during use.

The uneven surface of natural fibers (cotton) usually has an irregular arrangement of capillaries in the yarn, which affects the flow of liquid (sweat). Most man-made fibers (bamboo) as well as synthetic fibers (polyester) have a generally smooth surface with a generally round cross-section, which contributes to faster fluid flow [10]. Due to the constant compression of the shoe on the foot with the sock on, moisture is transferred from the skin to the knit and vice versa, or from the knit to the inside of the shoe, which leads to wetting of the feet, i.e. more moisture in the microclimate area. A significant share in this also has the so-called capillary wetting, which represents the spontaneous passage of liquid through a porous medium, fibers or bundles of fibers as well as the spaces between them.

Namely, micro-pores or micro-capillaries between the fibers in the yarn, and macro-pores or macro-capillaries between the yarns are responsible for capillary wetting [4, 11]. This wetting will be enhanced with bamboo or polyester blend socks, due to the regularity of the fiber form (smooth surface and round cross-section). Through dynamic movement and constant and regular rhythmic walking, pressure is exerted on the sock, which is sandwiched between the foot and the shoe, which results in the transfer of mass of moisture from the knitted fabric to the leather or shoe and vice versa.

A combination of fibers, natural and synthetic, e.g. for socks in the composition of cotton+polyester/polyamide/rubber, 77/22/1%, seems to give the best results for the comfort of the feet during walking in shoes, in the specific conditions of 20 °C and 50% relative humidity. Cotton/polyamide/rubber (77/22/1%) socks are very close.

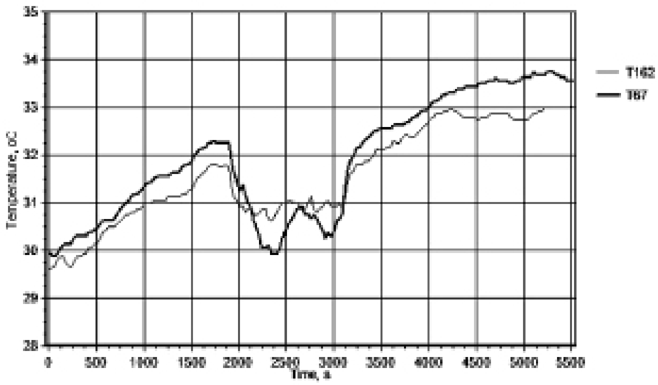

Figure 8. Microclimate temperature in the space between bamboo socks and shoes during testing under dynamic conditions.

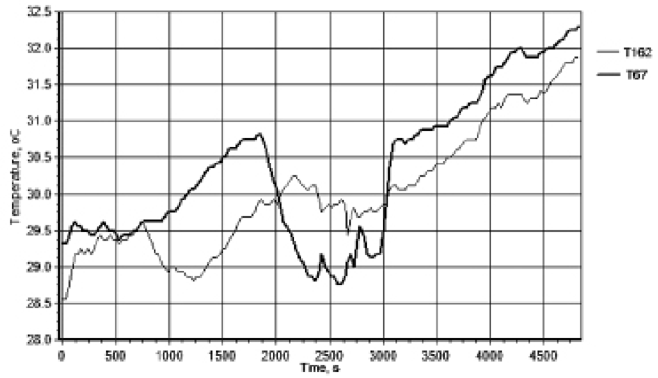

Figure 9. Microclimate temperatures in the space between cotton socks and shoes during testing under dynamic conditions.

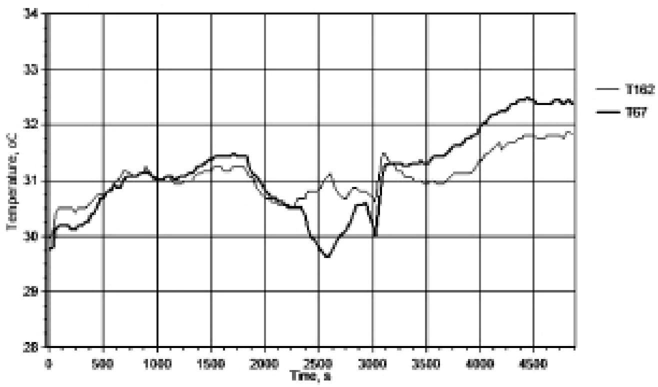

Figure 10. Microclimate temperatures in the space between cotton/polyester mixed socks and shoes during testing under dynamic conditions.

Conclusion

Based on the results of testing the thermo-physiological parameters of socks, obtained and based on dynamic experiments performed by one person, under simulated climatic conditions, the following conclusions can be drawn:

- Regardless of the raw material composition of the socks, the temperature on the surface of the skin of the feet is always the highest during walking (phases, load I and II) and the lowest during the resting phase, i.e. rest.
- The lowest value of foot skin temperature, during the entire experiment, was determined in socks with cotton base yarn, while the highest temperature was registered in bamboo socks.
- The tested sock models, according to the results for the temperature of the skin of the feet, are not suitable from the aspect of clothing comfort under the mentioned climatic conditions during the stay in the climate chamber during fast walking in the second part of the test. The socks, which are dominated by a mixture of 60% cotton and 40% polyester, are closer to the comfort zone than other products.
- Regardless of the phase of the experiments, wearing bamboo socks creates more moisture on the skin, which is associated with the properties of this fiber: greater swelling and greater retention of moisture in the knit structure.
- Regarding the moisture present on the skin of the feet, there is a partially impaired comfort when walking in all-fiber socks in the test chamber, especially in the last phase of the experiment, load II. The best product, in terms of physiological comfort, turned out to be a sock dominated by a 60/40% cotton/polyester mix.
- The microclimate temperature when wearing socks with bamboo base yarn is higher (about 1.5 °C) in the whole range compared to the microclimate temperature of socks with other fibers.
- Combination of fibers, natural and synthetic, e.g., for socks in the composition of cotton+polyester/polyamide/rubber, 77/22/1%, gives the best results for the comfort of the feet while walking in shoes, in specific environmental conditions of 20 °C and 50% relative humidity. Very close are the cotton/polyamide/rubber socks, 77/22/1%.

Considering the obtained research results and the determined influence of the raw material composition of socks on thermal-physiological comfort during practical use, it is concluded that the conducted research represents a contribution in the area of comfort and convenience when wearing socks and walking.

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Izvod

UTICAJ SIROVINSKOG SASTAVA MUŠKIH ČARAPA NA TERMOFIZIOLOŠKI KOMFOR U DINAMIČKIM USLOVIMA

Predrag Tasić[1], Dušan Trajković[2], Jelka Geršak[3], Svetomir Golubović[4]

(ORIGINALNI NAUČNI RAD)
UDK 687.254.8:677.017.8
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[1]"Vunil" d.o.o., Leskovac, Srbija
[2]Univerzitet u Nišu, Tehnološki fakultet, Leskovac, Srbija
[3]Univerzitet u Mariboru, Mašinski Fakultet, Centar za istraživanje i inovacije za dizajn i nauku o odeći, Maribor, Slovenija
[4]Akademija strukovnih studija južna Srbija, Odsek za tehnološko umetničke studije, Srbija

Uticaj uslova sredine na termofiziološku udobnost muških čarapa istražena je primenom objektivne ocene komfornosti u dinamičkim uslovima. Korišćene su muške čarape izrađene u prepletaju – rebrasti 3:1, od tri vrste osnovnih pređa (77%): bambus, pamuk i mešavina pamuk/poliestar. Ostatak sastava čarapa je identičan: filamentna poliamidna pređa (22%) i obmotana gumena nit (1%) za tzv. render čarape. Analiziran je uticaj klimatskih faktora koji su veštački stvoreni u klima komori merenjem tri fiziološka parametra: temperature kože, relativne vlažnosti kože i mikroklime u prostoru između čarape i cipele na oba stopala. Rezultati istraživanja pokazuju da sirovinski sastav osnovne pređe u izradi muških čarapa ima značajan uticaj na termofiziološku udobnost čarapa. Za veštački stvorene uslove u klima komori, za temperaturu okoline od 20 °C i relativnu vlažnost od 50% (jesenji i prolećni uslovi), prednost se daje čarapama sa osnovnom pređom od pamuka, zatim čarapama sa osnovnom pređom od mešavine pamuk/poliestar i na kraju čarapama sa osnovnom pređom od bambusa, za navedene uslove ispitivanja. Podaci iz istraživanja pružaju vredne informacije za industriju odeće u dizajniranju i definisanju izbora osnovne pređe za izradu čarapa, shodno uslovima upotrebe.

Ključne reči: toplotna svojstva, fiziološka svojstva, komfor, MSR merni instrument.