

THERMAL, PHYSIOLOGICAL, AND THERMOGRAPHIC ANALYSIS OF MEN'S BAMBOO SOCKS IN A RIGHT-LEFT KNIT STRUCTURE

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The study utilizes the results of thermal and physiological methods, as well as thermographic imaging, to obtain information about the condition of bamboo socks on the foot. Bamboo socks in a right-left knit (plain knit) exhibit satisfactory physical properties, including thickness, bulk density, and porosity. The hydrophilic properties of bamboo socks are highly pronounced, as these fibers strongly absorb moisture and also have good air permeability. Thermal properties, according to the Thermo Lab II and Thermal Manikin methods, reveal that bamboo socks leave a cool sensation on the skin and have lower thermal resistance but higher thermal conductivity, making them recommended for wear on warmer days. According to the results of infrared radiation measurements, i.e., by comparing the measured temperature values on different parts of the foot, it is concluded that bamboo socks are more suitable for wearing during higher temperatures in closed footwear.

Keywords: thermo-physiology, thermography, men's socks, bamboo fibers, plain knit fabrics.

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INTRODUCTION

When the human body is in motion, air movement occurs within the microclimate of the garment, both between layers of textile material and around the body. The volume of air spaces dynamically moves due to compression and decompression, caused by different body parts in relation to the clothing. When one part presses on the garment, the air spontaneously moves to another part of the microclimatic interspace, transferring heat via conduction from the body to the layers of clothing and exiting through an opening to the surrounding environment [1-3].

The foot, like the entire human body, is homeothermic, meaning it is capable of maintaining its internal temperature within certain physiological limits, regardless of the surrounding temperature. Foot thermoregulation is the process by which excess heat is lost, with thermoreceptors in the skin of the foot playing a vital role in these mechanisms. Several such mechanisms exist in the foot, such as blood flow, sweating, and metabolic heat production [4].

Internal body heat increases during physical activity, and as a result, the skin shows an increase in blood flow, sweating, and temperature, which are the main mechanisms for dissipating the heat produced. Since the feet remain covered by socks and shoes during physical activity, they are subjected to an increase in temperature. Different heat transfer mechanisms observed in the skin include conduction, convection, evaporation, and radiation. Socks can affect all of these mechanisms, especially if made from high-quality fibers, enabling better heat conduction from the feet to the socks, shoes, and surrounding environment through direct contact [5,6].

Bamboo socks are becoming an increasingly popular choice due to their exceptional characteristics and advantages compared to traditional cotton or synthetic socks. These socks are known for their hygroscopic properties, meaning their ability to absorb moisture efficiently. Bamboo fibers can absorb up to 60% more moisture than cotton, making these socks ideal for people with sweaty feet. Although they absorb moisture well, bamboo socks allow for quick evaporation of that moisture, keeping the feet dry and reducing the risk of unpleasant odors or infections. Thanks to the natural antimicrobial properties of bamboo, absorbed moisture does not promote bacterial growth, which further helps in reducing odors. Even after intense activities, the socks remain dry and comfortable to wear.

In the examination of thermal properties of clothing, infrared thermography can be used to determine heat losses from parts of the body to the surrounding environment. This technique has a very significant application in studying heat losses caused by vertical airflow through the microclimate between clothing and body parts, as well as in analyzing temperature changes on the textile surface when it comes into contact with the body part [7,8].

Thermography is a technique that uses a thermal camera to capture and analyze temperature differences on various surfaces that emit radiation. The camera detects the infrared radiation emitted by an object (body) and converts it into thermal images.

This research analyzes the results of thermal, physiological, and thermographic methods after testing bamboo socks, in order to obtain information about the thermophysiological state and comfort of wearing these socks.



MATERIALS AND METHODS

The study used short men's socks made from three yarns: bamboo (dominant yarn), PA 6.6 filament yarn, and rubber-wrapped yarn. The sock, made in size M, has a foot length of 28 cm, a sock leg length without the welt of 16 cm, and a welt width of 4 cm. These sock dimensions correspond to a shoe size of 42-43. The sock, made in size L, has a foot length of 29 cm, a sock leg length without the welt of 17 cm, and a welt width of 4 cm. These sock dimensions correspond to a shoe size of 43-44.

The examination of the sock characteristics was performed according to the appropriate standards and methods:

- Thickness, according to standard EN ISO 5084.
- Horizontal and vertical density, according to standard DIN 53883.
- Loop length, according to standard EN 14970.
- Surface mass, according to standard EN 12127.
- Total loop density is the product of the horizontal and vertical density of the knitted fabrics.
- Bulk density of the knitted fabric represents the ratio of the mass per unit area to the thickness of the knitted fabric [9].
- Porosity of the knitted fabric defined as the total amount of air in the knitted fabric (between and within the yarns) [9].
- Relative humidity, according to standard SRPS EN ISO 139:2007.
- Water retention capacity, according to standard DIN 53814:1974-10.
- Water vapor permeability, according to standard ASTM E-96/E96 M-16.
- Air Permeability, according to standard SRPS EN ISO 9237:2010.
- Warm/Cool sensation, the measuring instrument Thermo Lab KES-F7 was used.
- Thermal conductivity coefficient, the measuring instrument Thermo Lab KES-F7 was used.
- Coefficient of heat retention capacity, the measuring instrument Thermo Lab KES-F7 was used.
- Thermal Resistance, the measuring instrument Thermo lab KES-F7 was used.
- Thermal Resistance - Thermal Manikin, according to standard ISO 15831:2004.
- For thermographic measurements, the FLIR ThermoCAM™ P65 thermographic system was used. It is a mobile system that utilizes the long-wave infrared spectral range (LWIR), with wavelengths from 7.5 to 13 μm . The lenses project the object's image onto a microbolometer with resolutions of 640×480, 384×288, and 320×240 pixels. The electrical signal from the detector (microbolometer) is then processed in the camera system's internal electronics [10-12].

Table 1 provides data on the raw material composition and important parameters of the yarns from which the sock is made. According to the various values in this table, the dominant yarn is single-ply with a high twist number, and there is also a polyamide two-ply multifilament yarn, with a much lower twist number. The rubber thread is the coarsest



and present in the smallest amount in the sock composition, only 1%, and is used for making the sock at the beginning, the so-called welt of the sock. This rubber thread is flat and without twist. The linear density of yarns of the yarn with the appropriate degree of twist of the fibers around the yarn body affects the properties of the manufactured socks, such as: texture, wear, pilling, absorption properties, and others [13].

Table 1. Raw material composition and key properties of the yarn

Sock raw material composition (%)	Nominal linear density of yarns (tex)	Nominal yarn twist number (m ⁻¹)
Bamboo, 77%	31	772 Z
Polyamide, 22%	4.4/13×2	90 S
Rubber-wrapped yarn, 1%	100	-

RESULTS AND DISCUSSION

Table 2 presents the results of the most important physical properties of bamboo socks. There is no significant difference in parameters when it comes to sock sizes. Size M (42-43) socks have lower thickness and porosity, but higher surface mass and bulk density compared to size L. The thickness of the sock (0.918 mm and 0.925 mm) depends on the type of base yarn as well as the knit structure itself, and it affects permeability, comfort, deformability, etc. The surface mass of the sock (283 g/m² and 268.5 g/m²) is an important technological parameter and largely depends on its horizontal and vertical density. In addition, this parameter integrates all the important parameters of the knit structure and is an important economic factor because it significantly influences the cost [14].

The bulk density of the sock knitted fabric (0.308 g/cm³ and 0.290 g/cm³) best reflects and defines the structural parameters of the socks, as it represents the mass of the knitted fabric of a specific volume, which is directly related to the thickness, type of stitch, and surface mass of the knitted fabric.

Compactness - porosity of knitted fabrics represents the filling of the empty space between loops or the empty space within the loop itself. Good porosity is a consequence of the very structure of knitted products. During movement, i.e., wearing the sock, the interstices in the sock change their shape, leading to the displacement of air and accelerated air exchange, resulting in a pleasant sensation. The porosity of the knitted fabric (79.70 % and 80.9 %) indicates the volumetric proportion of voids in the knitted fabrics.

Table 2. Significant parameters of bamboo socks size

Sock size	Thickness, (mm)	Surface mass (g/m ²)	Bulk density, (g/cm ³)	Porosity, (%)
42-43	0.918	283	0.308	79.7
43-44	0.925	268.5	0.290	80.9



Table 3 presents the results of key physiological parameters for bamboo socks in a plain jersey. The size L sock has slightly higher numerical values for these examined parameters compared to the size M sock.

The relative humidity of socks depends on the raw material composition, the type of stitch design, and other structural indicators. It is known that bamboo, as a chemical fiber, significantly absorbs and retains moisture (9.42% and 9.70%), followed by natural fibers, and finally synthetic fibers.

The water retention capacity is relatively high for bamboo socks (50.6% and 50.9%), which is due to a greater ability to absorb moisture, and it is also known that these fibers have a higher relative humidity than all other fibers.

Water vapor permeability, according to the results from Table 3 (3437 g/m²/24h and 3605 g/m²/24h), reveals that this sorption characteristic is pronounced in bamboo socks with a plain jersey. Considering that hydrophilic bamboo fibers, in addition to allowing vapor to pass through, also absorb water vapor, swelling occurs, which reduces the size of the air-filled spaces between the fibers, thereby slowing down the diffusion process. Water vapor permeability is a crucial property of knitted fabrics, especially for clothing worn in working conditions (sweating) or socks that are enclosed in footwear.

Air permeability and water vapor permeability are fundamental hygienic and thermal insulation properties of textile materials. Since knitted fabrics have a porous structure, they possess good hygienic and thermal insulation properties. According to the results in Table 3, air permeability (56.1 m³/m²/min. and 61.2 m³/m²/min.) is pronounced and correlated with water vapor permeability. Generally, a material with higher air permeability also has higher water vapor permeability.

Table 3. Physiological parameters of bamboo socks

Sock size	Relative Humidity (%)	Water Retention Capacity (%)	Water Vapor Permeability (g/m ² /24h)	Air Permeability (m ³ /m ² /min.)
42-43	9.42	50.6	3437	56.1
43-44	9.70	50.9	3605	61.2

Tables 4 and 5 contain the results of the thermal properties of bamboo socks according to the Thermo Lab method and the Thermal Manikin. The size M sock has a higher numerical value for the warm-cool sensation, the thermal conductivity coefficient is identical, while it has lower numerical values for the coefficient of heat retention capacity and thermal resistance compared to size L.

The first characteristic, the warm-cool sensation, indicates a cooler feeling with a higher numerical value and a warmer feeling with a lower value; in other words, a higher value signifies a textile with faster heat loss, creating a cooling effect. The value for the warm-cool sensation parameter is relatively higher (0.115 W/cm² and 0.111 W/cm²) and significantly depends on the raw material composition. Bamboo socks leave a cool sensation on the skin, making them recommended for use on warmer days, specifically in spring and summer. Additionally, the warm-cool sensation parameter is quite dependent on the moisture content in the fibers (especially important for bamboo fiber



yarn), where an increase in relative humidity also leads to an increase in the warm-cool sensation parameter.

Thermal conductivity is a crucial parameter for the insulation capability of a material, and the measurement is based on the transfer of heat from the warmer to the cooler area, following the principles of heat conduction. As the thermal conductivity coefficient increases (0.065 W/mK for both sock sizes), the thermal resistance of the socks decreases, while the ability for thermal conductivity increases. This parameter typically depends on the raw material composition of the socks and the stitch design. Therefore, socks with a plain jersey have lower thermal resistance and higher thermal conductivity, making them recommended for use on warmer days.

The thermal resistance parameter - Thermo Lab II of socks (0.0815 m²/KW and 0.0824 m²/KW) depends on the stitch design and the raw material composition. Practically, the sock allows a greater or lesser flow of heat into the environment, which is expressed by the thermal resistance constant. Essentially, thermal resistance represents the thermal insulation of the material and is highest in a state of rest because, in that case, the air beneath the sock also remains still [15].

Single-cylinder knitting (plain jersey) implies a structure that has a larger contact surface and a more uniform number of contact points compared to other knits (e.g., double-cylinder knitting). This ensures a greater contact area with the skin, thereby resulting in weaker heat dissipation.

Table 4 presents the results of the thermal resistance testing of bamboo fiber socks in a plain jersey (Thermal Manikin). A slightly lower thermal resistance (0.01796 m²/KW and 0.01806 m²/KW) was observed in this specific case for bamboo socks. This value refers to the thermal resistance of the socks on the Thermal Manikin when the socks are in a stretched, slightly extended state, similar to when they are being worn.

It should be noted that surface and volumetric mass are inversely proportional, while porosity is directly proportional to the thermal resistance of socks in a tense state. Additionally, a higher number of binding points per unit area of the socks, where the mutual contact of fibers in the yarn is intensified, accelerates heat conduction.

Table 4. Thermal properties of bamboo socks – Thermo Lab II

Sock size	Warm-Cool sensation (W/cm ²)	Thermal conductivity coefficient (W/mK)	Coefficient of heat retention capacity (%)	Thermal resistance (m ² /KW)
42-43	0.115	0.065	22.03	0.0815
43-44	0.111	0.065	22.88	0.0824



Table 5. Thermal properties of bamboo socks – Thermal Manikin

Sock size	The appearance of the sock stitch design	Appearance of the knitted socks	Thermal resistance (m ² /KW)
42-43			0.01796

To highlight the heat losses from a garment, thermography was utilized, allowing temperature comparisons over a large surface through a visible image. The result of the thermographic measurement is a thermogram that, using a specific color code, provides a visual representation of the temperature distribution across the surface. The temperature distribution indirectly provides information about the condition of the surface itself, but also reflects the internal state of the observed object.

In the thermographic images of the surface of men's socks (M size) on the feet, maximum and minimum temperature areas can be observed, as shown in Figs. 1 - 3.

In Figure 1, a thermogram of feet in socks before walking is presented (climate chamber, 60 minutes, 20 °C, relative air humidity 50%, air circulation 0.5 m/s). On the right side of the thermogram, a temperature scale is shown, ranging from 27 to 31 °C. The darkest blue color indicates a temperature of 27 °C, while the yellow-orange transitioning into red represents the highest temperature on this thermogram, 31 °C.

Before walking, the dorsal region of the foot in socks has the highest temperature (31 °C), the arch of the foot or plantar area is around 29 °C. The coolest part of the foot in socks is near the toes, with an average temperature of about 28 °C. Generally, the temperature of the right foot with a sock is slightly higher (by 1-2 °C) than that of the left foot before walking, which is associated with the physical condition of the feet (circulation status, etc.).

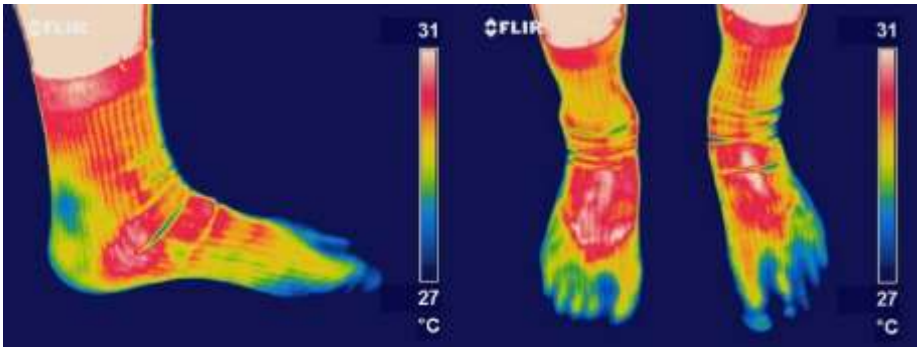


Figure 1. Thermograms of the lateral and dorsal (upper) surface of the feet in socks before walking



The purpose of thermography for shoes with feet and socks relates to footwear ergonomics, injury prevention, medical applications, sock selection, and more. In footwear ergonomics, analyzing heat distribution within the shoes is essential to determine comfort and design adequacy, as well as to assess ventilation and thermoregulation. Additionally, this technique allows for evaluating how different layers (socks, footwear, insoles) affect the thermal balance of the feet.

In Figure 2, a thermogram of shoes with feet and socks after walking is shown. As expected, the dorsal part of the foot inside the shoe is the warmest (around 29 °C), while the edges, i.e., the shoe area near the toes, are the coolest (around 24 °C). No significant differences were found between the temperatures of the left and right shoe.

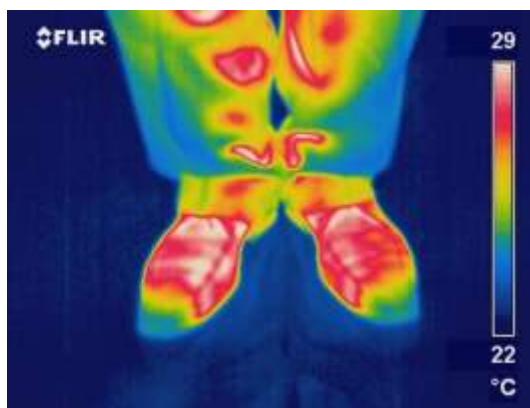


Figure 2. Thermogram of shoes with feet and socks after walking

Foot thermography with socks assesses how different types of socks affect heat distribution, thermoregulation, and overall foot health. It analyzes the socks' ability to maintain a uniform temperature across the foot or identify areas where heat accumulates or excessive cooling occurs. For instance, the analysis of socks used in extreme conditions (cold or hot environments) is particularly important, helping in the selection of socks that reduce the risk of overheating or sweating during intense activities.

The feet with socks, after walking, have a higher temperature than before walking, as expected. The dorsal part of both feet is the warmest, 31-32 °C, while the edges are somewhat cooler, 26-27 °C, as shown in Figure 3. There are no significant differences between the left and right feet in socks.

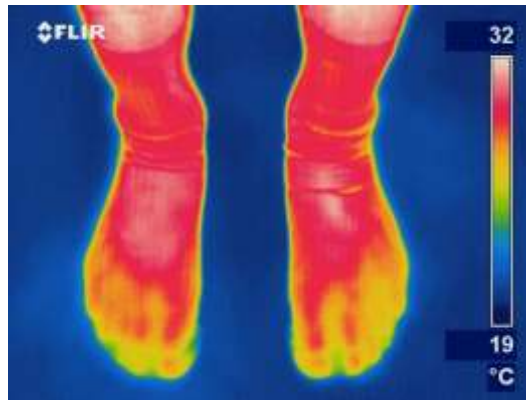


Figure 3. Thermogram of feet with socks after walking

The manufacturing and design of socks (with different knitting structures, thickness, and airspace ratio) should be organized in such a way that they reduce high plantar pressure in specific zones, which has a significant impact on controlling the temperature and humidity of the foot skin. This beneficial effect greatly improves metabolism and blood flow, and consequently, foot comfort. Additionally, when the raw material composition allows the sock to absorb heat from the feet, better thermoregulation is promoted, leading to improved physiological comfort [16,17].

It is evident that a bamboo sock cools the foot, providing a cooling effect, as part of the heat is absorbed by the bamboo fiber and transferred to the surrounding environment. According to the values from the thermo-physiological and thermographic measurements, feet in bamboo fiber socks fully meet the conditions for physiological comfort, as the skin temperature of the feet needed to prevent a feeling of cold is typically around 28–30 °C. Below these temperatures, the feet begin to cool down, and if the temperature drops below 25 °C, the risk of frostbite and other consequences, such as circulatory disorders and physiological discomfort, significantly increases.

CONCLUSIONS

The thermo-physiological comfort of socks during wear depends on numerous factors related to the structure of the yarn and the knitted fabric itself. Socks made from bamboo are particularly interesting because bamboo yarn provides lower porosity of the socks, lower bending stiffness, and allows for easy compression of the knitted loops, thereby reducing the thickness of the material.

Based on the results of these tests, insights are gained into thermal insulation, for example, how much the socks retain or lose heat, or whether the textile material provides sufficient breathability to dissipate excess heat, as well as to what extent the socks manage moisture, especially in the case of sweaty feet. Bamboo socks are more suitable for wear during higher temperatures or in summer when wearing closed footwear. The reason is the well-known cooling effect on the skin that bamboo fiber leaves, as well as its excellent moisture (sweat) absorption from the surface of the foot, which quickly evaporates due to the high ambient temperature.



Thermographic imaging of the feet with socks reveals how well the socks retain or lose heat, whether the textile material provides sufficient breathability to release excess heat, and to what extent the socks manage moisture, especially for sweaty feet. In the end, leather shoes combined with bamboo socks on the feet are physiologically comfortable, providing a natural combination of insulation, breathability, and durability under the specific conditions of this study.

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Izvod

TOPLOTNA, FIZIOLOŠKA I TERMOGRAFSKA ANALIZA MUŠKE ČARAPE OD BAMBUSA U DESNO-LEVOM PREPLETAJU

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Istraživanje koristi rezultate toplinskih i fizioloških metoda, kao i termtermografskih snimanja radi dobijanja informacija o stanju čarapa od bambusa na stopalu. Čarape od bambusa u desno-levom prepletaju imaju zadovoljavajuća fizička svojstva, debljinu, zapreminsku gustinu i poroznost. Hidrofilna svojstva čarapa od bambusa su jako



izražena, ova vlakna jako upijaju vlagu a imaju i dobra svojstva propustljivosti vazduha. Toplotna svojstva prema metodi Thermo Lab II i Thermal Manikin, otkrivaju da čarape od bambusa ostavljaju hladan osećaj na koži, kao i da imaju manju toplotnu otpornost a veću toplotnu provodljivost, pa se preporučuje za nošenje u toplijim danima. Prema rezultatima merenja infracrvenog zračenja, tj. upoređujući izmerene vrednosti temperature na različitim delovima stopala, zaključuje se da su čarape od bambusa pogodnije za nošenje tokom viših temperatura u zatvorenoj obući.

Ključne reči: termo-fiziologija, termografija, muška čarapa, bambus vlakna, desno-leva pletenina.

