IMPROVEMENT OF THERMOPHYSIOLOGICAL COMFORT OF ATHLETES BASED ON THERMOGRAPHIC EVALUATION OF SPORTSWEAR MATERIAL

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Thermography is a widely used method of measuring surface temperature and its distribution. It is based on the measurement of the radiation intensity in the infrared region of the electromagnetic spectrum. Infrared thermography is applicable in all spheres of human activity because it broadens the world's view and irreversibly changes the notion of space that surrounds us. One of the important issues in professional sports is maintaining the optimal level of comfort during intense sports activities. Therefore, this paper aims to investigate the possibilities of the application of thermography for testing the properties related to the comfort of athletes focusing on the transfer of liquid (sweat) through the materials intended for making sportswear. Moreover, the accent is given to the comparison of non-aged materials, and materials aged applying different protocols characteristic for football sportswear.

Keywords: Thermography, comfort, sport, material, sweat

Introduction

Infrared thermography (IRT) is a non-contact diagnostic method. This method measures the temperature and its distribution on the surface of the observed object, i.e. it is based on the measurement of the radiation intensity in the infrared range of the electromagnetic spectrum. The term "thermography" comes from the Greek words *therme*, meaning heat, and *grafein*, meaning to write [1]. This method can also be described as the process of observing some objects that emit infrared radiation. We can state that the role of the IR camera is to transfer the image from the invisible area to the visible image. In an IR device - a camera - an image, called a thermogram, of the observed object is electronically created in real-time, shifting part of the spectrum of electromagnetic waves invisible to the eye into the visible range [2, 3].

This method is now used in all areas of human life. Due to its characteristics, infrared thermography has proven to be an ideal method in areas where the temperature result or its distribution indicates a certain condition or unexpected changes within the building structure. The recording is done by thermographic cameras that record the emitted energy of the object's radiation to determine the object's surface temperature. The radiation passes through the optical system for deterioration and further falls on a sensor called a photodetector. Photodetectors convert the energy into signals.

The infrared camera screen displays thermograms that appear after the rising and falling edges of the signal are directed at the screen (Fig.1).

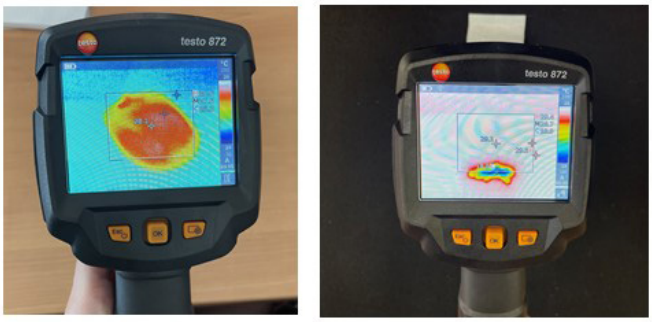

Figure 1. IR camera testing

A thermogram is a record of the distribution of infrared radiation coming from the surface of an observed object. Thermograms are recorded at time intervals and based on them, information about the properties of the material is obtained with the help of software. Thermograms can be displayed in shades of grey or in a colour code that gives a picture of the apparent temperature distribution on the surface of the observed object [4 - 6].

Infrared thermography is divided into two different groups. The first division is into passive and active thermography. Passive thermography is a method of thermographic analysis of objects that are in a stationary state

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for a long period and where a temperature difference of at least 10°C is required to generate a heat flux. Excitation in active thermography can be ultrasonic, electrical, thermal, and mechanical. The second division is qualitative and quantitative, where for qualitative measurements it is important that they are recorded and noted; whereas for qualitative, precision is important [7, 8]. Qualitative thermography provides only a framework of information about the observed object in terms of the distribution of its temperature. This confirms that it provides a limited amount of information in a very short period. Since it is easy to identify the areas with unusual temperatures on the thermogram, conclusions can be drawn about necessary interventions. The accuracy of the estimated data may be questionable if the characteristics of the observed surface are not known. Based on quantitative thermography, the exact temperature data are obtained, so it is necessary to calculate the data obtained on the thermogram. For this purpose, it is necessary to know the emission characteristics of the observed object, as well as the conditions of the atmosphere located between the object and the camera, and finally the state of the environment [9 - 11].

Infrared thermography is applicable in all spheres of human activity because it represents and broadens the view of the world and irreversibly changes the notion of space that surrounds us [7]. The maintenance and supervision of the machinery and the apparatus is the most popular area in which thermography is applied. This is its original commercial purpose. A typical example of the application of IRT is in the field of building construction. However, it is worth mentioning that thermography is used in many fields and professions, such as medicine and veterinary diagnostics, mechanical engineering, electrical engineering, research and development, etc. [12]. A very important application of IRT is also the textile industry, which we will discuss in more detail later in the text [4, 10, 13].

Infrared thermography in the textile application

Thermography is the most popular tool in the textile industry and in fashion technology to test the insulating properties of clothing. As an aid in the testing itself, a great deal of information is obtained about the distribution of temperature on the surface of the skin under different climatic conditions, as well as with different sets of clothing. The tests focus on clothing worn at extremely low or extremely high temperatures, i.e. protective clothing (in firefighting) and special clothing such as police and military uniforms. When measuring thermal comfort, the distribution of temperature on the skin plays a major role, as the skin is one of the most important indicators of thermal changes between the body and its environment [14 - 16].

Infrared thermography has gained popularity among researchers in various fields of scientific research or professional activities related to the textile industry. Much research has been done in the field of sports. The changes in skin temperature were observed before and after an active workout. The intensity of the training was changed to observe the temperature changes. Infrared thermography has also been used for the early detection of injuries to help coaches and athletes prevent muscle injuries and take care of athletes' health. When it comes to sportswear, this method is used to observe the amount of moisture, sweat, and human saliva on a textile fabric [17, 18].

Research done by Slavinec and his colleagues focused on the heat-conducting of the absorbent cloth for the increased relative amount of water in the cloth. The results show that the effective heat conduction of the cloth with low levels of dampness is proportionate to the relative amount of water that is absorbed by the textile. Further, they show that the increase of the relative amount of water in the material or cloth stabilizes the effective heat conduction around the value comparable to the heat conduction of water. Thermography is also valuable in observing the effect of flammability of certain groups of material cloths that are used as covers. Precisely, it is used in observing the cloth when the temperature exceeds 450 degrees Celsius. Results obtained for the cloths used as covers show a decreased capability toward inflammation with a considerable decrease in the temperature of the surface and the isothermal surface. On the other hand, the authors cite an absence of the decrease of the capability toward inflammation with decreased density and rinsing with ions of the alkaline metals of the simpler cotton cloths [19].

The work of Dema and colleagues represents a new method of measuring the horizontal capillarity and characteristics of drying cloth using thermal imaging with the help of machines. Paying attention to the damp area of the textile sample, five new characteristics are measured. These characterize the key periods of capillarity and the process of drying. Significant differences are shown in the experimental results in fabrics treated with products that enhance the capillary characteristics of the fabric. Furthermore, analysis shows that the possibility of repeating this method signifies advancement in present industrial standards [20].

Mijovic et al. chose as a goal of their study whether thermography can be used to determine the transfer of warmth and dampness inside clothing that is used by police officers in the field. With the help of an infrared system of recording, a sample of temperature is taken from the bodies of healthy, grown-up men who practice moderate physical activity, and in an environment with a controlled temperature. Their research shows that thermography is a valuable tool for determining the temperature of the skin, but also for the dissipation of sweat from the clothes. The collected data can be applied in designing new clothing styles providing a maximum cooling effect on the body through sweat evaporation [21].

Studies conducted by Čubrić et al. show a wide range of applications of infrared thermography in various aspects of human interaction. The paper researches the

comfort of wearing an item of clothing. Humidity, warmth, and overall comfort before and after moderate work were tested. The results obtained in three environmental conditions showed that with the increasing temperature there is a smaller feeling of comfort and an increase in the feeling of humidity and heat. An evident change in temperature was observed at the sites of sweating, which were examined with an infrared thermographic camera [14].

Material and methods

The experiment presented in this paper focuses on the use of thermography to evaluate the properties of non-aged and aged materials.

Material

For the experimental part of this paper, four representative single-jersey knitted fabrics are used. All materials are intended for football shirt making. The characteristics of the materials are shown in Table 1.

Table 1. Properties of materials

Sample ID	Material 1	Material 2	Material 3	Material 4
Composition	87% polyester 13% elastane	100 % polyester	100 % polyester	97% polyester 3% elastane
Mass, g/m^2	236.44	116.52	177.65	154.70
Thickness, mm	0.62	0.55	0.59	0.56

Material ageing

To investigate changes in the material's ability for sweat management due to the ageing of the material, for the samples shown in Table 1, three types of ageing are conducted:

I. Environmental & and use ageing

Materials were exposed to outdoor conditions during the cold season and the processes of material care (including machine washing and drying). The total duration of exposure to outdoor conditions was 12 hours (simulating 12 pieces of outdoor training) and the number of care cycles was 12 (one after each hour of outdoor exposure).

II. Environmental ageing only

Materials were exposed to outdoor conditions during the cold season, without the additional process of material care. The total duration of exposure to outdoor conditions was 12 hours in total.

III. Use ageing only

Materials were exposed to the processes of material care (12 in total), without exposure to outdoor conditions.

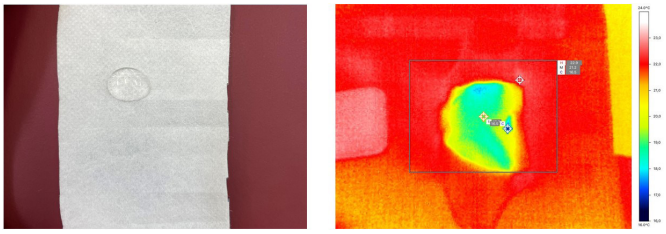
Thermographic measurement

After completed ageing, sweating was simulated on materials by applying an equal amount of liquid sweat (1 ml) to the material and measuring the behaviour of the liquid on the material itself (Fig. 2a). Upon application of liquid on selected materials, thermographic camera FLIS E6 and corresponding software for image analysis (Fig. 2b) are used for detection of breakpoints that mark the start and finish of three important phases, i.e.:

1. Wetting phase – starts with the application of liquid on the surface of the material and ends at the moment when the liquid is completely spread along the surface,
2. Static phase – starts after the wetting phase is completed and lasts until the moment when the drying phase starts (this breakpoint is determined using a thermal camera, the trigger is the moment when the wetted area starts to shrink),
3. Drying phase - this feature indicates the time required for a certain amount of water to evaporate from the material surfaces. It starts at the moment when the static phase is completed and lasts until the moment when the material is completely dry (i.e. until there is no difference in temperatures of the wetted and non-wetted area of material).

Additionally, during the process of measurement were also measured the following properties:

1. Wetting speed – this characteristic separates itself as a steep slope of the linear section of wetting. It represents the speed of liquid through the material. The wetting speed was calculated using the wetting diameter and measuring the time needed for the applied liquid to spread to the maximum diameter.
2. Wetting surface - the largest surface of the wetted area. It is determined by the multiplication of the largest wetting diameters in the directions of the x-axis and y-axis.



a. b

Figure 2. Measurement with the thermal camera: a) application of liquid on the surface of the material, b) example of a thermogram

During the measurements, the thermal camera was kept fixed at a distance of 200 mm from the surface of the material. For each specimen, five measurements were conducted. The statistical analysis of obtained data is conducted using the TIBCO Statistica™ 14.0.0. software.

Results and discussion

The results of the investigation are shown in the following tables and graphs.

Table 2 shows the diameter of wetting in the x-axis and y-axis directions. Multiplying these two values gives a wetting surface. It shows the values of the wetting speed in the direction of the x-axis and y-axis. The results obtained show that the largest wetting diameter is found in material 4, after performing environmental and

use ageing. The same material, the non-aged sample, shows the lowest values of wetting speed among all materials. Material 2, made of 100% polyester, shows the smallest wetting surface on the sample exposed only to environmental ageing, but on the other hand, it can be observed that the same material shows the longest wetting speed. The wetting speed in the x-axis direction for a sample exposed only to use ageing is 37.54 seconds, and in the y-axis direction for a sample exposed to both environmental and use ageing is 48.77 seconds. Interestingly, the materials with the largest wetting surface area also have the highest liquid wetting speed. Conversely, the materials with the smallest wetting surface area also have the lowest wetting speed.

Table 2. Wetting diameter and wetting speed

Sample ID	Type of ageing	Wetting diameter, mm x-axis	Wetting diameter, mm y-axis	Wetting surface, mm²	Wetting speed, mm/s x-axis	Wetting speed, mm/s y-axis
Material 1	Non-aged	39.5	32.5	1283.75	38.5	7.05
	Environmental & use ageing	45	44	1980	26.01	25.45
	Use ageing	40.5	44.5	1802.25	33.74	37.67
	Environmental ageing	42	38.5	1617	18.54	16.99
Material 2	Non-aged	39.5	33.5	1323.25	17.29	14.73
	Environmental & use ageing	38	42.5	1615	33.98	48.57
	Use ageing	41.5	43.5	1805.25	37.54	39.42
	Environmental ageing	33	37.5	1237.5	10.90	12.37
Material 3	Non-aged	40	37.5	1500	14.50	13.63
	Environmental & use ageing	37.5	47.5	1781.25	17.80	23.01
	Use ageing	42.5	52.5	2231.25	14.02	17.85
	Environmental ageing	35	40	1400	14.97	17.02
Material 4	Non-aged	38.5	42	1617	6.12	6.65
	Environmental & use ageing	52.5	52	2730	9.02	9.00
	Use ageing	40	44	1760	9.41	11.36
	Environmental ageing	46.5	50	2325	7.61	8.20

To investigate the strength of the relationship between the material main properties (mass and thickness) and measured properties related to sweat management (i.e. the wetting diameter, wetting surface and wetting speed), correlation coefficients are given in Table 3. As can be seen from the results presented, material thickness has a higher influence on the observed properties of material than the material mass. The relationship between the material thickness and wetting speed is moderate, with coefficients of 0.5093 and 0.6313. The analysis revealed the fact that material structure has a higher influence on wetting properties than material mass and thickness. This outcome widens the knowledge related to the design of materials for the improved performance of athletes.

Table 3. The correlation coefficient between observed variables

Variable	Mass	Thickness	Wetting diameter x-axis	Wetting diameter y-axis	Wetting surface	Wetting speed x-axis	Wetting speed y-axis
Mass	1,0000						
Thickness	0,4074	1,0000					
Wetting diameter, x-axis	0,1522	0,1129	1,0000				
Wetting diameter, y-axis	0,0126	-0,2359	**0,5809**	1,0000			
Wetting surface	0,0613	-0,1151	**0,8707**	**0,9032**	1,0000		
Wetting speed, x-axis	0,3724	**0,6313**	-0,1130	-0,2940	-0,2577	1,0000	
Wetting speed, y-axis	0,0717	**0,5093**	-0,1386	0,1111	-0,0284	**0,6999**	1,0000

Marked correlations are significant at p < .0500

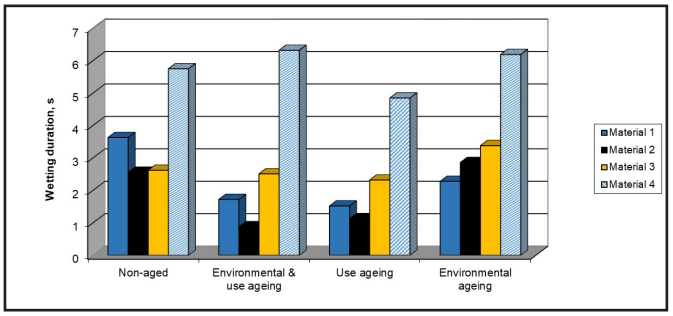


Figure 3. Graphic representation of the wetting duration of investigated materials

Figure 3 shows the wetting duration, i.e. the duration of the wetting phase, expressed in seconds for all the materials studied. As can be seen, the overall duration of wetting is in the range of 0.8 to 6.1 s. From the results obtained for material 4, it can be seen that the wetting time is the longest among the non-aged materials, i.e. it is 5.6 seconds. In comparison, the wetting duration for material 2 is twice as short, i.e. 2.2 seconds only. This leads to the conclusion that the sweat accumulated on the skin of an athlete due to intensive activity will remain non-absorbed longer if wearing the material 4, thus leading to the increased feeling of discomfort. The results revealed that the wetting duration, on average, decreases after the combined exposure of materials to the environmental & use ageing, as well as to the use only. The shortest wetting time among non-aged samples is measured for material 2. In general, by looking at all the samples tested, it can be concluded that material 4 has the highest values under all the conditions tested.

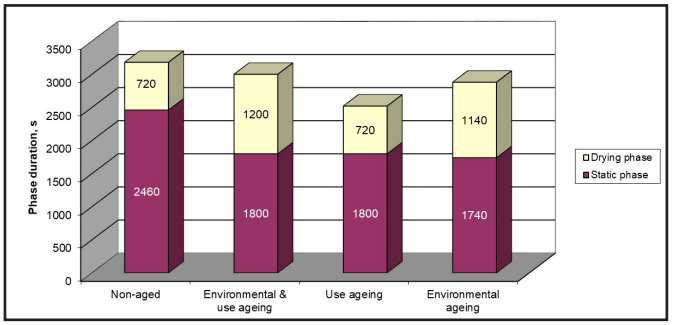


Figure 4. Identification of breakpoints that mark the duration of each phase for material 1

Figure 4 shows the duration of the static and drying phase of material 1 (from wet to dry). The results obtained show that the static phase is the longest for the sample that is non-aged (2460 s). It decreases for aged materials, but the influence of a certain type of ageing is insignificant. From the duration of the drying phase, it could be seen that the material exposed to the environmental and use ageing takes the longest period to dry completely (1200 s). If the total drying time is taken into account, it is found that the highest value is recorded for the non-aged sample and the lowest for the sample exposed only to use ageing.

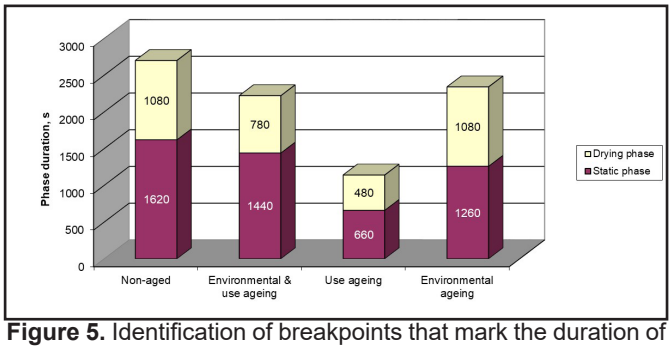


Figure 5. Identification of breakpoints that mark the duration of each phase for material 2

From the graph for material 2 (Fig. 5), it can be seen that the lowest total drying time, from the time the material is wetted to complete dryness, is for the material exposed to use ageing only. In addition, the non-aged sample and the sample exposed to environmental ageing have the same values for the longest drying time, which is 1080 seconds.

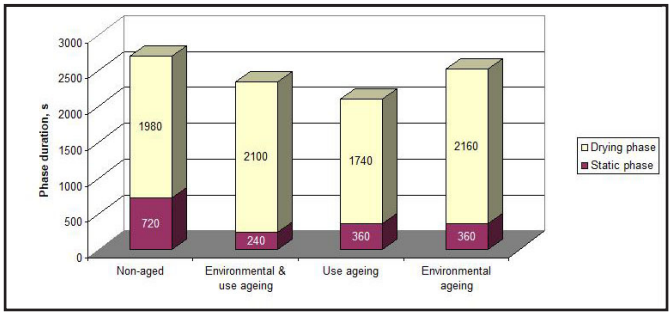


Figure 6. Identification of breakpoints that mark the duration of each phase for material 3

The graphical representation of material 3 (Fig. 6) shows an extremely long drying time followed by a very short duration of the static phase. For each sample (under all conditions observed), it can be seen that the duration of the static phase is significantly shorter than the drying of the material itself. The longest total drying time is exhibited by a sample that is not exposed to ageing, and the shortest time is exhibited by a sample that is only use-ageing.

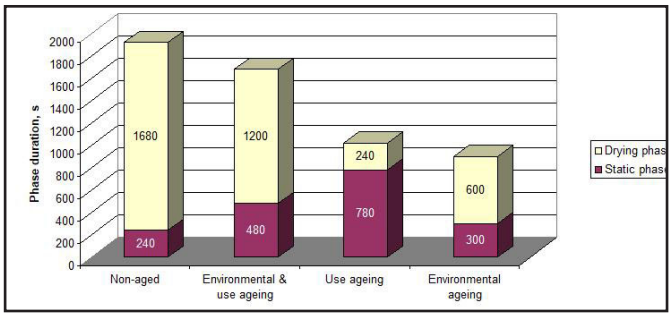


Figure 7. Identification of breakpoints that mark the duration of each phase for material 4

The results obtained for material 4 (Fig. 7) show that the non-aged sample has the longest drying time of the material and the shortest duration of the static phase, while the sample exposed only to use ageing shows the opposite values. The static phase is 780 seconds, while the drying time of the material is 240 seconds.

A summary of the duration of all observed phases can be found in Table 4. The results indicate that material 1, which has not been aged, takes the longest time (3183.63 s) to dry from the moment of liquid application (i.e. the start of sweating). The reason for such behaviour should be explained by the material basic characteristics given in Table 1, i.e. the highest mass and thickness among the investigated materials and the fact that the material is plated with additional yarn (i.e. 13% of the elastane yarns). The addition of elastane yarn into the structure of the material increases the material contraction and touch properties, but as seen from the experiment presented, also increases the duration of drying which has a negative impact on the perception of thermophysiological comfort of an athlete. Among the materials in the investigated set, the shortest total drying time, from wet to dry material, was determined for material 4. This makes material 4 most desirable for use from the aspect of wetting. Despite the addition of elastane in the structure of material 4, the main reason for such an outcome is to be explained by the specifics of the structure, i.e. increased porosity due to the holes in the structure. The duration of phases decreases due to all types of ageing except for material 3. Surprisingly, there is no unambiguous effect of a particular type of ageing on the change in phase duration for all observed samples. This is to be associated with a specific structure of knitted materials, so future work should be focused on a wider set of materials.

Table 4. The total duration of phases

	The total duration of phases, s			
Type of ageing	**Non-aged**	**Environmental & use ageing**	**Use ageing**	**Environmental ageing**
Material 1	3183.63	3001.72	2521.52	2882.28
Material 2	2705.56	2220.88	1141.13	2342.86
Material 3	2072.62	2342.51	2102.32	2523.38
Material 4	1925.75	1686.23	1024.85	906.19

Conclusion

To sum up, the investigation presented in this paper confirmed the high potential of the use of thermography for the precise identification of phases related to sweat management, which is an important step for the assurance of thermophysiological comfort. The evidence from this study implies that the relationship between the material thickness and wetting speed is moderate. It also reveals the fact that material structure has a higher influence on wetting properties than material mass and thickness. The results suggest that the wetting time is the longest for the non-aged materials and it decreases due to all types of ageing. Results also suggested that the duration of the static and drying phase significantly differ for different material structures. Furthermore, the duration of drying is to be associated with the material basic characteristics, i.e. the highest mass and thickness, as

well as the addition of elastane, which consequently has a negative impact on the perception of thermophysiological comfort of an athlete. Still, there is no unambiguous effect of a particular type of ageing on the change in phase duration for all observed samples, which should be further validated by a larger sample size.

Acknowledgement

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Izvod

POBOLJŠANJE TERMOFIZIOLOŠKOG KOMFORA SPORTISTA NA OSNOVU TERMOGRAFSKE PROCENE MATERIJALA SPORTSKE ODEĆE

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Termografija je široko korišćena metoda merenja površinske temperature i njene distribucije. Zasnovana je na merenju intenziteta zračenja u infracrvenom području elektromagnetnog spektra. Infracrvena termografija je primenljiva u svim sferama ljudske delatnosti jer proširuje pogled na svet i nepovratno menja predstavu o prostoru koji nas okružuje. Jedno od važnih pitanja u profesionalnom sportu je održavanje optimalnog nivoa udobnosti tokom intenzivnih sportskih aktivnosti. Stoga, ovaj rad ima za cilj da istraži mogućnosti primene termografije za ispitivanje svojstava koja se odnose na udobnost sportista sa fokusom na prenošenje tečnosti (znoja) kroz materijale namenjene za izradu sportske odeće. Takođe, akcenat je stavljen na poređenje neostarenih materijala i starih materijala primenom različitih protokola karakterističnih za sportsku odeću za fudbalere.

Ključne reči: Termografija, komfort, sport, materijali, znoj