Infrared thermography used for handball footwear heat detection during the training

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ABSTRACT – REZUMAT

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The purpose of this paper is to present an experimental thermal transfer analysis of sports footwear to identify the areas that ensure the best foot ventilation for comfort and performance in training sessions. The measurements were performed on seven athletes (subjects) during a handball training session, wearing the same footwear that the handballers typically use for indoor sports. The thermographic recordings were made during training at five different times: moment zero (before the start of training), moment one (2 minutes of training), moment two (5 minutes of training), moment three (15 minutes of training), and moment four (at the end of the handball training session). For the other three subjects, although they have different models of the same sports footwear, the analysis of the thermal distribution values shows that they are within the minimum and maximum limits of the four subjects analysed in the paper. Based on the thermographic values recorded, a mathematical model was determined using polynomial regression in Matlab to predict temperature values outside the range of the experimental data. In the present paper, research was carried out in order to identify the thermal transfer of indoor sports shoes used in handball training so as to detect the heat exchange between the foot and the outdoor environment. Thermography can be a valuable tool for manufacturers to evaluate the effectiveness of a shoe's insulation and ventilation systems. By using thermography, manufacturers can assess how well the footwear regulates temperature and moisture, which are crucial factors in maintaining comfort and performance for athletes, particularly in a high-intensity sport like handball.

Keywords: *thermal imaging, Flir ResearchIR Max, heat transfer, indoor sports*

Termografie în infraroșu utilizată pentru detectarea căldurii încălțămintei de handbal în timpul antrenamentului

Scopul acestei lucrări este de a prezenta o analiză experimentală a transferului termic al încălțămintei sportive pentru a identifica zonele care asigură cea mai bună ventilație a piciorului pentru confort și performanță în sesiunea de antrenament. Măsurătorile au fost efectuate pe șapte sportivi (subiecți) în cadrul unei sesiuni de antrenament de handbal, purtând aceeași încălțăminte de handbal utilizată pentru sporturile de sală. Înregistrările termografice au fost efectuate în timpul antrenamentului în cinci momente diferite: momentul zero (înainte de începerea antrenamentului), momentul unu (2 minute de antrenament), momentul doi (5 minute de antrenament), momentul trei (15 minute de antrenament) și momentul patru (la sfârșitul sesiunii de antrenament la handbal). Pentru ceilalți trei subiecți, deși au modele diferite ale aceleiași încălțăminte sport, analiza valorilor distribuției termice arată că acestea se încadrează în limitele minime și maxime ale celor patru subiecți analizați în lucrare. Pe baza valorilor de înregistrare termografică obținute, a fost determinat un model matematic folosind regresia polinomială în Matlab pentru a prezice valorile de temperatură din afara intervalului datelor experimentale. În lucrarea de față, cercetarea a fost efectuată cu scopul de a identifica transferul termic al pantofilor sport de interior utilizați în antrenamentele de handbal, astfel încât să se detecteze schimbul de căldură dintre picior și mediul exterior. Termografia poate fi un instrument valoros pentru producători, pentru a evalua eficiența sistemelor de izolare și de ventilație ale unui pantof. Prin utilizarea termografiei, producătorii pot evalua cât de bine reglează încălțămintea temperatura și umiditatea, care sunt factorii esențiali în menținerea confortului și performanței sportivilor, în special într-un sport de intensitate ridicată precum handbalul.

Cuvinte-cheie: *imagistică termică, Flir ResearchIR Max, transfer de căldură, sporturi de interior*

INTRODUCTION

Research on using infrared thermography for handball footwear heat detection during training is limited, but there are some studies that have explored the use of this technique in other sports and activities [1, 2]. Infrared thermography is a quick and easy technique to implement, requiring only a thermal imaging camera and a trained operator. By regularly monitoring the heat generated within handball footwear during training sessions, coaches and athletes can proactively address issues before they become more serious problems. One study published at an international level investigated the use of infrared thermography to monitor foot temperature changes in runners during a marathon. The researchers found that infrared thermography was a reliable and effective method for detecting variations in foot temperature, which could help identify potential injury risks and inform training strategies. Another work has focused on enhancing the thermal container and physiological comfort of athletes through thermographic evaluation of sportswear materials [3–6]. In the case of handball footwear, thermography can be used to analyse the heat distribution inside the shoe during physical activity.

Thermography can provide real-time data on temperature distribution inside the shoe, allowing manufacturers to identify any areas of potential heat build-up or poor ventilation. This information can help them make informed design decisions to optimise the shoe's performance and comfort. By using thermography in handball footwear, manufacturers can assess the effectiveness of the shoe's insulation and ventilation systems. This technology can help identify hot spots or areas of discomfort within the shoe, allowing for modifications to improve overall comfort and performance. This information can help designers create more efficient and comfortable footwear for handball players. Numerous studies have explored the intersection of sustainability and footwear, emphasising the importance of sustainability in the design, production, and end-of-life management of sports footwear. This research highlights the potential benefits of adopting sustainable materials, processes, and practices in handball footwear to minimise environmental impact and promote long-term sustainability within the sports industry [7–9]. As regards the material used in the assembly of the sports footwear presented in this work, this is a knitted textile material. The knitted textile material is made from a structure with retained links and loop deposition, made of a poly filament yarn, 100% PES, made on a 14''E fineness knitting machine. The knitted material has 12 links in the row direction (horizontal) and 12 rows in the string direction (vertical) /1 cm. Weight 0.651 g/1 cm^2. Characteristics include wear resistance, high elasticity. By integrating sustainable and technologically advanced materials in the design of handball footwear, it is possible to improve both performance and comfort while reducing the environmental footprint of sports equipment [10, 11].

MATERIALS AND METHODS

Experimental research on footwear temperature according to the journal format

While there is limited research specifically focused on infrared thermography in handball footwear, these studies suggest that infrared thermography can be a valuable tool for monitoring foot temperature changes during training sessions in various sports. Further research specifically focused on handball footwear and players could provide valuable insights into the potential benefits of using infrared thermography in this context. Thermography measurements were conducted at the University Sports Club in Oradea using the FLIR SC 640 thermal imaging camera, a portable thermographic scanning device with the most powerful IR detector available, a resolution of 640 × 480 pixels, and an exceptional thermal sensitivity of <0.04°C. The thermal imaging camera featured in figure 1 includes a laser pointer, a germanium lens, an SD card, a USB, and a video connector for enhanced functionality.

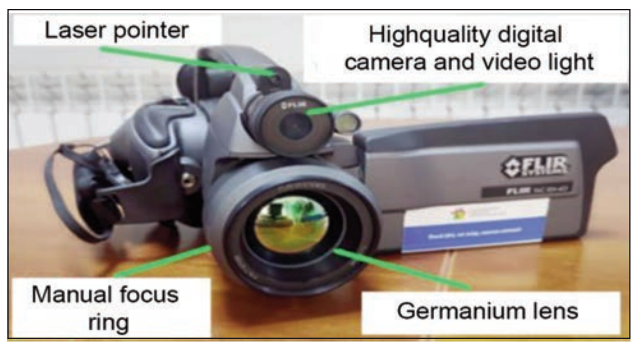

Fig. 1. Thermal imaging camera FLIR SC 640 components

Fig. 2. IR and real spectrum image of the seven subjects: *a* – infrared image; *b* – real image

Fig. 3. Footwear image for footwear type A used for indoor sports

The data presented in this study is significant as it showcases the minimum and maximum thermal distribution values of footwear type A for indoor sports, selected as the most representative for the seven subjects involved in handball training analysis. Analysis of the other 3 subjects, although having different models of the same sports footwear, shows that the thermal distribution values are within the minimum and maximum limits of the seven subjects analysed in the paper. In this research work, thermography measurements were performed as the most representative four athletes (subjects) were selected from the seven subjects analysed, as shown in figure 2, who have worn sports footwear type A shown in figure 3 (subjects 1, 2, 3 and 4) in a handball training session. Based on the temperature distribution value for handball footwear, we used the polyfit function in Matlab to predict temperature values outside the range based on the mathematical model determined from the experimental data using polynomial regression [12–14].

RESULTS AND DISCUSSION

Thermographic scans were conducted on athletic footwear at five distinct intervals: moment zero (before training commencement), moment one at 2 minutes into training, moment two at 5 minutes into training, moment three at 15 minutes into training, and moment four at the completion/end of handball training. The purpose of these scans was to pinpoint the regions that promote optimal foot ventilation to enhance comfort during physical activity. As shown in figure 4 of the left foot of subject 1 at time zero (before the start of handball training), the maximum temperature along the line Li1, positioned on the central part of the foot, is 27.1°C, and the minimum temperature is 24.2°C. The temperature variation along the Li1 line is 2.9°C, and the emissivity is 0.83, at time zero for subject 1. On the side along the Li2 line, the maximum temperature is 28.3°C, and the minimum temperature is 24.5°C, at time zero for subject 1. The temperature variation along the Li2 line is 3.8°C, and the emissivity is 0.83 at time zero for subject 1. As shown in figure 4 for the left foot of subject 1 at time one (before the start of handball training), the maximum temperature along the line Li3, positioned on the central part of the foot, is 27.4°C, and the minimum temperature is 25.6°C. The temperature variation along the Li3 line is 1.8°C, and the emissivity is 0.83, at time zero for subject 1. On the side along the Li4 line, the maximum temperature is 28.0°C, and the minimum temperature is 25.3°C, at time zero for subject 1. The temperature variation along the Li4 line is 2.7°C, and the emissivity is 0.83 at time zero for subject 1.

In figure 4, for the right foot of subject 2 at time zero (before the start of handball training), the maximum temperature along the line Li5, positioned on the central part of the leg, is 28.6°C, and the minimum temperature is 25.2°C. The temperature variation along the Li5 line is 3.4°C, and the emissivity is 0.83, at time zero for subject 2. On the side along the Li6 line, the maximum temperature is 28.5°C, and the minimum temperature is 25.0°C, at time zero for subject 2. The temperature variation along the line Li6 is 3.5°C, and the emissivity is 0.83, at time zero for subject 2.

For the left foot of subject 2 at time zero, the maximum temperature along the Li7 line positioned on the central side is 27.4°C, and the minimum temperature is 24.9°C. The temperature variation along the Li7 line is 2.5°C, and the emissivity is 0.83, at time zero for subject 2. On the side along the Li8 line, the maximum temperature is 28.8°C, and the minimum temperature is 25.9°C, at time zero for subject 2. The temperature variation along the line Li8 is 2.9°C, and the emissivity is 0.83, at time zero for subject 2. Thermography measurements for subject 3 for the left foot at time zero (before starting the handball training) show that the maximum temperature along the Li9 line, positioned at the centre of the foot, is 27.5°C, and the minimum temperature is 24.6°C. The temperature variation along the Li9 line is 2.9°C, and the emissivity is 0.95, at time zero for subject 3. On the side along the Li10 line, the maximum temperature is 28.7°C, and the minimum temperature is 25.2°C, at moment zero for subject 3. The temperature variation along the Li10 line is 3.5°C, and the emissivity is 0.83, at moment zero for subject 3. For the right foot of subject 3 at time zero, the maximum temperature along the Li11 line positioned on the central side is 28.3°C, and the minimum temperature

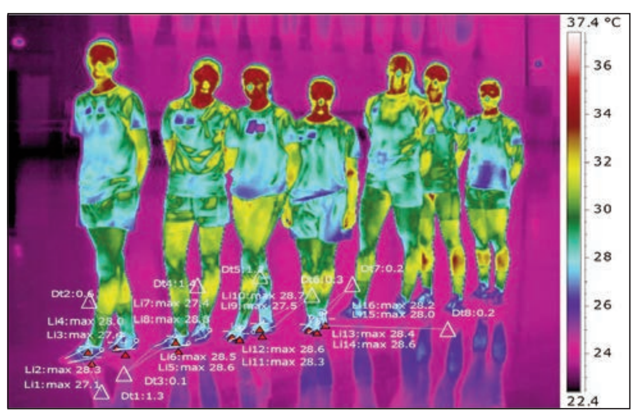

Fig. 4. Variation of sports footwear type A temperature at time zero in the 4 subjects in the infrared

is 25.4°C. The temperature variation along the Li11 line is 2.9°C, and the emissivity is 0.83, at time zero for subject 3. On the side along the Li12 line, the maximum temperature is 28.6°C, and the minimum temperature is 27.0°C, at time zero for subject 3. The temperature variation along the line Li12 is 1.6°C, and the emissivity is 0.83, at time zero for subject 3. In figure 4, for the right foot of subject 4 at time zero (before starting the handball training), the maximum temperature along the Li13 line, positioned at the centre of the foot, is 28.4°C, and the minimum temperature is 25.4°C. The temperature variation along the Li13 line is 3.0°C, and the emissivity is 0.83, at time zero for subject 4. On the side along the Li14 line, the maximum temperature is 28.6°C, and the minimum temperature is 25.7°C, at time zero for subject 4. The temperature variation along the line is 2.9°C, and the emissivity is 0.83, at time zero for subject 4. For the left foot of subject 4 at time zero, the maximum temperature along the Li15 line positioned on the central side is 28.0°C, and the minimum temperature is 26.2°C. The temperature variation along the Li15 line is 1.8°C, and the emissivity is 0.83, at time zero for subject 4. On the side along the Li16 line, the maximum temperature is 28.2°C, and the minimum temperature is 26.5°C, at time zero for subject 4. The temperature variation along the line Li16 is 1.7°C, and the emissivity is 0.83, at time zero for subject 4. The graphs realised with the help of Matlab presented in figure 5 show the measured temperature variation along the lines afferent to subject 1, subject 2, subject 3 and subject 4 on each footwear at time zero and approximation curves realised by polynomials of 4th degree.

In the case of subject 1 at time zero, as shown in figure 5, *a*, the relation obtained is a polynomial function of degree four (equation 1).

$$y = 0.005547x4 - 0.6184x3 + 25.67x2 - 469.9x + 3224 \quad (1)$$

The R-squared value of the model is 0.9099, indicating that approximately 90.99% of the variance in the data is explained by the model. In the case of subject 2 at time zero, as shown in figure 5, *b*, the relation obtained is a polynomial function of degree four (equation 2).

$$y = 0.02032x4 - 2.234x3 + 91.59x2 - 1660x + 11250 \quad (2)$$

The R-squared value of the model is 0.9022, indicating that approximately 90.22% of the variance in the data is explained by the model. In the case of subject 3 at time zero, as shown in figure 5, *c*, the relation obtained is a polynomial function of degree four (equation 3).

$$y = 0.00638x4 - 0.7086x3 + 29.31x2 - 534.5x + 3651 \quad (3)$$

The R-squared value of the model is 0.9727, indicating that approximately 97.27% of the variance in the data is explained by the model. In the case of subject 4 at time zero, as shown in figure 5, *d*, the relation obtained is a polynomial function of degree four (equation 4).

$$y = 0.008946x4 - 0.9873x3 + 40.62x2 - 737.7x + 5015 \quad (4)$$

The R-squared value of the model is 0.9274, indicating that approximately 92.74% of the variance in the

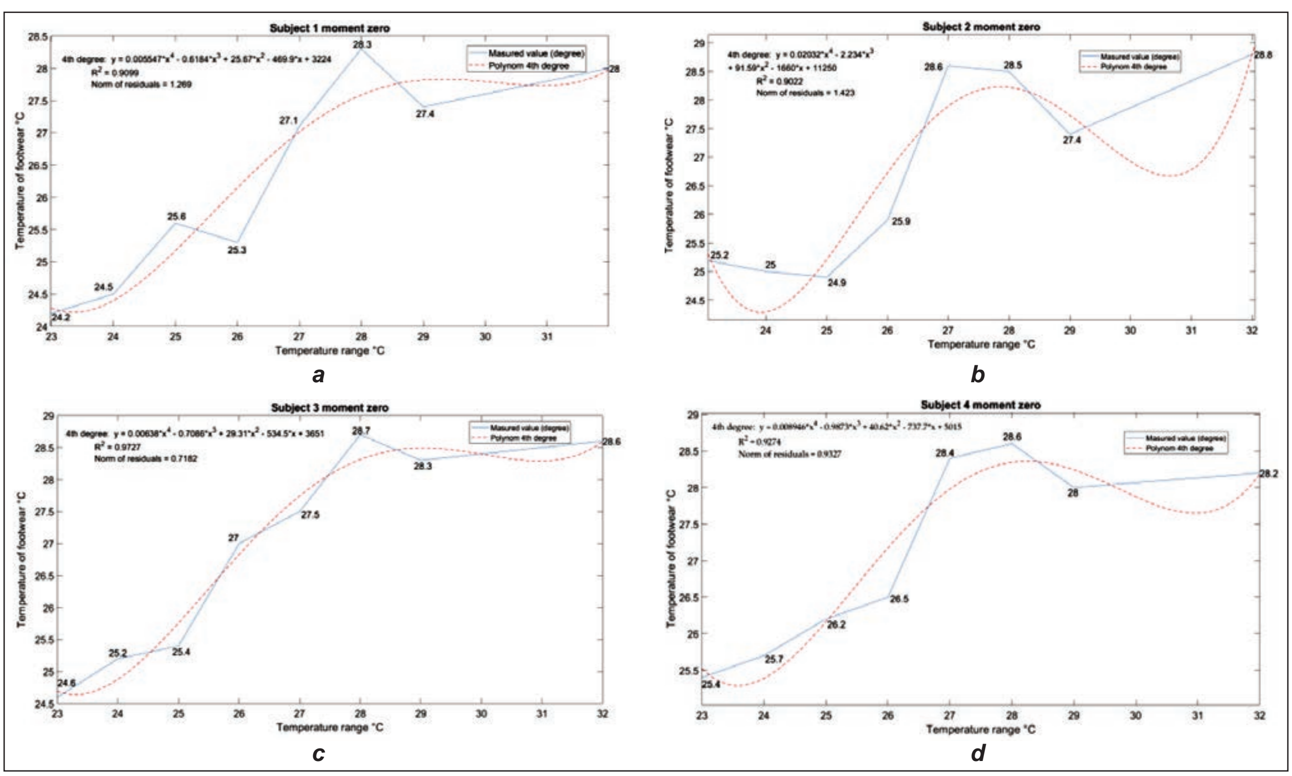

Fig. 5. Temperature variation on sports footwear type A for: *a* – subject 1 at time zero; *b* – subject 2 at time zero; *c* – subject 3 at time zero; *d* – subject 4 at time zero

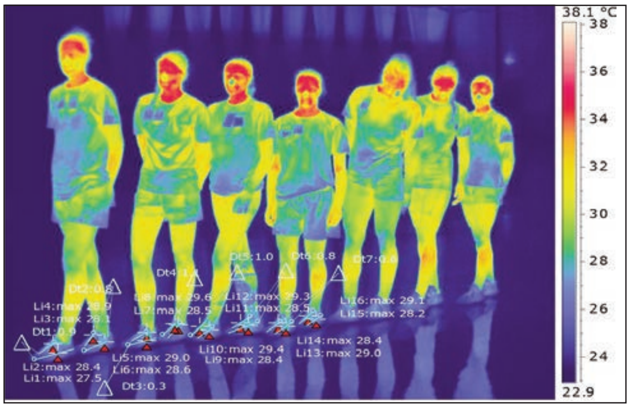

Fig. 6. Variation of sports footwear type A temperature at time one on the 4 subjects in the infrared

data is explained by the model. As shown in figure 6 for the left foot of subject 1 at time one (two minutes of training), the maximum temperature along the line Li1, positioned on the central part of the foot, is 27.5°C, and the minimum temperature is 24.0°C. The temperature variation along the Li1 line is 3.5°C, and the emissivity is 0.83, at time one for subject 1. On the side along the Li2 line, the maximum temperature is 28.4°C, and the minimum temperature is 25.3°C, at time one for subject 1. The temperature variation along the Li2 line is 3.1°C, and the emissivity is 0.83 at time one for subject 1.

As shown in figure 6 for the right foot of subject 1 at time one (two minutes of training), the maximum temperature along the line Li3, positioned on the central part of the foot, is 28.1°C, and the minimum temperature is 24.7°C. The temperature variation along the Li3 line is 3.4°C, and the emissivity is 0.83, at time one for subject 1. On the side along the Li4 line, the maximum temperature is 28.9°C, and the minimum temperature is 25.6°C, at time one for subject 1. The temperature variation along the Li4 line is 3.2°C, and the emissivity is 0.83 at time one for subject 1. In figure 6, for the right foot of subject 2 at time one (two minutes of training), the maximum temperature along the line Li5, which is positioned on the central part of the leg, is 29.0°C, and the minimum temperature is 24.9°C. The temperature variation along the Li5 line is 4.0°C, and the emissivity is 0.83, at time one for subject 2. On the side along the Li6 line, the maximum temperature is 28.6°C, and the minimum temperature is 25.5°C, at time one for subject 2. The temperature variation along the line Li6 is 3.1°C, and the emissivity is 0.83, at time one for subject 2. For the left foot of subject 2 at time one, the maximum temperature along the Li7 line positioned on the central side is 28.5°C, and the minimum temperature is 25.1°C. The temperature variation along the Li7 line is 3.5°C, and the emissivity is 0.83, at time one for subject 2. On the side along the Li8 line, the maximum temperature is 29.6°C, and the minimum temperature is 26.2°C, at time one for subject 2. The temperature variation along the line Li8 is 3.4°C, and the emissivity is 0.83, at time one for subject 2. Thermography measurements for subject 3 for the left foot at time one (two minutes of training) show that the maximum temperature along the Li9 line, which is positioned at the centre of the foot, is 28.4°C, and the minimum temperature is 25.0°C. The temperature variation along the Li9 line is 3.4°C, and the emissivity is 0.83, at time one for subject 3. On the side along the Li10 line, the maximum temperature is 29.4°C, and the minimum temperature is 24.9°C, at moment one for subject 3. The temperature variation along the Li10 line is 4.5°C, and the emissivity is 0.83, at moment one for subject 3. For the right foot of subject 3 at time one, the maximum temperature along the Li11 line positioned on the central side is 28.5°C, and the minimum temperature is 24.7°C. The temperature variation along the Li11 line is 3.8°C, and the emissivity is 0.83, at time one for subject 3. On the side along the Li12 line, the maximum temperature is 29.3°C, and the minimum temperature is 25.3°C, at time one for subject 3. The temperature variation along the line Li12 is 3.9°C, and the emissivity is 0.83, at time one for subject 3.

In figure 7, for the right foot of subject 4 at time one (two minutes of training), the maximum temperature along the Li13 line, positioned at the centre of the foot, is 29.0°C, and the minimum temperature is 24.9°C. The temperature variation along the Li13 line is 4.1°C, and the emissivity is 0.83, at time one for subject 4. On the side along the Li14 line, the maximum temperature is 28.4°C, and the minimum temperature is 24.3°C, at time one for subject 4. The temperature variation along the line is 4.1°C, and the emissivity is 0.83, at time one for subject 4. For the left foot of subject 4 at time one, the maximum temperature along the Li15 line positioned on the central side is 28.2°C, and the minimum temperature is 25.1°C. The temperature variation along the Li15 line is 3.1°C, and the emissivity is 0.83, at time one for subject 4. On the side along the Li16 line, the maximum temperature is 29.1°C, and the minimum temperature is 25.3°C, at time one for subject 4. The temperature variation along the line Li16 is 3.8°C, and the emissivity is 0.83, at time one for subject 4

The graphs realised with the help of Matlab presented in figure 7 show the measured temperature variation along the lines afferent to subjects 1, subject 2, subject 3 and subject 4 on each footwear at time one and approximation curves realised by polynomials of 4th degree.

In the case of subject 1 at time one, as shown in figure 7, *a*, the relation obtained is a polynomial function of degree four (equation 5).

$$y = 0.002347x4 - 0.2734x3 + 11.81x2 - \\ - 223.7x + 1592 \quad (5)$$

The R-squared value of the model is 0.9253, indicating that approximately 92.53% of the variance in the data is explained by the model.

In the case of subject 2 at time one, as shown in figure 7, *b*, the relation obtained is a polynomial function of degree four (equation 6).

$$y = 0.01235x4 - 1.364x3 + 56.18x2 - 1022x + 6957 \quad (6)$$

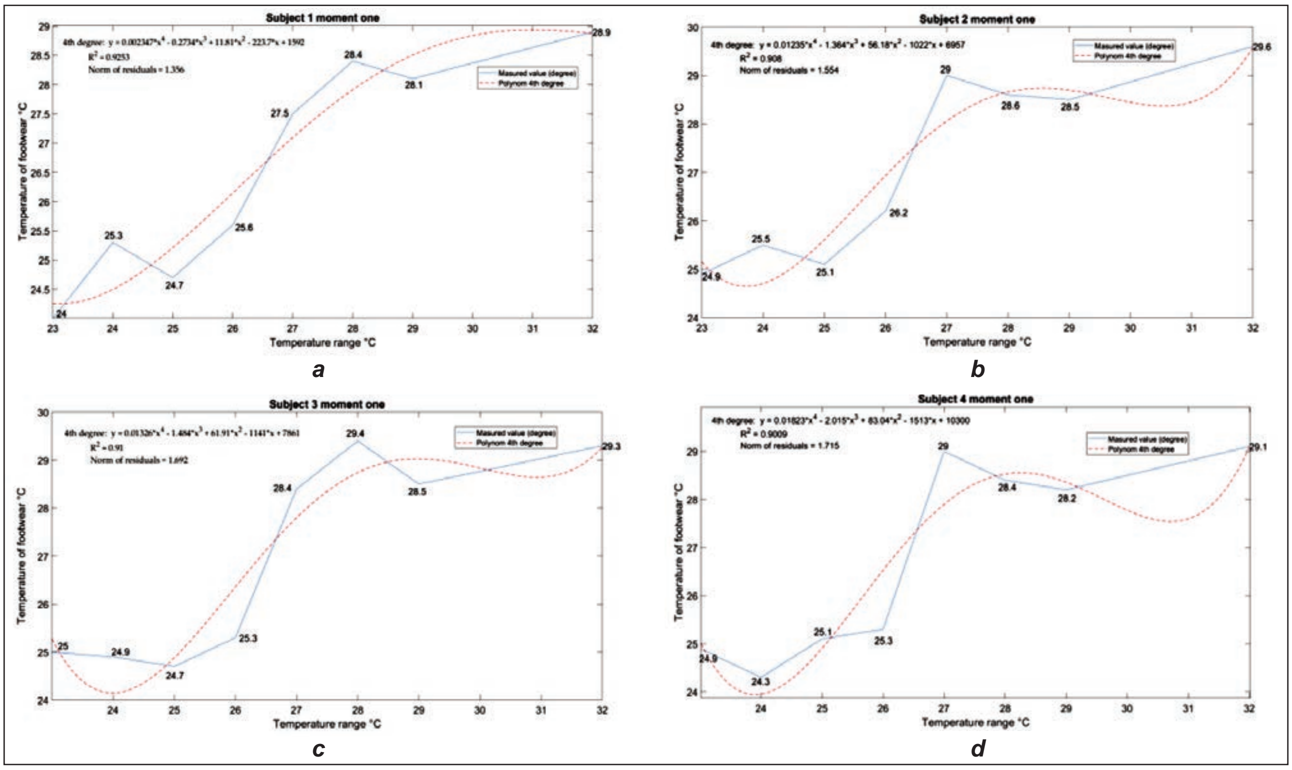

Fig. 7. Temperature variation on sports footwear type A for: *a* – subject 1 at time one; *b* – subject 2 at time one; *c* – subject 3 at time one; *d* – subject 4 at time one

The R-squared value of the model is 0.908, indicating that approximately 90.8% of the variance in the data is explained by the model.

In the case of subject 3 at time one, as shown in figure 7, *c*, the relation obtained is a polynomial function of degree four (equation 7).

$$y = 0.01326x4 - 1.484x3 + 61.91x2 - 1141x + 7861 \quad (7)$$

The R-squared value of the model is 0.91, indicating that approximately 91% of the variance in the data is explained by the model. In the case of subject 4 at time one, as shown in figure 7, *d*, the relation obtained is a polynomial function of degree four (equation 8).

$$y = 0.01823x4 - 2.015x3 + 83.04x2 - 1513x + 10300 \quad (8)$$

The R-squared value of the model is 0.9009, indicating that approximately 90.09% of the variance in the data is explained by the model.

As shown in figure 8 for the left foot of subject 1 at time two (five minutes of handball training), the maximum temperature along the line Li1, which is positioned on the central part of the foot, is 27.5°C, and the minimum temperature is 24.3°C. The temperature variation along the Li1 line is 3.2°C, and the emissivity is 0.81, at time two for subject 1. On the side along the Li2 line, the maximum temperature is 28.7°C, and the minimum temperature is 23.7°C, at time two for subject 1. The temperature variation along the Li2 line is 5.0°C, and the emissivity is 0.81 at time two for subject 1.

As shown in figure 8 for the right foot of subject 1 at time two (five minutes of handball training), the maximum temperature along the line Li3, which is positioned on the central part of the foot, is 28.3°C, and the minimum temperature is 25.2°C. The temperature variation along the Li3 line is 3.1°C, and the emissivity is 0.81, at time two for subject 1. On the side along the Li4 line, the maximum temperature is 29.4°C, and the minimum temperature is 25.4°C, at time two for subject 1. The temperature variation along the Li4 line is 4.0 °C, and the emissivity is 0.81 at time two for subject 1. In figure 8, for the right foot of subject 2 at time two (five minutes of handball training), the maximum temperature along the line Li5, positioned on the central part of the leg, is 29.3°C, and the minimum temperature is 25.5°C. The temperature variation along the Li5 line is 3.8°C, and the emissivity is 0.81, at time two for subject 2. On the side along the Li6 line, the maximum temperature is 29.0°C, and the minimum temperature is 24.9°C, at time two for subject 2. The temperature variation along the line Li6 is 4.0°C, and the emissivity is 0.81, at time two for subject 2. For the left foot of subject 2 at time two, the maximum temperature along the Li7 line positioned on the central side is 28.6°C, and the minimum temperature is 24.3°C. The temperature variation along the Li7 line is 4.3°C, and the emissivity is 0.81, at time two for subject 2. On the side along the Li8 line, the maximum temperature is 29.7°C, and the minimum temperature is 26.4°C, at time two for subject 2. The temperature variation along the line Li8 is 3.3°C, and the emissivity is 0.81, at time two for subject 2. Thermography measurements for subject 3 for the left foot at time two (five minutes of handball

training) show that the maximum temperature along the Li9 line, which is positioned at the centre of the foot, is 28.6°C, and the minimum temperature is 25.3°C. The temperature variation along the Li9 line is 3.3°C, and the emissivity is 0.81, at time two for subject 3. On the side along the Li10 line, the maximum temperature is 30.2°C, and the minimum temperature is 26.2°C, at moment two for subject 3. The temperature variation along the Li10 line is 4.0°C, and the emissivity is 0.81, at moment two for subject 3. For the right foot of subject 3 at time two, the maximum temperature along the Li11 line positioned on the central side is 28.9°C, and the minimum temperature is 27.1°C. The temperature variation along the Li11 line is 1.8°C, and the emissivity is 0.81, at time two for subject 3. On the side along the Li12 line, the maximum temperature is 29.6°C, and the minimum temperature is 27.4°C, at time two for subject 3. The temperature variation along the line Li12 is 2.2°C, and the emissivity is 0.81, at time two for subject 3.
In figure 8, for the right foot of subject 4 at time two (five minutes of handball training), the maximum temperature along the Li13 line, positioned at the centre of the foot, is 29.1°C, and the minimum temperature is 26.9°C. The temperature variation along the Li13 line is 2.2°C, and the emissivity is 0.81, at time two for subject 4. On the side along the Li14 line, the maximum temperature is 28.9°C, and the minimum temperature is 24.4°C, at time two for subject 4. The temperature variation along the line is 4.5°C, and the emissivity is 0.81, at time two for subject 4.
For the left foot of subject 4 at time two, the maximum temperature along the Li15 line positioned on the central side is 28.6°C, and the minimum temperature is 25.0°C. The temperature variation along the Li15 line is 3.6°C, and the emissivity is 0.81, at time two for subject 4. On the side along the Li16 line, the

Fig. 8. Variation of sports footwear temperature at time two on the 4 subjects in infrared

maximum temperature is 29.5°C, and the minimum temperature is 25.2°C, at time two for subject 4. The temperature variation along the line Li16 is 4.2°C, and the emissivity is 0.81, at time two for subject 4.
The graphs realised with the help of Matlab presented in figure 9 show the measured temperature variation along the lines afferent to subject 1, subject 2, subject 3 and subject 4 on each footwear at time two and approximation curves realised by polynomials of 4th degree.
In the case of subject 1 at time two, as shown in figure 9, *a*, the relation obtained is a polynomial function of degree four (equation 9).

$$y = 0.01126x4 - 1.253x3 + 52x2 - 953x + 6530 \quad (9)$$

The R-squared value of the model is 0.9687, indicating that approximately 96.87% of the variance in the data is explained by the model. In the case of subject 2 at time two, as shown in figure 9, *b*, the relation obtained is a polynomial function of degree four (equation 10).

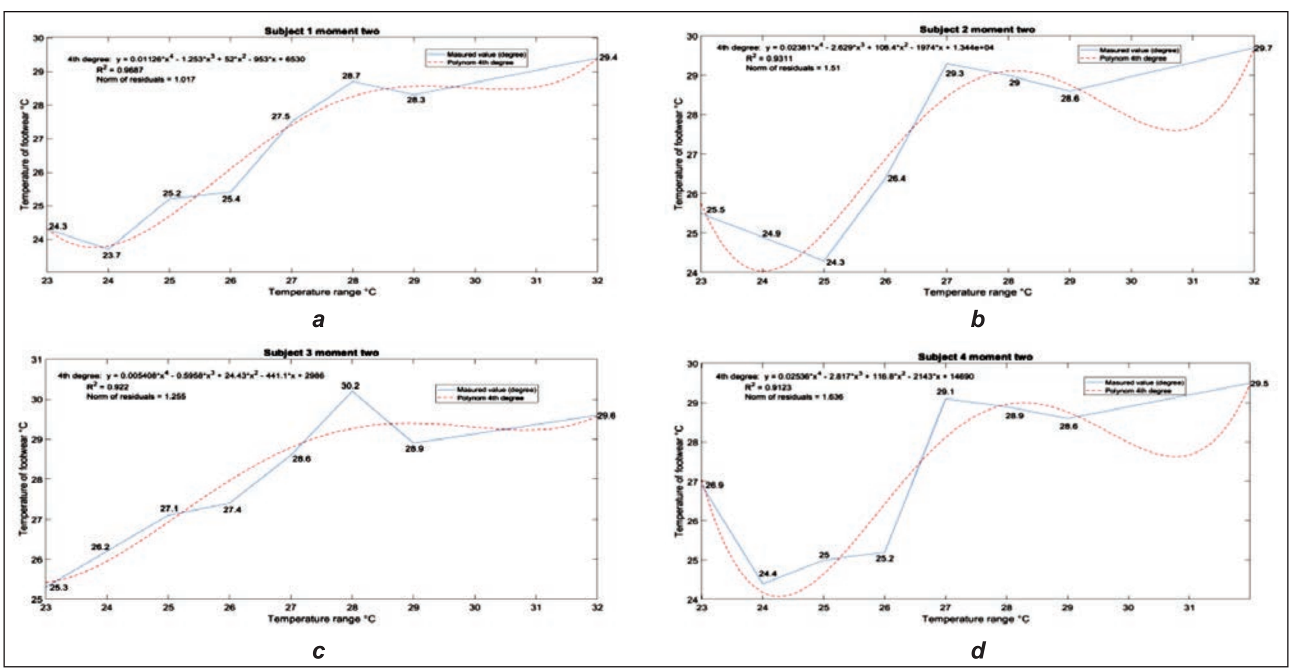

Fig. 9. Temperature variation on sports footwear for: *a* – subject 1 at time two; *b* – subject 2 at time two; *c* – subject 3 at time two; *d* – subject 4 at time two

$$y = 0.02381x^4 - 2.629x^3 + 108.4x^2 - 1974x + 13440 \quad (10)$$

The R-squared value of the model is 0.9311, indicating that approximately 93.11% of the variance in the data is explained by the model. In the case of subject 3 at time two, as shown in figure 9, *c*, the relation obtained is a polynomial function of degree four (equation 11).

$$y = 0.005408x^4 - 0.5958x^3 + 24.43x^2 - 441.1x + 2986 \quad (11)$$

The R-squared value of the model is 0.922, indicating that approximately 92.2% of the variance in the data is explained by the model. In the case of subject 4 at time two, as shown in figure 9, *d*, the relation obtained is a polynomial function of degree four (equation 12).

$$y = 0.02536x^4 - 2.817x^3 + 116.8x^2 - 2143x + 14690 \quad (12)$$

The R-squared value of the model is 0.9123, indicating that approximately 91.23% of the variance in the data is explained by the model.

Fig. 10. Variation of sports footwear type A temperature at time three on the 4 subjects in infrared

As shown in figure 10 for the left foot of subject 1 at time three (15 min of handball training), the maximum temperature along the line Li1, positioned on the central part of the foot, is 30.9°C, and the minimum temperature is 26.5°C. The temperature variation along the Li1 line is 4.4°C, and the emissivity is 0.80, at time three for subject 1. On the side along the Li2 line, the maximum temperature is 30.2°C, and the minimum temperature is 27.7°C, at time three for subject 1. The temperature variation along the Li2 line is 2.5°C, and the emissivity is 0.80 at time three for subject 1.

As shown in figure 10 for the right foot of subject 1 at time three (15 min of handball training), the maximum temperature along the line Li3, which is positioned on the central part of the foot, is 30.4°C, and the minimum temperature is 28.1°C. The temperature variation along the Li3 line is 2.3°C, and the emissivity is 0.80, at time three for subject 1. On the side along the Li4 line, the maximum temperature is 30.7°C, and the minimum temperature is 28.4°C, at time three for subject 1. The temperature variation along the Li4 line is 2.3°C, and the emissivity is 0.80 at time three for subject 1.

In figure 10, for the right foot of subject 2 at time three (15 minutes of handball training), the maximum temperature along the line Li5, which is positioned on the central part of the leg, is 30.6°C, and the minimum temperature is 27.6°C. The temperature variation along the Li5 line is 3.0°C, and the emissivity is 0.80, at time three for subject 2. On the side along the Li6 line, the maximum temperature is 30.3°C, and the minimum temperature is 26.6°C, at time three for subject 2. The temperature variation along the line Li6 is 3.7°C, and the emissivity is 0.80, at time three for subject 2. For the left foot of subject 2 at time three, the maximum temperature along the Li7 line positioned on the central side is 31.7°C, and the minimum temperature is 27.3°C. The temperature variation along the Li7 line is 4.4°C, and the emissivity is 0.80, at time three for subject 2. On the side along the Li8 line, the maximum temperature is 31.2°C, and the minimum temperature is 29.3°C, at time three for subject 2. The temperature variation along the line Li8 is 1.8°C, and the emissivity is 0.80, at time three for subject 2. Thermography measurements for subject 3 for the right foot at time three (15 min of handball training) show that the maximum temperature along the Li9 line, which is positioned at the centre of the foot, is 30.1°C, and the minimum temperature is 26.4°C. The temperature variation along the Li9 line is 3.7°C, and the emissivity is 0.80, at time three for subject 3. On the side along the Li10 line, the maximum temperature is 31.1°C, and the minimum temperature is 26.6°C, at moment three for subject 3. The temperature variation along the Li10 line is 4.5°C, and the emissivity is 0.80, at moment three for subject 3. For the left foot of subject 3 at time three, the maximum temperature along the Li11 line positioned on the central side is 29.7°C, and the minimum temperature is 27.2°C. The temperature variation along the Li11 line is 2.5°C, and the emissivity is 0.80, at time three for subject 3. On the side along the Li12 line, the maximum temperature is 31.0°C, and the minimum temperature is 27.9°C, at time three for subject 3. The temperature variation along the line Li12 is 3.1°C, and the emissivity is 0.80, at time three for subject 3. In figure 10, for the right foot of subject 4 at time three (15 minutes of handball training), the maximum temperature along the Li13 line, which is positioned at the centre of the foot, is 30.5°C, and the minimum temperature is 27.9°C. The temperature variation along the Li13 line is 2.6°C, and the emissivity is 0.80, at time three for subject 4. On the side along the Li14 line, the maximum temperature is 31.0°C, and the minimum temperature is 28.2°C, at time three for subject 4. The temperature variation along the line is 2.7°C, and the emissivity is 0.80, at time three for subject 4. For the left foot of subject 4 at time three, the maximum temperature along the Li15 line positioned on the central side is 29.9°C, and the minimum temperature is 28.3°C. The temperature variation along the Li15 line is 1.6°C,

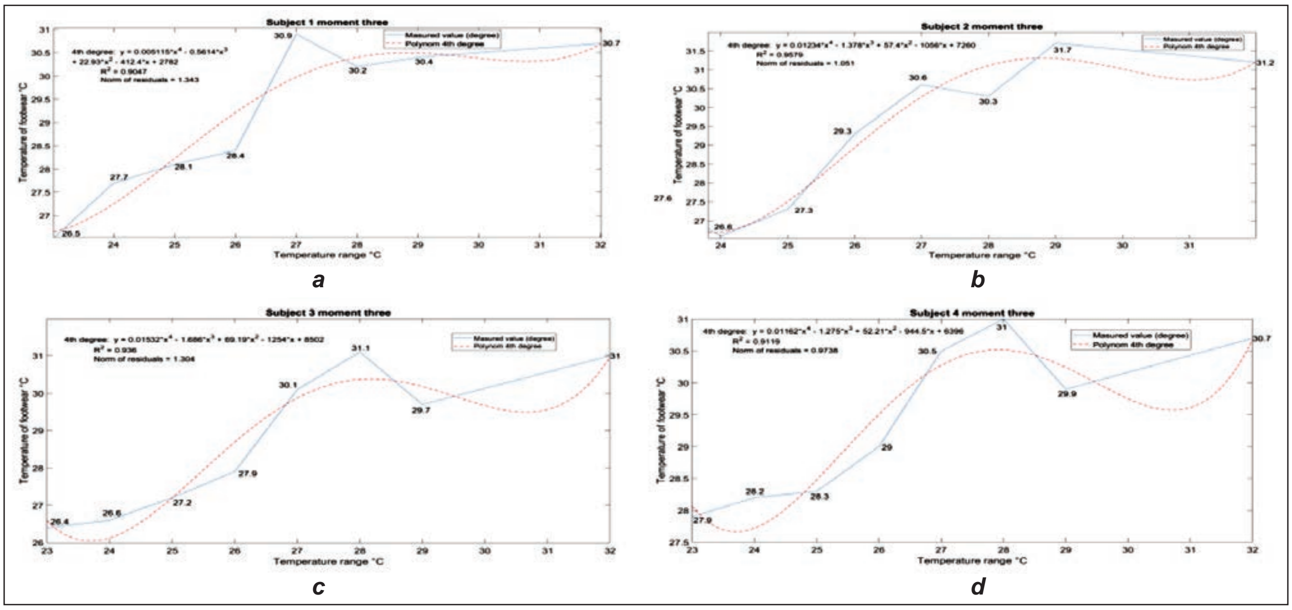

Fig. 11. Temperature variation on sports footwear for: *a* – subject 1 at time three; *b* – subject 2 at time three; *c* – subject 3 at time three; *d* – subject 4 at time three

and the emissivity is 0.80, at time three for subject 4. On the side along the Li16 line, the maximum temperature is 30.7°C, and the minimum temperature is 29.0°C, at time three for subject 4. The temperature variation along the line Li16 is 1.7°C, and the emissivity is 0.80, at time three for subject 4. The graphs realised with the help of Matlab presented in figure 11 show the measured temperature variation along the lines afferent to subject 1, subject 2, subject 3 and subject 4 on each footwear at time three and approximation curves realised by polynomials of 4th degree. In the case of subject 1 at time three, as shown in figure 11, *a*, the relation obtained is a polynomial function of degree four (equation 13).

$$y = 0.005115x4 – 0.5614x3 + 22.93x2 – – 412.4x + 2782 \quad (13)$$

This equation has been fitted to the given data, resulting in an R-squared value of 0.9047. An R-squared value of 0.9047 indicates that about 90.47% of the variance in the dependent variable (y) can be explained by the independent variable (x) using this 4th degree polynomial model. In the case of subject 2 at time three, as shown in figure 11, *b*, the relation obtained is a polynomial function of degree four (equation 14).

$$y = 0.01234x4 – 1.378x3 + 57.4x2 – 1056x + 7260 \quad (14)$$

The R-squared value of 0.9579 indicates that 95.79% of the variance in the dependent variable (y) can be explained by the independent variable (x) using this 4th degree polynomial model. This high R-squared value suggests that the model is a good fit for the data. In the case of subject 3 at time three, as shown in figure 11, *c*, the relation obtained is a polynomial function of degree four (equation 15).

$$y = 0.01532x4 – 1.686x3 + 69.19x2 – 1254x + 8502 \quad (15)$$

The R-squared value of 0.936 indicates that approximately 93.6% of the variance in the dependent variable (y) can be explained by the independent variable (x) using this 4th-degree polynomial model. A higher R-squared value suggests that the model provides a good fit to the data. In the case of subject 4 at time three, as shown in figure 11, *d*, the relation obtained is a polynomial function of degree four (equation 16).

$$y = 0.01162x4 – 1.275x3 + 52.21x2 – 944.5x + + 6396 \quad (16)$$

This model has an R-squared value of 0.9119, indicating that approximately 91.19% of the variance in the data is explained by the model.

As shown in figure 12 for the left footwear of subject 1 at time four (at the end of handball training), the maximum temperature along the line Li1, which is positioned on the central part of the foot, is 32.8°C, and the minimum temperature is 31.0°C. The temperature variation along the Li1 line is 1.8°C, and the emissivity is 0.79, at time four for subject 1. On the side along the Li2 line, the maximum temperature is 31.1°C, and the minimum temperature is 26.0°C, at

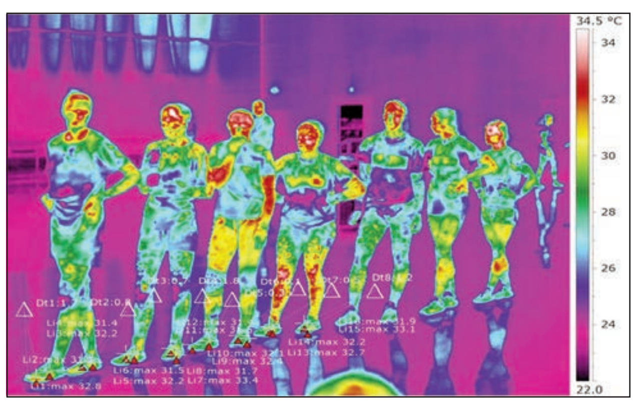

Fig. 12. Variation of sports footwear temperature at time four on the 4 subjects in infrared

time four for subject 1. The temperature variation along the Li2 line is 5.0°C, and the emissivity is 0.79 at time four for subject 1. As shown in figure 12 for the right foot of subject 1 at time four (at the end of handball training), the maximum temperature along the line Li3, which is positioned on the central part of the foot, is 32.2°C, and the minimum temperature is 27.8°C. The temperature variation along the Li3 line is 4.4°C, and the emissivity is 0.79, at time four for subject 1. On the side along the Li4 line, the maximum temperature is 31.4°C, and the minimum temperature is 28.9°C, at time four for subject 1. The temperature variation along the Li4 line is 2.4°C, and the emissivity is 0.79 at time four for subject 1.

In figure 12, for the right footwear of subject 2 at time four (at the end of handball training), the maximum temperature along the line Li5, which is positioned on the central part of the leg, is 32.2°C, and the minimum temperature is 27.8°C. The temperature variation along the Li5 line is 4.4°C, and the emissivity is 0.78, at time four for subject 2. On the side along the Li6 line, the maximum temperature is 31.5°C, and the minimum temperature is 29.4°C, at time four for subject 2. The temperature variation along the line Li6 is 2.1°C, and the emissivity is 0.78, at time four for subject 2. For the left foot of subject 2 at time four, the maximum temperature along the Li7 line positioned on the central side is 33.4°C, and the minimum temperature is 29.1°C. The temperature variation along the Li7 line is 4.4°C, and the emissivity is 0.78, at time four for subject 2. On the side along the Li8 line, the maximum temperature is 31.2°C, and the minimum temperature is 31.7°C, at time four for subject 2. The temperature variation along the line Li8 is 1.9°C, and the emissivity is 0.78, at time four for subject 2. Thermography measurements for subject 3 for the right foot at time four (at the end of handball training), show that the maximum temperature along the Li9 line, positioned on the centre of the foot, is 32.4°C, and the minimum temperature is 30.4°C. The temperature variation along the Li9 line is 2.0°C, and the emissivity is 0.78, at time four for subject 3. On the side along the Li10 line, the maximum temperature is 32.1°C, and the minimum temperature is 28.5°C, at moment four for subject 3. The temperature variation along the Li10 line is 3.6°C, and the emissivity is 0.78, at moment four for subject 3. For the left foot of subject 3 at time four, the maximum temperature along the Li11 line positioned on the central side is 31.5°C, and the minimum temperature is 29.2°C. The temperature variation along the Li11 line is 2.3°C, and the emissivity is 0.78, at time four for subject 3. On the side along the Li12 line, the maximum temperature is 31.4°C, and the minimum temperature is 29.5°C, at time four for subject 3. The temperature variation along the line Li12 is 1.9°C, and the emissivity is 0.78, at time four for subject 3.

In figure 12, for the right foot of subject 4 at time four (at the end of handball training), the maximum temperature along the Li13 line, which is positioned at the centre of the foot, is 32.7°C, and the minimum temperature is 29.6°C. The temperature variation along the Li13 line is 3.1°C, and the emissivity is 0.77, at time four for subject 4. On the side along the Li14 line, the maximum temperature is 32.2°C, and the minimum temperature is 30.3°C, at time four for subject 4. The temperature variation along the line is 1.9°C, and the emissivity is 0.77, at time four for subject 4. For the left foot of subject 4 at time four, the maximum temperature along the Li15 line positioned on the central side is 33.1°C, and the minimum temperature is 30.4°C. The temperature variation along the Li15 line is 2.7°C, and the emissivity is 0.77, at time four for subject 4. On the side along the Li16

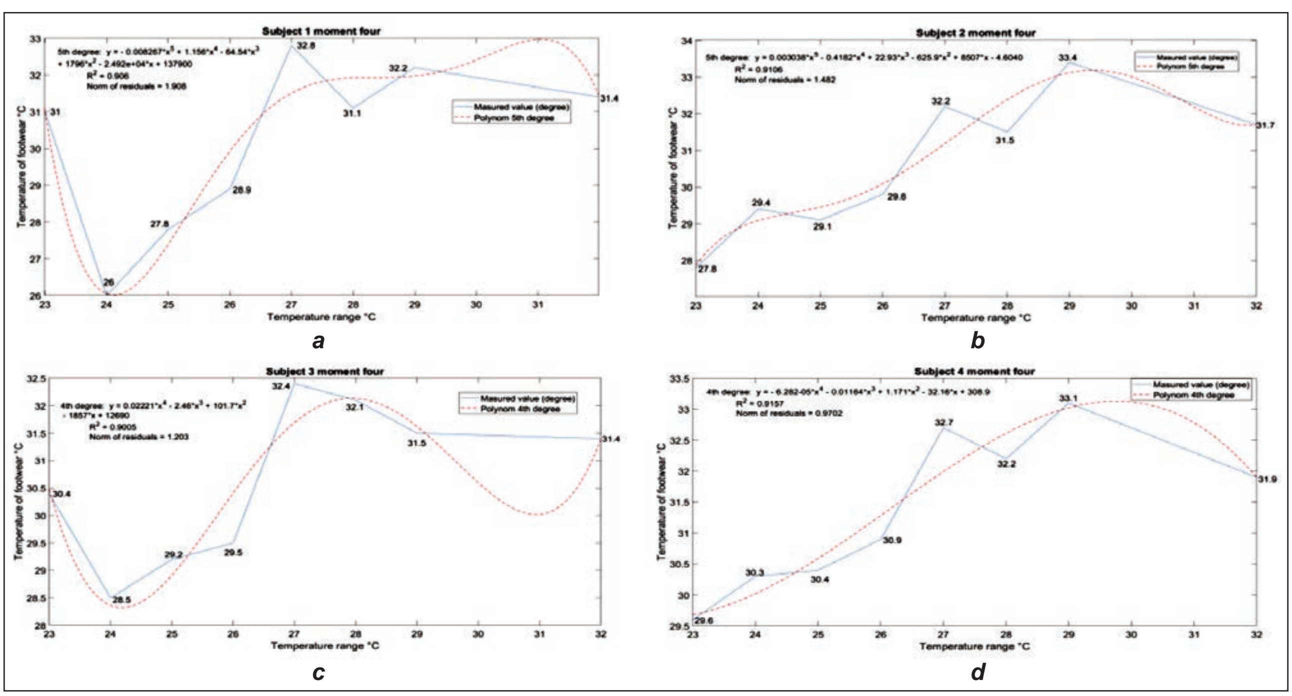

Fig. 13. Temperature variation on sports footwear for: *a* – subject 1 at time four; *b* – subject 2 at time four; *c* – subject 3 at time four; *d* – subject 4 at time four

line, the maximum temperature is 31.9°C, and the minimum temperature is 30.9°C, at time four for subject 4. The temperature variation along the line Li16 is 1.0°C, and the emissivity is 0.77, at time four for subject 4.

The graphs realised with the help of Matlab presented in figure 13 show the measured temperature variation along the lines afferent to subject 1, subject 2, subject 3 and subject 4 on each footwear at time four and approximation curves realised by polynomials of 4th and 5th degree. In the case of subject 1 at time four, as shown in figure 13, *a*, the relation obtained is a polynomial function of degree five (equation 17).

$$y = -0.008267x5 + 1.156x4 - 64.54x3 + 1796x2 - 24920*x + 137900 \quad (17)$$

This model has an R-squared value of 0.906, indicating that approximately 90.6% of the variance in the data is explained by the model. In the case of subject 2 at time four, as shown in figure 13, *b*, the relation obtained is a polynomial function of degree five (equation 18).

$$y = 0.003038x5 - 0.4182x4 + 22.93x3 - 625.9x2 + 8507*x - 46040 \quad (18)$$

The R-squared value of the model is 0.9106, indicating that approximately 91.06% of the variance in the data is explained by the model. In the case of subject 3 at time four, as shown in figure 13, *c*, the relation obtained is a polynomial function of degree four (equation 19).

$$y = 0.02221x4 - 2.46x3 + 101.7x2 - 1857x + 12690 \quad (19)$$

The R-squared value of the model is 0.9005, indicating that approximately 90.05% of the variance in the

Table 1

THE TEMPERATURE OF THE SPORTS FOOTWEAR DURING HANDBALL TRAINING FOR THE 4 SELECTED SUBJECTS OUT OF THE 7 ANALYSED

Subject	Time zero	Time one	Time two	Time three	Time four
Subject 1	Li1 max 27.1°C	Li1 max 27.5°C	Li1 max 27.5°C	Li1 max 30.9°C	Li1 max 32.8°C
	Li1 min 24.2°C	Li1 min 24.0°C	Li1 min 24.3°C	Li1 min 26.5°C	Li1 min 31.0°C
	Li2 max 28.3°C	Li2 max 28.4°C	Li2 max 28.7°C	Li2 max 30.2°C	Li2 max 31.1°C
	Li2 min 24.5°C	Li2 min 25.3°C	Li2 min 23.7°C	Li2 min 27.7°C	Li2 min 26.0°C
	Li3 max 27.4°C	Li3 max 28.1°C	Li3 max 28.3°C	Li3 max 30.4°C	Li3 max 32.2°C
	Li3 min 25.6°C	Li3 min 24.7°C	Li3 min 25.2°C	Li3 min 28.1°C	Li3 min 27.8°C
	Li4 max 28.0°C	Li4 max 28.9°C	Li4 max 29.4°C	Li4 max 30.7°C	Li4 max 31.4°C
	Li4 min 25.3°C	Li4 min 25.6°C	Li4 min 25.4°C	Li4 min 28.4°C	Li4 min 28.9°C
Subject 2	Li5 max 28.6°C	Li5 max 29.0°C	Li5 max 29.3°C	Li5 max 30.6°C	Li5 max 32.2°C
	Li5 min 25.2°C	Li5 min 24.9°C	Li5 min 25.5°C	Li5 min 27.6°C	Li5 min 27.8°C
	Li6 max 28.5°C	Li6 max 28.6°C	Li6 max 29.0°C	Li6 max 30.3°C	Li6 max 31.5°C
	Li6 min 25.0°C	Li6 min 25.5°C	Li6 min 24.9°C	Li6 min 26.6°C	Li6 min 29.4°C
	Li7 max 27.4°C	Li7 max 28.5°C	Li7 max 28.6°C	Li7 max 31.7°C	Li7 max 33.4°C
	Li7 min 24.9°C	Li7 min 25.1°C	Li7 min 24.3°C	Li7 min 27.3°C	Li7 min 29.1°C
	Li8 max 28.8°C	Li8 max 29.6°C	Li8 max 29.7°C	Li8 max 31.2°C	Li8 max 31.7°C
	Li8 min 25.9°C	Li8 min 26.2°C	Li8 min 26.4°C	Li8 min 29.3°C	Li8 min 29.8C
Subject 3	Li9 max 27.5°C	Li9 max 28.4°C	Li9 max 28.6°C	Li9 max 30.1°C	Li9 max 32.4°C
	Li9 min 24.6°C	Li9 min 25.0°C	Li9 min 25.3°C	Li9 min 26.4°C	Li9 min 30.4°C
	Li10 max 28.7°C	Li10 max 29.4°C	Li10 max 30.2°C	Li10 max 31.1°C	Li10 max 32.1°C
	Li10 min 25.2°C	Li10 min 24.9°C	Li10 min 26.2°C	Li10 min 26.6°C	Li10 min 28.5°C
	Li11 max 28.3°C	Li11 max 28.5°C	Li11 max 28.9°C	Li11 max 29.7°C	Li11 max 31.5°C
	Li11 min 25.4°C	Li11 min 24.7°C	Li11 min 27.1°C	Li11 min 27.2°C	Li11 min 29.2°C
	Li12 max 28.6°C	Li12 max 29.3°C	Li12 max 29.6°C	Li12 max 31.0°C	Li12 max 31.4°C
	Li12 min 27.0°C	Li12 min 25.3°C	Li12 min 27.4°C	Li12 min 27.9°C	Li12 min 29.5°C
Subject 4	Li13 max 28.4°C	Li13 max 29.0°C	Li13 max 29.1 °C	Li13 max 30.5°C	Li13 max 32.7°C
	Li13 min 25.4°C	Li13 min 24.9°C	Li13 min 26.9 °C	Li13 min 27.9°C	Li13 min 29.6°C
	Li14 max 28.6°C	Li14 max 28.4°C	Li14 max 28.9°C	Li14 max 31.0°C	Li14 max 32.2°C
	Li14 min 25.7°C	Li14 min 24.3°C	Li14 min 24.4°C	Li14 min 28.2°C	Li14 min 30.3°C
	Li15 max 28.0°C	Li15 max 28.2°C	Li15 max 28.6°C	Li15 max 29.9°C	Li15 max 33.1°C
	Li15 min 26.2°C	Li15 min 25.1°C	Li15 min 25.0°C	Li15 min 28.3°C	Li15 min 30.4°C
	Li16 max 28.2°C	Li16 max 29.1°C	Li16 max 29.5°C	Li16 max 30.7°C	Li16 max 31.9°C
	Li16 min 26.5°C	Li16 min 25.3°C	Li16 min 25.2°C	Li16 min 29.0°C	Li16 min 30.9°C

data is explained by the model. In the case of subject 4 at time four, as shown in figure 13, *d*, the relation obtained is a polynomial function of degree four (equation 20).

$$y = -0.00006282x4 - 0.01164x3 + 1.171x2 - 32.16x + 308.9 \quad (20)$$

The R-squared value of the model is 0.9157, indicating that approximately 91.57% of the variance in the data is explained by the model. The measurements were performed on seven athletes (subjects) in a handball training session, wearing the same footwear type A handball used for indoor sports. For the other three subjects, although having different models of the same sports footwear, the analysis of the thermal distribution values shows they are within the minimum and maximum limits of the seven subjects analysed in the paper, Depending on the intensity of the training, the 4 subjects wearing a footwear type A show an increase in temperature along the measured Li1–Li16 lines up to a maximum temperature of 33.4 at the time four analysed in a handball training session.

The temperature of the sports footwear varied during handball training when measurements were taken for the 4 selected subjects out of the 7 analysed, and are presented in table 1.

By implementing eco-friendly materials, transparent supply chains, waste reduction measures, energy efficiency, recycling initiatives, and further innovation, sports footwear brands can reduce their environmental impact and contribute to a more sustainable future.

To conclude, the temperature, increase and emissivity decrease are interconnected phenomena in handball footwear construction. Understanding these relationships is crucial for designing high-quality products that provide optimal thermal performance, comfort, and durability.

CONCLUSIONS

In the present paper, research was carried out in order to identify the thermal variation of indoor sports shoes used in volleyball training so as to detect the heat exchange between the foot and the outdoor environment.

For textile materials used in the manufacture of sports footwear (e.g. nylon, polyester and polypropylene), the emissivity decreases with increasing temperature due to the contact between the foot and the footwear. Heat transfer can become more difficult with decreasing emissivity; the ability of the textile material to release heat is affected, thus resulting in increased heat accumulation and potentially uncomfortable conditions.

Therefore, the test was valuable for showing the temperature distribution along the lines for each shoe and showing the strengths and weaknesses of the design of the tested footwear compared to the research done in the field. In the current study, the authors utilised a thermographic camera placed on a tripod to capture real-time images from various angles of the handball training during both static and dynamic activities. In the case of subjects 1, 2, 3 and 4 using type A footwear, there is an uneven distribution of the maximum temperature variation along the analysed lines Li1, Li2, Li3, Li4, Li5, Li6, Li7, Li8, Li9, Li10, Li11, Li12, Li13, Li14, Li15, Li16 at the five times when the measurements were taken.

In the case of the type A footwear analysed on the four athletes (subjects) during the handball training in the five moments, it can be concluded that the minimum and maximum temperature varies between 24.2°C at subject 1 at moment 0, before the beginning of the training, and 33.4°C at subject 2 at time four, at the end of the training. In the case of subjects 1, 2, 3 and 4, who use type A footwear, it can be seen that the R2 regression of the polynomial function has a value greater than 0.9 within the five analysed moments. In those cases, where the R^2 regression of the polynomial function has a value greater than 0.9, the mathematical model represents the real situation. Based on the thermographic values recorded, researchers created a mathematical model using polynomial regression in Matlab. This model helps predict temperature values that fall outside the range of the experimental data. By analysing the thermographic data, the team was able to identify patterns and trends in temperature changes. The use of polynomial regression allows for a more accurate estimation of temperatures even in conditions not covered by the original experiments. This approach enhances our understanding of temperature variations and can be useful in various scientific applications.

Taking into account the data obtained from static and dynamic temperature measurements during handball training in type A footwear, predictions of thermal distribution can be made through polynomial regression using neural networks.

The authors of this paper aim to perform temperature measurements during a men's handball training session to examine the distribution along temperature lines between subjects in the same environmental conditions and the advantages obtained by examining each shoe.

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