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Article

Thermal Response in Two Models of Socks with Different 3-D Weave Separations

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Abstract: Socks with the same three-dimensional plantar design, but with different compositions in the separation of their weaves could have different thermoregulatory effects. The objective of this study was therefore to evaluate the temperatures on the sole of the foot after a 10-km run, using two models of socks with different weave separations. In a sample of 20 individuals (14 men and 6 women), plantar temperatures were analysed using a Flir E60bx® (Flir Systems) thermographic camera before and after a run of 10 km wearing two models of socks that had different separations between the fabric weaves (5 mm versus 3 mm). After the post-exercise thermographic analysis, the participants responded to a Likert type survey to evaluate the physiological characteristics of the two models of socks. There was a significant increase in temperature in the areas of interest ($p<0.001$) after the 10-km run with both models of sock. The temperature under the 1st metatarsal head was higher with the AWC 2.1 model than with the AWC 1 (33.6±2.0°C vs 33.2±2.1°C) ($p = 0.014$). No significant differences were found in the scores on the physiological characteristics comfort survey ($p>0.05$ in all cases. The two models presented similar thermoregulatory effects on the soles of the feet, although the model with the narrowest weave separation generated greater temperatures (+0.4°C) under the first metatarsal head.

Keywords: Sock; infrared thermography; temperature; comfort

1. Introduction

Running is a sports activity that provides great health benefits, improves the general physical condition [1], prevents cardiovascular diseases [2], and has a positive impact on mental health [3]. Various factors related to the foot and its support, such as the ergonomics of the shoe or the running technique, have been exhaustively studied, but the type of sock used has received little attention in the literature. Socks have the main function of protecting the foot from friction from the sports shoe and maintaining adequate conditions of temperature and humidity [4]. During a run, the foot acts as a dynamic support and lever to push the body weight. It is also the main shock absorber, and allows the mechanical work to dissipate as thermal energy – a mechanism that finds a physical barrier in the materials of the sport shoe [5,6]. This results in higher temperatures and humidity inside the sports shoe, which makes the perception of comfort difficult [7,8]. In addition, the temperature increase may be conditioned by other factors such as the weather, but also by the mechanical interaction of the foot with the ground, because the greater the number of strides (increase in distance) the greater the expected increase in overall temperature [9]. For all these circumstances, innovation within the textile industry has generated new designs and has introduced new materials such as bioceramic [10], copper [11], or oleofin [12] fibres in order to improve moisture management, fit, and

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softness against the skin, seeking better thermal comfort than with cotton or other common fibres.

Recently, three-dimensional plantar elements have been incorporated that have shown to reduce the temperature [13] and plantar pressure on the central forefoot [14,15]. There are currently on the market socks with rib-shaped elements that have different separations between the waves. Thus, one might think that the greater wave separation models (5 mm) could be beneficial for plantar thermoregulation because part of the heat generated could dissipate between the waves, resulting in a cooler and more breathable sock than models with closer three-dimensional waves. Since the foot dissipates mechanical energy, the increase in foot temperature may be the result of the repetitive forces encountered during the run [16], so that closer weaves should help slightly reduce the friction, even if it is at the cost of a lower potential evacuation of the heat generated. Thus, widely separated three-dimensional weaves would be recommended for asphalt runs, in hot weather, and over relatively short distances (up to 10 km). Models with narrower weave separation, and therefore with a somewhat thicker knit, would be recommended for longer runs or different types of ground.

These thermal responses can be identified using infrared thermography, evaluating the thermoregulatory response and identifying the potential benefits of the different designs. The objective of this study was therefore to evaluate the temperatures reflected on the sole of the foot after a 10-km run, using two models of sock with the same three-dimensional plantar design, but a different composition of the separation of the weaves.

2. Materials and Methods

The sample comprised 20 individuals (14 men and 6 women) who were active in sports, mean age 37.7 years, weight 65.05 kg, height 1.69 m, and body mass index 22.69 kg/m² (Table 1). The participants were informed verbally and in writing about the objectives and procedures to be followed before they signed their informed consent (Annex I). The study was approved by the Bioethics and Biosafety Commission of the University of Extremadura (ID: 180/2020).

Table 1. Anthropometric characteristics.

	N	Minimum	Maximum	Average	SD
Age (years)	20	18	53	37.70	11.622
Foot size (EU size)	20	36	45	41.17	2.208
Weight (Kg)	20	52	84	65.05	8.287
Height (m)	20	2	2	1.69	.063
BMI (Kg/m²)	20	19.6	28.1	22.69	2.2044

The inclusion criteria for the study were: (a) being between 18 and 65 years old, (b) being active in sports, (c) presenting a structurally normal foot, without obvious deformities, and (d) presenting no important ailments on the sole of the foot. Excluded were those individuals who (i) presented injuries in their lower limbs that would prevent normal running, or (ii) had suffered some fracture or undergone surgical intervention in the last 12 months

2.1. Measurement protocol

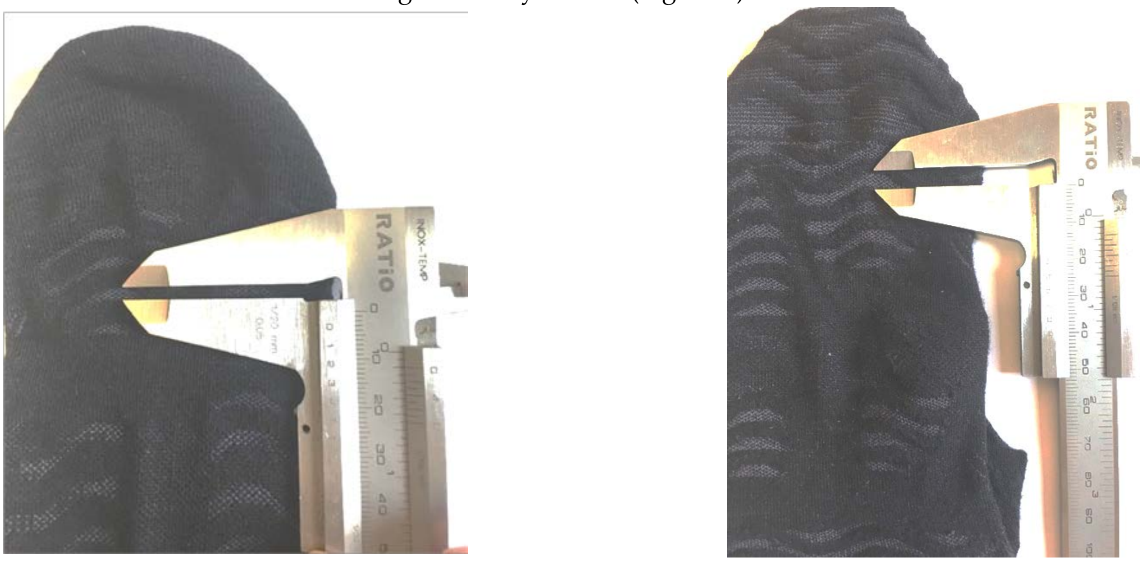
The participant sat on a stretcher, and took off their shoes and socks without touching any surface. Next, they were asked to place their feet in light dorsiflexion with 5-10 cm of separation between them and a black guillotine was positioned in the ankle area to avoid the reflection of heat from the rest of the body. We waited 1 minute to take the thermographic image to obviate conditioning by previous activity or foot manipulation.

2.1.1. Thermographic measurement

Prior to the run, a plantar thermographic image was taken with a Flir E60bx® camera (Flir Systems, Oregon, USA) placed on a tripod 1 metre away from both feet, following the protocol of Gatt et al. [17]. The temperature and humidity of the study room were controlled at all times (T 20°C, RH 40-45%). The environmental conditions were also controlled since all the measurements were carried out at the same time of the year (winter of 2022), in the same time slot, and without bad weather conditions such as wind or rain.

2.2. Socks

After taking the first photograph, two socks were given to each participant – the Lurbel© Pro-Line AWC 1 model and the Lurbel© Pro-Line AWC 2.1 model (MLS Textiles 1992, Ontinyent, Valencia). These were made from 50% Regenactiv (cellulosic base fibre with added ionic chitosan particles), 25% Cool-Tech, 17% ionized polyamide, and 8% Lycra. Both socks incorporated the AWC (Air Waves Control) technology, but with different plantar ribbing separations. The AWC 1 model had a plantar rib configuration of 5 mm separation, and the AWC 2.1 had a separation of 3 mm (Figure 1). The individual was told to put one sock model on one foot and the other on the opposite foot, with the foot for each model being randomly chosen (Figure 2).



(**a**) (**b**)

Figure 1. Configuration of plantar ribbing in sock models AWC 1 (a) and AWC 2.1 (b).

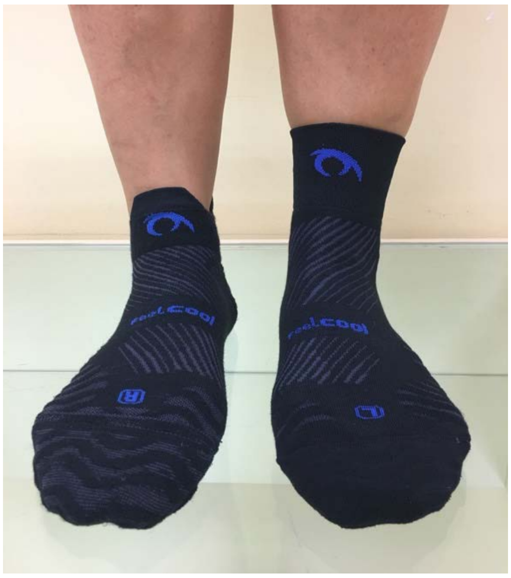


Figure 2. Subject with the two models of sock.

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After putting on the socks and their shoes, all the participants ran a distance of 10 km (average run time 51 minutes and 58 seconds, maximum 60 min and minimum 41 min) on a flat asphalt circuit. Once the established distance had been covered, the participants returned to the measurement room and, following the protocol explained above, a second thermographic image was taken.

ThermoHuman software was used to extract the temperatures from the thermal images taken. This method had shown excellent reliability as well as saving time in the manual analysis of the images [18,19]. The sole of the foot was divided into 9 regions of interest (ROIs) (Figure 3): (1) minor toes; (2) hallux; (3) 5th metatarsal head; (4) 2nd, 3rd, and 4th metatarsal heads; (5) 1st metatarsal head; (6) lateral midfoot; (7) medial midfoot; (8) lateral heel; (9) medial heel. To obviate bias, the researcher responsible for thermographic analyses was blind to the study.

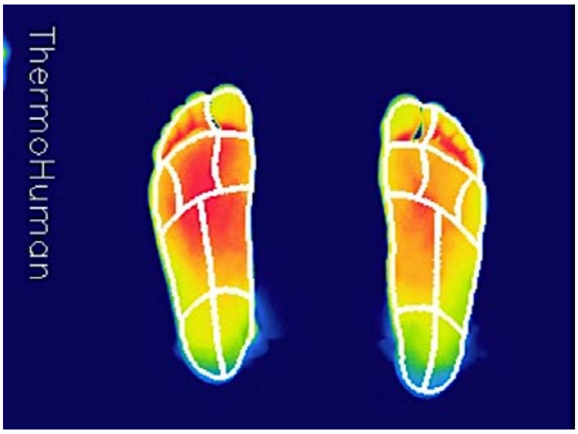

Figure 3. The 9 plantar regions of interest.

Finally, the participants were given a comfort survey relative to the physiological characteristics of each sock, scoring on a Likert type scale aspects such as humidity, thermal sensation, and cushioning. The scoring was from 1 to 5 with the worst possible score being 1 and 5 the best. At no time did the participants know what each sock was since they evaluated it based on the length of the leg (AWC 1 model short leg, AWC 2.1 model long leg; Figure 2). An open response item was also included in order for the respondents to express, in their own words, the sensations they had felt with the socks.

	Very wet -Very dry
Humidity / Transpiration	1 2 3 4 5
	Very hot -Very cool
Thermal sensation	1 2 3 4 5
	Little cushioning - Strong cushioning
Cushioning (overall)	1 2 3 4 5

Is there anything you want to tell us about the socks that we haven't asked you? ……

2.3. Statistical analysis

Since the distribution of the data did not meet the normality parameters (Shapiro-Wilk test <0.05 in temperature variables by area), non-parametric hypothesis contrast tests were used. A Wilcoxon test was applied to compare plantar temperatures. Spearman correlation was applied to compare the temperature dependence of perceived comfort. Statistical analyses were performed using SPSS version 22.0 (UEX campus license). A significance level of 5% ($p<0.05$) was set.

3. Results

The mean of the overall temperature of both feet was 28.93±2.23°C before the run. After the run it had increased significantly by 4°C ($p<0.001$) to 32.92±1.89°C. When using

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the AWC 1 sock, a significant increase in temperature was found in all 9 ROIs (p<0.001). The greatest increase in temperature (5.5°C) was recorded under the lesser toes, with a mean temperature of 26.66±3.35°C before the exercise and 32.20±2.62°C after. The area where the temperature increased the least (3°C) was in the medial midfoot (Table 2).

Table 2. Pre- and post-exercise temperature when using the AWC 1 model sock.

ROI´s		Mean	SD (ºC)	Delta	*p* value
Lesser toes	Pre	26.6640	3.35983	5.5	<0.001
	Post	32.2085	2.62808		
Hallux	Pre	26.6125	3.72359	5.3	<0.001
	Post	31.9045	2.72577		
5th MTH	Pre	28.1220	2.37087	4.4	<0.001
	Post	32.4750	1.86412		
2nd – 4th MTH	Pre	29.2090	2.30740	4.3	<0.001
	Post	33.4655	2.05450		
1st MTH	Pre	28.5625	2.62544	4.6	<0.001
	Post	33.1600	2.10110		
Lateral Midfoot	Pre	29.7130	2.01408	3.2	<0.001
	Post	32.9280	1.76186		
Medial Midfoot	Pre	30.4885	1.86801	3.0	<0.001
	Post	33.5055	1.76778		
Lateral Heel	Pre	28.4525	2.42308	3.9	<0.001
	Post	32.3680	2.16007		
Medial Heel	Pre	28.8245	2.06475	3.4	<0.001
	Post	32.2370	2.24553		

ROI´s Regions of interest. MTH, metatarsal head.

With the AWC 2.1 sock, a general increase in temperature after the exercise was also found in all the areas analysed (p<0.001). As with the AWC 1 case, the greatest increase in temperature was recorded under the lesser toes, while the medial midfoot was the area in which it increased the least (5.8°C and 3.2°C, respectively) (Table 3).

Table 3. Pre- and post-exercise temperature when using the AWC 2.1 model sock.

ROI´s		Mean	SD (ºC)	Delta	*p* value
Lesser toes	Pre	26.7225	3.20699	5.8	<0.001
	Post	32.5485	2.45015		
Hallux	Pre	26.8670	3.85992	5.3	<0.001
	Post	32.1210	2.51612		
5th MTH	Pre	28.3450	2.36038	4.2	<0.001
	Post	32.5260	1.97296		
2nd – 4th MTH	Pre	29.1555	2.48492	4.5	<0.001
	Post	33.6900	1.96286		
1st MTH	Pre	28.6210	2.69162	4.9	<0.001
	Post	33.5535	2.02587		
Lateral Midfoot	Pre	29.7305	2.00523	3.4	<0.001
	Post	33.1050	1.70930		
Medial Midfoot	Pre	30.5335	1.82020	3.2	<0.001
	Post	33.7400	1.67626		

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Lateral Heel	Pre	28.3955	2.54759	4.0	<0.001
	Post	32.3785	2.22356		
Medial Heel	Pre	28.8305	2.25478	3.7	<0.001
	Post	32.4920	2.08029		

ROI´s Regions of interest. MTH, metatarsal head.

When comparing the temperatures of the 9 ROIs after the 10-km run, a higher temperature was found in the area of the 1st metatarsal head when using the AWC 2.1 sock (33.6º±2.0°C) compared with AWC 1 (33.2±2.1°C) (p=0.014). In the rest of the areas analysed there were no statistically significant differences (Table 4).

Table 4. Comparison of post-exercise temperature between the AWC 1 and AWC 2.1 sock models.

ROI´s		**Tª (ºC)**		
		Mean	**SD**	***p* value**
Lesser toes	AWC 1	32.2	2.6	0.079
	AWC 2.1	32.5	2.5	
Hallux	AWC 1	31.9	2.7	0.228
	AWC 2.1	32.1	2.5	
5ª MTH	AWC 1	32.5	1.9	0.769
	AWC 2.1	32.5	2.0	
2nd – 4th MTH	AWC 1	33.5	2.1	0.091
	AWC 2.1	33.7	2.0	
1st MTH	AWC 1	33.2	2.1	**0.014**
	AWC 2.1	33.6	2.0	
Lateral Midfoot	AWC 1	32.9	1.8	0.208
	AWC 2.1	33.1	1.7	
Medial Midfoot	AWC 1	33.5	1.8	0.084
	AWC 2.1	33.7	1.7	
Lateral Heel	AWC 1	32.4	2.2	0.954
	AWC 2.1	32.4	2.2	
Medial Heel	AWC 1	32.2	2.2	0.186
	AWC 2.1	32.5	2.1	

ROI´s Regions of interest. MTH, metatarsal head.

When assessing the physiological characteristics perceived with the socks, the participants scored the moisture and cushioning with an average score greater than 4 except for thermal sensation, which had a score of 3.6±1.3 points in the AWC 1 model and 3.5±1 points in the AWC 2.1. There were no statistically significant differences when comparing the two models of socks (p>0.05 in all cases) (Table 5).

Table 5. Perceived comfort in terms of physiological characteristics between the AWC 1 and AWC 2.1 sock models.

	Model	**Mean**	**SD**	***p value***
Moisture	AWC 1	4.1	0.9	1
	AWC 2.1	4.1	0.9	
Termal sensation	AWC 1	3.6	1.3	0.606
	AWC 2.1	3.5	1.0	
Cushioning	AWC 1	4.2	0.8	0.789
	AWC 2.1	4.1	0.9	

There were no significant correlations between the temperature measured in any of the areas and the means of the humidity, thermal sensation. and cushioning scores given

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by the participants for either the AWC 1 or the AWC 2.1 models (Table 6, $p > 0.05$ in all cases).

Table 6. Correlations between the perceived comfort of the sock models and the T values of the areas of interest.

	AWC 1		AWC 2.1	
	Spearman Correlation	*p* value	Spearman Correlation	*p* value
Lesser toes	-.433	.056	-.119	.617
Hallux	-.332	.153	-.047	.845
5th MTH	-.401	.080	-.098	.682
2nd-4th MTH	-.379	.099	-.054	.820
1ª MTH	-.361	.117	.021	.930
Lateral midfoot	-.341	.141	.095	.689
Medial midfoot	-.287	.220	.126	.596
Lateral heel	-.250	.287	.079	.741
Medial heel	-.208	.378	.151	.526

4. Discussion

The objective of this study was to evaluate the thermoregulatory effect of two models of sock with rib-shaped elements with different separations between them. With both models, the average temperature of the foot after the run had increased by 4°C. This result was expected because, during physical exercise, the internal heat of the body increases, which generates an increase in blood flow, sweating, and skin temperature including that of the feet which also remain covered by socks and sports shoes. This 4°C increase seems small when compared with other studies which found a total 10°C temperature increase of the sole of the foot by 10º a 30-minute treadmill run [20]. The measurement conditions, the type of terrain, the distance run, or the intensity of the exercise will condition the increase in temperature of the body in general and the soles of the feet in particular. Thus, Reddy et al. [9] found that foot temperature increased by 4.6°C after 45 minutes of walking, and Martínez Nova et al. [13] found increases of 3°C after 10 minutes of walking at an easy pace. Because of all the above, the thermoregulatory effect provided by the socks studied allows the foot temperature to be maintained in ranges similar to those generated by a low intensity physical activity, thus being effective in their mission.

With both socks, the area where there was the greatest increase in temperature was under the lesser toes, with a difference of 5.5°C between pre- and post-exercise in AWC 1 (Table 2) and 5.8°C in AWC 2.1 (Table 3). The area where the temperature increased least was the medial midfoot, where there was an increase of around 3°C after the exercise (Tables 2 and 3). This greater increase in temperature in the lesser toe area may be due to the fact that this area starts from a lower initial temperature, due to greater rubbing in the shoes, or because of the biomechanical involvement of this area during the take-off phase in the run [21].

The comparison of plantar temperatures between the two models (Table 4), which have the same composition but with different separations of their three-dimensional plantar weaves, shows them to have similar thermoregulatory performance. The statistically significant higher temperature under the first metatarsal head (+0.4°C) in the 2.1 sock seems to be of little clinical relevance, and could be due to the greater density of the fabric in this model (due to the 3-mm weave separation) which would make dissipation of the heat generated slightly less efficient. Although a priori the AWC 1 model could have been expected to have a greater thermoregulatory effect due to the greater space between the weaves, it was observed that both the 3 or 5 mm separations are equally effective in performing this task. Thus, there would predominate the composition of the fibres in the three-dimensional configuration of the plantar part of the sock, with the mixture of natural (viscose) and synthetic (polyester, polyamide) fibres seeming to efficiently manage the temperature of the skin of the sole of the foot. The viscous fibre retains a small capacity to absorb the moisture generated, which keeps it thermoregulated. The synthetic fibres, by means of their multichannel cross-section, wick out the excess moisture generated, keeping the foot relatively dry and cool. The loss of radiative and evaporative heat in the acclimatization period could have cooled the foot, but the heat generation in intense exercise has a stronger impact than these possible heat losses [16]. To avoid excessive temperature increases, such as have been detected in compression socks or stockings [22], both models fit well to the foot, without compressing podal structures or seeking for gradual compression.

Although the AWC 2.1 sock presented a higher temperature under the 1st MTH, this had no impact on the participants' perception of comfort or thermal sensation (Table 5). They evaluated both models positively, with no differences between them. In addition, the final temperature (after the run) was not correlated with the score on the comfort scale, not even for the first metatarsal head, which reinforces our opinion that the highest temperature does not seem clinically relevant. This sense of comfort is perceived through the thermal (heat transfer) and tactile (friction and softness) integration that occurs in the skin [23,24]. Thus, possible discomfort may not be related to areas of high temperature and humidity, but to tactile signs caused by the movement of the foot in the shoe in areas of high biomechanical participation [25]. Despite the above, the increase in temperature in the AWC 2.1 model at the level of the 1st MTH could have some negative clinical implication in runs longer than 10 km since, as it is an area of high biomechanical participation, the greater heat generated could lead to the appearance of chafing or blisters in this area, making the practice of sport difficult.

4.1. Study limitations

The present study has demonstrated the thermoregulatory effect of the AWC 1 and AWC 2.1 sock models for a short distance (10 km) run. These results should therefore not be extrapolated to longer distances.

5. Conclusions

After a 10 km run, the plantar temperature of both feet only increased by 4°C, with both socks maintaining excellent thermoregulation. However, the AWC 1 sock was 0.4°C cooler under the first metatarsal head, an area of great biomechanical importance in running, which did not negatively impact the perceived comfort.

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