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Definition of a thermal comfort rating scale for mountaineering boots

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ABSTRACT

This study investigates the thermal insulation and moisture management of three types of mountaineering boots and simulated hiking activities under controlled environmental conditions with two elite athletes. Temperature and humidity were determined with six wireless probes placed on the most exposed parts of the foot (hallux, middle toe, little toe, dorsum, ankle and sole). Thermal images were taken to record the thermal insulation of each sample. Methodologically, the study aims to simulate every movement and activity of alpinism in order to realistically evaluate the conditions of use of this kind of footwear (also taking into account the lacing pressure exerted on the foot). Based on the results obtained, in a further step it will be possible to define the best solution in terms of combination of materials by creating a comfort scale for hiking boots.

Keywords
mountaineering boots,
thermal insulation,
footwear,
protection against cold,
thermal comfort

1 Introduction

The feet are one of the areas of the body most exposed to cold because of their large surface area compared to their volume. Furthermore, vasoconstriction effectively reduces blood flow to the extremities in cold conditions to minimize heat exchange with the environment [1], resulting in uncomfortably low foot temperatures and risk of frostbite in extreme conditions. For this reason, and because the feet are the only part of the body that is constantly exposed to cold surfaces (conductive heat transfer through the sole), insulating footwear is essential for adequate cold protection. Among the factors that strongly influence thermal comfort in footwear, thermal insulation and moisture management play an important role.

The body temperature is the result of the thermal balance between the heat generated by the body and the heat released to the environment. This second can be convective, radiative or conductive [2] in dry conditions. As far as insulation is concerned, several factors influence the performance of footwear, such as the thermal properties of the materials used or the clothing worn. Often, however, the feeling of cold in the feet is due to sweating and damp feet. When air trapped in the dry fibres is replaced by moisture, the footwear can lose up to 35% of its insulating properties [3,4]. According to the literature [5], sweat production on the foot accounts for 3-4% of the sweat production of the entire body and is therefore a significant cooling factor. In addition, cold can be divided into three ranges that can help in choosing the right footwear [3]:

- For temperatures above +5 °C, no special requirements are necessary for footwear insulation. The only specifications concern water repellency and internal moisture management (sweat tends to move away from the feet to colder areas with lower water vapour pressure and condense there [6]);
- at temperatures between +5 °C and -10 °C, the choice is more complicated due to the changing weather condition around the freezing point of water. In this case, higher thermal insulation and excellent tightness are crucial;
- at temperatures below -10 °C (the context in which our research takes place), moisture from the outside is a minor concern, but internal moisture management and thermal resistance becomes the most important property of the materials involved.

The skin temperature of the feet for thermal comfort has been shown to be 25 °C [3]. When the skin temperature drops, discomfort begins at 20-21 °C in the toe area, a strong cold sensation develops and the first signs of pain are felt at 15 °C. When the temperature drops to 10 °C, the sensation of pain becomes unbearable. Based on these ranges, one can relate the insulating properties of shoes to the temperatures at the foot and toes.

Nowadays, there is no rating scale for assessing the thermal insulation of mountain boots. The international standards [7-11] only report a definition of conformity. However, this assessment is not complete and reliable: The same footwear that is rated as “protection against cold” under the test conditions may not be the right protection under harsher environmental conditions.

The aim of our project is to determine more precisely the thermal performance of mountaineering footwear as a function of environmental conditions and metabolic rate. The experimental campaign aims to evaluate the skin temperature and moisture of the feet with three different types of mountaineering boots by testing them under different environmental conditions and with different physical intensity, with the aim to get as close as possible to actual use.

2 Materials and methods

2.1 Materials

Three different types of boots were tested (listed in Table 1). The three models were designed and manufactured by the company S.C.A.R.P.A. (Italy). All the boots tested are designed for professional use at very high altitudes: PHANTOM TECH (MODEL A) is a technical boot for mountaineering and ice climbing, PHANTOM 6000 (MODEL B) is designed for extreme mountaineering and PHANTOM 8000 (MODEL C) is a double boot designed for Himalayan mountaineering activities, at high altitudes and in extremely cold conditions. The MODEL C has an active electric heating system integrated into the boot. The tester used this model with the heating on one foot and the heating off on the other foot. Each sample was conditioned for 24 hours at T = 22 °C and relative humidity (RH) = 50% before the test.

A special structure was designed to emulate climbing and mountaineering activities, as shown in Fig. 1. The structure was located in a climate chamber where temperature and humidity were set according to the intended use of each boot model, as described in the following section.

Table 1. Description of the tested sample.

MODEL A	MODEL B	MODEL C
		
Mass = 810 g European size: 42	Mass = 1042 g European size: 42/43	Mass = 1320 g European size: 43

Figure 1. Structure projected for climbing simulation.

2.2 Experiments

Two elite athletes were involved in the test campaign. The physical features of the testers are reported in Table 2:

Table 1. Physical features of the testers.

Tester	Age	Height (cm)	Mass (kg)	BMI
1	31	183	69.9	20.87
2	57	174	77.9	25.56

Each sample was tested according to a specific protocol and under specific conditions, as reported in Table 3. Protocols differs according to the use intended for each sample.

The environmental conditions were set as reported below:

- MODEL A: T = -15 °C, RH = 40%;
- MODEL B: T = -20 °C, RH = 40%;
- MODEL C: T = -30 °C, RH = 40%.

Table 2. Physical activity of the different protocols.

PHASE	MODEL A	MODEL B	MODEL C
1	10' walking on a treadmill (8%)	10' walking on a treadmill (18%)	10' walking on a treadmill (18%)
2	10' rest	5' rest	5'rest
3	10' climbing simulation	10' climbing on a ladder	10' climbing on a ladder
4	10' rest	5' rest	10' walking on a treadmill (18%)
5	10' climbing simulation	15' climbing on a ladder	10' rest
6	-	5' climbing on a ladder	10' walking on a treadmill (18%)
7	-	10' rest	15' rest

2.3 Monitored parameters

Several parameters were monitored during the tests, namely the average skin temperature and humidity, the temperature and humidity of three toes, the dorsum and the ankle of the right foot, the temperature and humidity of the left insole, boots external surface temperature and the lacing pressure exerted on the foot. The average skin temperature and moisture were evaluated according to the International Standard EN ISO 9886 based on the 14-point method (for cold environment). Skin temperature was measured in 14 districts using the I-button Maxim Integrated DS1923 temperature and humidity probes.

The formula used to assess the average skin temperature is defined in the standard and given below:

$$\mathrm{Tsk} = \sum_{\mathrm{i}=1}^{14} 0{,}0714 * \mathrm{Ti},$$

where *i* is the index for the fourteen areas of the body (forehead, neck, right scapula, left upper chest, right arm upper location, left arm lower location, left hand, right abdomen, left paravertebral, right anterior thigh, left posterior thigh, right shin, left calf, right instep).

The same formula was used to evaluate average skin humidity, even though no specific standard is given to evaluate skin wettedness. Temperature and humidity for hallux, middle toe, little toe, ankle and dorsum of the right feet were measured with the use of temperature and humidity probes and stored in a MSR 147 datalogger.

Temperature and humidity of the left insole were obtained using the I-button Maxim Integrated DS1923 temperature and humidity probe.

Thermal images were acquired with a Nec G100ex camera during the entire duration of the tests to map the heat sinks from the boots and their surface temperature.

The pressure of the laces was also measured before entering the climate chamber to ensure that there was no existing overpressure on the foot that could affect blood circulation. The pressure in the dorsum area was measured after a short walk on the right foot.

3 Results

Since the tests were part of a pilot project, not all Testers were trained to resist under all environmental conditions and types of exercise, data are shown according to what is reported as follows:

- Tester 1 results for MODEL A;
- Tester 1 and Tester 2 results for MODEL B;
- Tester 2 results for MODEL C.

Greater lacing pressures were detected for Tester 1 compared to Tester 2. Results are shown in Table 4.

Table 3. Pressure exerted on the right foot.

Tester	Model	Pressure (mmHg)
1	A	83
1	B	80
2	B	60
2	C	54

3.1 Temperature

Skin temperature data for each model are shown in Figure 2. For MODEL A and MODEL B, data were collected on the right foot. For MODEL C, data were collected on the right foot for the standard model and on the left foot for the model with the heating system. The dashed lines represent the different phases of the test. As shown in Figure 2 (a, c, d), the temperature of the hallux was lower than the other toes in all cases, which is consistent with the results in the literature [3,11,12]. The only exception is the model with the heating system (which was located under the toes) in Figure 2 (e) and in Figure 2 (b), where no significant differences were observed between the skin temperatures of the toes.

The continuous decrease of toe temperature during the test is a signal of vasoconstriction.

The threshold of 15 °C was reached only in the case of MODEL A in Figure 2 (a). The temperature dropped below the comfort threshold in about 40 minutes from the start of the test, while the middle toe and the little toe were still above this threshold at the end of the test. However, in no case thermal equilibrium was reached during the test. This indicates that the temperature of the toes is likely to continue to decrease and fall below the comfort range under longer test duration.

By observing the results for MODEL B (Figure 2 (b) and (c)), the influence of different body composition (as shown in Table 2) and training level on cold is clear. Tester 2 not only has a higher BMI, but is also better trained to withstand low temperatures, as he is an alpinist with many years of experience in Himalayan expeditions.

With MODEL C, the heated boot (Figure 2 (e)), higher and more constant skin temperature values than the standard model were recorded. The toes particularly benefited from the effect of the heating system and a smaller drop in skin temperature was observed, suggesting that toe temperature can remain in a comfortable range for longer in extremely cold environments. In fact, during low intensity activities, the greater cause of injuries is reflected by the temperature drop in toes [12]. In particular, the temperature difference between the heated and non-heated boot at the beginning and end of the phase (considering the toes) is shown in Table 5.

Table 4. Temperature drop in the final rest phase for both models in toes.

Model	Hallux	Middle toe	Little toe
Normal	-2,9 °C	-2,7 °C	-2,1 °C
Heated	-1,7 °C	-1,8 °C	-1,6 °C

Thermal images were also taken during the tests. Significant results were obtained for MODEL A and MODEL B (due to the severe environmental conditions, no significant data could be obtained for MODEL C). The thermographs shown in Figure 3 were taken at the end of the test for both MODEL A and B. For a more direct comparison, both thermal images are shown for Tester 1 only. The dashed elliptical area on the left image represents the Region of Interest (ROI) that was considered for the calculation of the average temperature of the sole.

The sole temperature is lower for MODEL B (Figure 3 (b)), which leads to better thermal insulation in this case. The average temperature was -12 °C for MODEL A and -20 °C for MODEL B. This statement is also confirmed by the higher temperatures in the microclimate of the foot in the case of MODEL B (Figure 4 (b)) despite the lower environmental temperature during the test. The probe was positioned in the inner area of the sole, where there was no contact between the foot and the shoe, thus creating an air layer, in order to evaluate the microclimate in the boots. In both cases, the thermography shows that the higher temperatures were mainly reached in the area of the toes and the midsole of the foot.

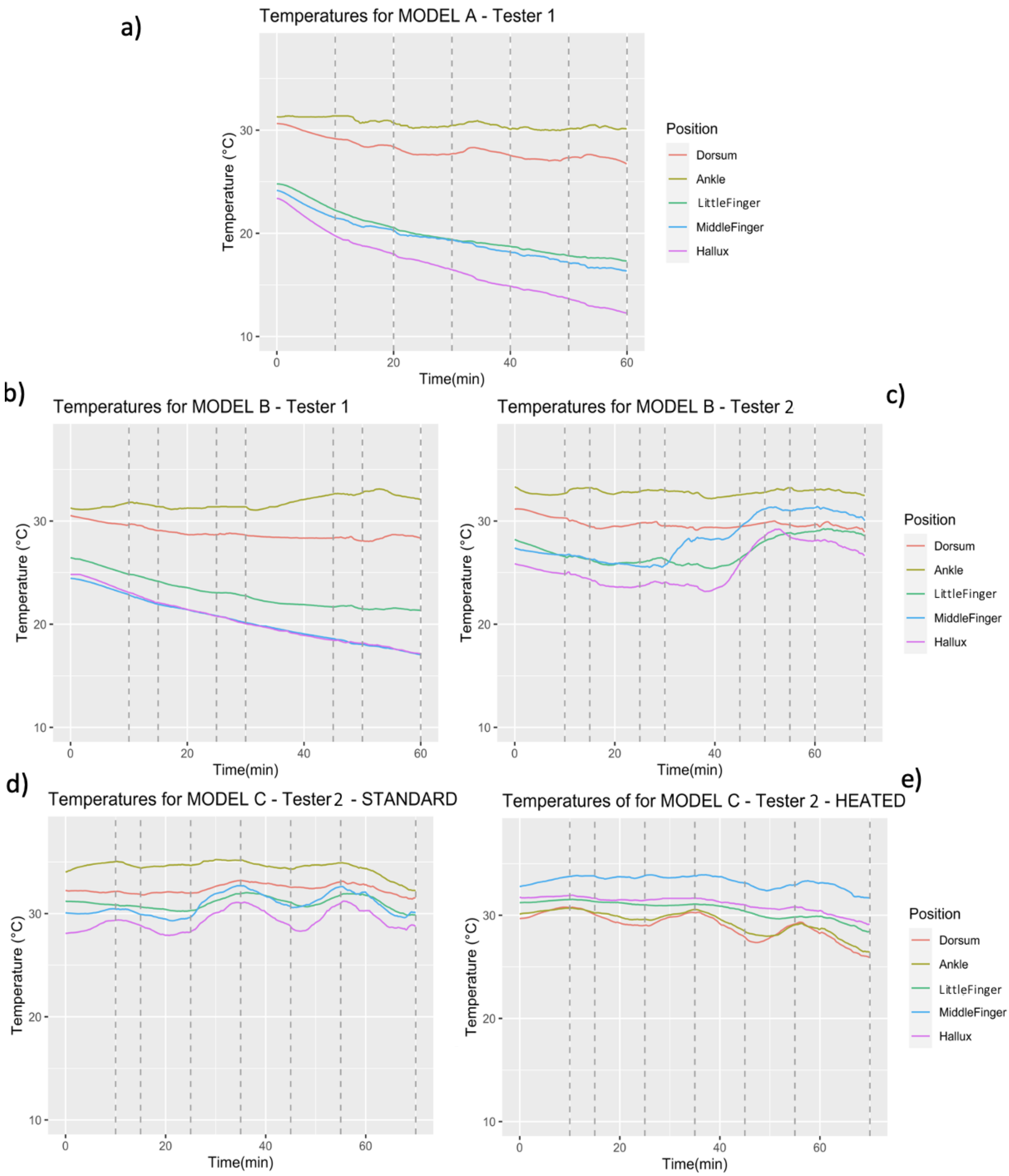

Figure 2. Temperature data for MODEL A (a), MODEL B for Tester 1 (b), MODEL B for Tester 2 (c), MODEL C without the heating system (d) and with the heating system (e).

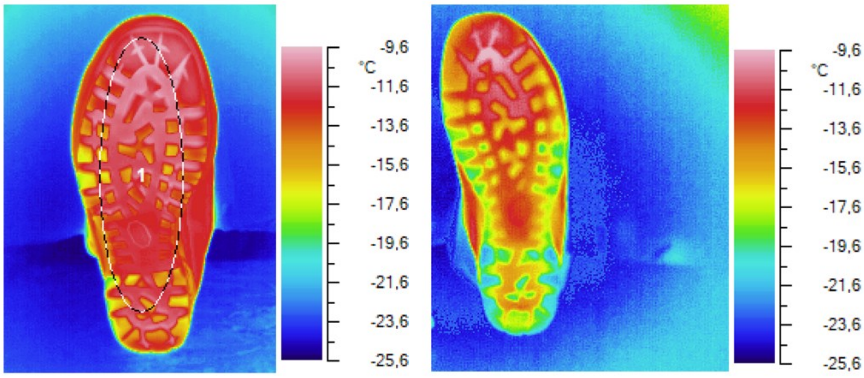

Figure 3. Termal images acquired at the end of the test for MODEL A (a) and MODEL B (b) both for Tester 1.

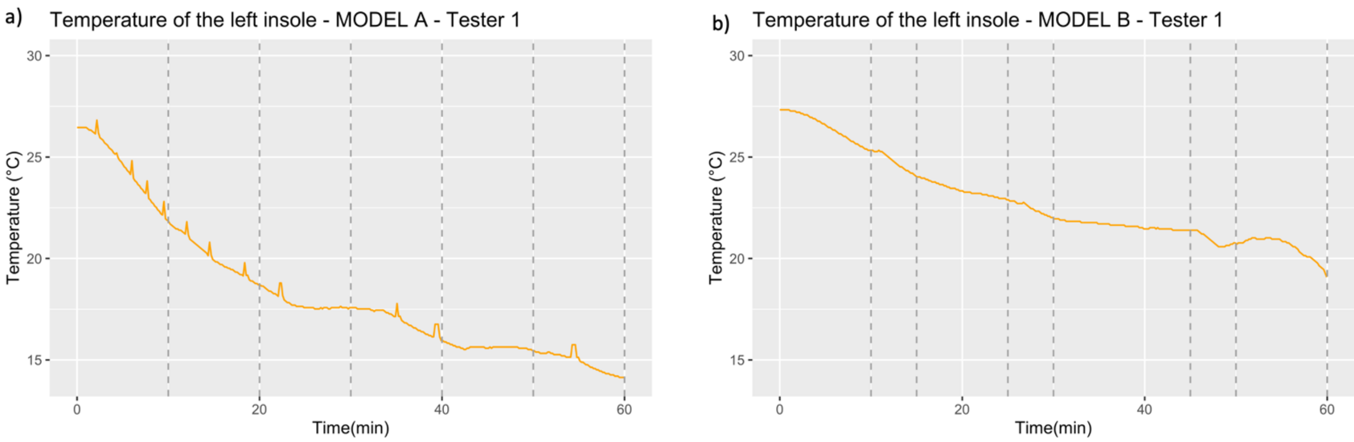

Figure 4. Temperature of the left insole for Tester 1 with MODEL A (a) and MODEL B (b).

3.2 Humidity

Skin humidity data are shown in Figure 5. Skin humidity was lower at the toes than at the ankles and dorsum (these results fully confirm the literature [5]). The skin humidity of the toes also decreased during the test, which can be attributed to the decreasing temperature. Indeed, perspiration decreases when the sensation of cold increases [13]. As already observed with the temperature data, the tester did not reach a state of equilibrium.

Furthermore, the sweat rate does not seem to be affected by the varying intensity of the activity. The strong difference between the two testers also in terms of sweat rate highlight the need of a greater number of testers for a statistical analysis.

The lower sweat production in the heated model (Figure 5 (e)) compared to the standard one (Figure 5 (d)) is due to the fact that although the heating system was located under the toes and their temperature was higher in the modified model than in the other case, both sweat production and thermoreceptors in the toes are negligible compared to the other foot zones [10,13].

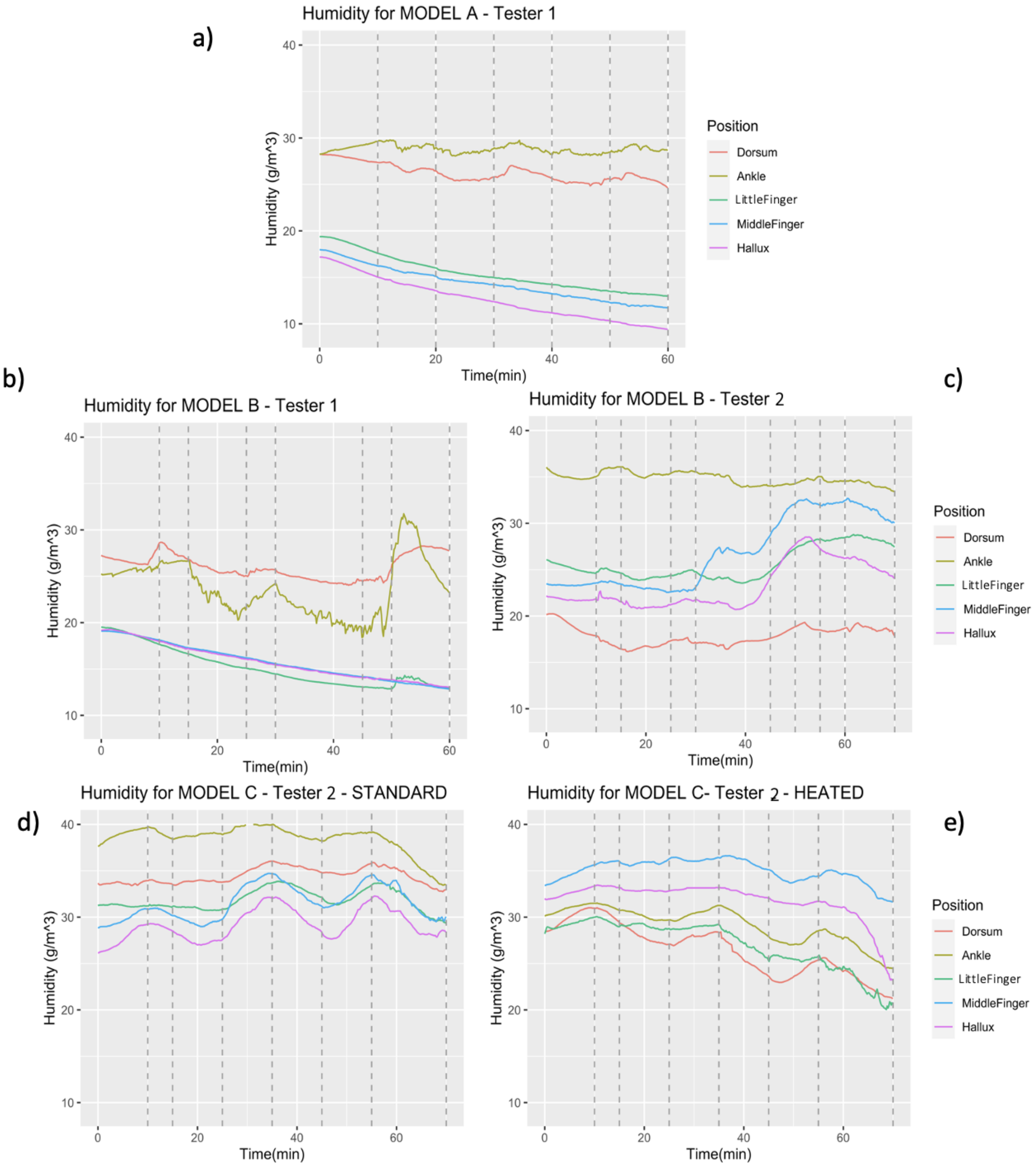

Figure 1. Humidity data for MODEL A (a), MODEL B for Tester 1 (b), MODEL B for Tester 2 (c), MODEL C without the heating system (d) and with the heating system (e).

Compared to the temperature data shown in Figure 4, unexpected higher value for humidity can be observed in Figure 6 (a), while the temperature values were lower. This could have affected the insulating properties of MODEL A, as humidity from outside could have replaced the air in the insulating layers of the boots [14].

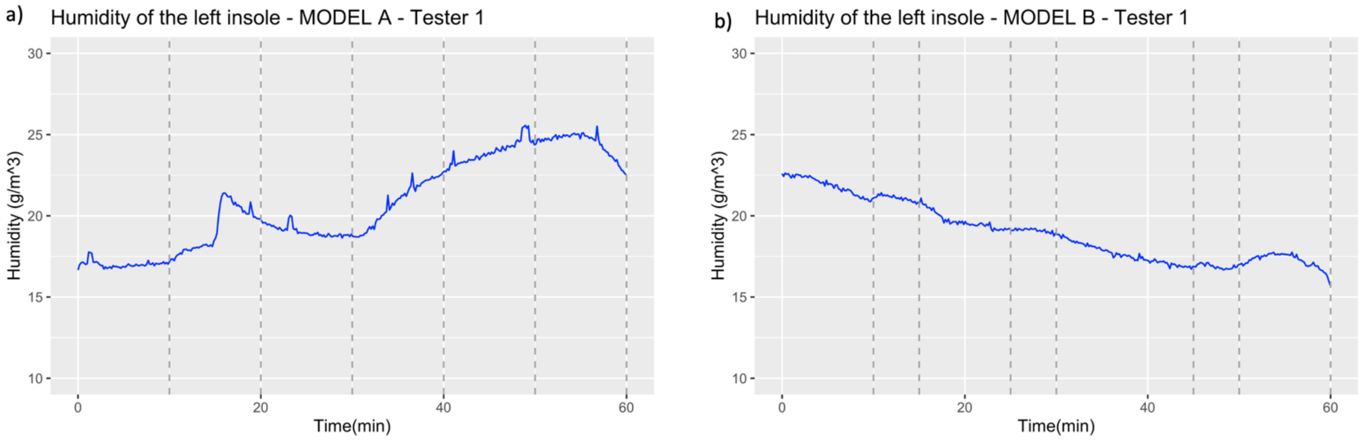

Figure 6. Humidity of the left insole for Tester 1 with MODEL A (a) and MODEL B (b).

4 Discussion

These tests were useful in determining the advantages and limitations of the established experimental protocol. Only in a few cases the skin temperature was lower than the comfort temperature. This suggests that the test duration was too short and the environmental conditions were not severe enough to assess the ability of the tested footwear to prevent dangerous cold conditions of the foot. For this reason, further tests will be conducted under harsher environmental conditions (including wind, which is responsible for the decrease in thermal insulation [8]). It should also be considered that thermal equilibrium has not yet been reached and longer tests are needed.

In all tests, the skin temperature at the toes was lower than the temperature at the dorsum and ankles, except for the test of the heated model (tester 2 – MODEL C). The most important result of this test is the different cooling rate of the models: under severe environmental conditions, heat retention is fundamental for the safety of the user. The prototype indeed shows that warming systems can ensure better thermal conditions compared to conventional systems. A more in-depth comparison needs to be made between the higher metabolic rate required for the greater weight carried by the heated model and the benefits it carries itself. The literature [14] states that sweating greatly reduces the thermal insulation of footwear, both through evaporative heat loss and by reducing insulation due to the damp layer. Moisture transfer in footwear, especially cold weather footwear, is always problematic due to the water repellent and waterproof properties required. According to previous studies [10], transpiration tends to be lower on the sole of the foot and toes than on the dorsum. These findings are confirmed by our results.

Due to the difference in body composition, there are significant differences in both temperature and humidity between Testers: Tester 1, with a lower BMI, basically had lower temperatures and sweat rates. Despite these differences, according to the thermal imaging camera recordings, the warmest area in each test was the top and the coldest was the sole and toe cap. These results are consistent with those found in the literature [11].

5 Conclusion

The authors believe that a more appropriate analysis of the thermal performance of mountain boots during in vivo testing is possible by examining the limitations of this experimental campaign. One of the main improvements deal with the introduction of a simple and clear questionnaire as is reported in literature [4] in order to collect subjective evaluation avoiding influencing factors not related to thermal comfort.

The use of a thermal imaging camera to map the heat exchange between the boots and the environment will help to better understand the nature of heat dissipation and improve the protection of the footwear from cold. The need for a more reliable evaluation of the thermal properties of footwear in cold environments was confirmed by the different performances of the three different models depending on the environment, which underlines the need for a more in-depth evaluation of footwear against cold.

Author Contributions

E. Bianca: conceptualization, methodology, formal analysis, investigation, data curation, writing – original draft preparation; F. Dotti: conceptualization, methodology, writing – review and editing, visualization, investigation, supervision, project administration; A. Ferri: conceptualization, writing – review and editing, supervision, project administration, funding acquisition. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The research work was carried out within the PhD project: "Definition of a rating scale for thermal comfort of mountaneering boots" co-financed by the manufacturing company S.C.A.R.P.A.

References

1. Lopardo, G. *Un Modello Matematico di Termoregolazione del Corpo Umano*, PhD thesis, Università degli studi di Salerno, 2011.
2. Kuklane, K.; Ueno, S.; Sawada, S.I.; Holmér, I. Testing Cold Protection According to EN ISO 20344: Is There Any Professional Footwear That Does Not Pass? *Ann. Occup. Hyg.* **2009**, *53*, 63-68. DOI: https://doi.org/10.1093/annhyg/men074.
3. Kuklane, K. Protection of Feet in Cold Exposure. *Industrial Health* **2009**, *47*, 242-253. DOI: https://doi.org/10.2486/indhealth.47.242.
4. Arezes, P.M.; Neves, M.M.; Teixeira, S.F.; Leão, C.P.; Cunha, J.L. Testing Thermal Comfort of Trekking Boots: An Objective and Subjective Evaluation. *Applied Ergonomics* **2013**, *44*, 557565. DOI: https://doi.org/10.1016/j.apergo.2012.11.007.
5. West, A.M.; Tarrier, J.; Hodder, S.; Havenith, G. Sweat Distribution and Perceived Wetness across the Human Foot: The Effect of Shoes and Exercise Intensity. *Ergonomics* **2019**, *62*, 1450-1461. DOI: https://doi.org/10.1080/00140139.2019.1657185.
6. Havenith, G.; Richards, M.G.; Xiaoxin, W.; Brode, P.; Candas, V.; Den Hartog, E.; Holmér, I.; Kuklane, K.; Meinander, H.; Nocker, W. Apparent Latent Heat of Evaporation from Clothing: Attenuation and "Heat Pipe" Effects. *J. Appl. Physiol.* **2008**, *104*, 142-149. DOI: https://doi.org/10.1152/japplphysiol.00612.2007.
7. International Standardization Organization UNI EN ISO 28802:2012 – Ergonomics of the Physical Environment — Assessment of Environments by Means of an Environmental Survey Involving Physical Measurements of the Environment and Subjective Responses of People (ISO 28802:2012) 2012.
8. Babič, M.; Lenarčič, J.; Žlajpah, L.; Taylor, N.A.S.; Mekjavić, I.B. A Device for Simulating the Thermoregulatory Responses of the Foot: Estimation of Footwear Insulation and Evaporative Resistance. *Strojniški vestnik – Journal of Mechanical Engineering* **2008**, *54*, 628-638.
9. Kuklane, K.; Holmér, I. Effect of Sweating on Insulation of Footwear. *International Journal Of Occupational Safety And Ergonomics* **1998**, *4*, 123-136. DOI: https://doi.org/10.1080/10803548.1998.11076385.
10. Smith, C.J.; Machado - Moreira, C.A.; Plant, G.; Hodder, S.; Havenith, G.; Taylor, N.A.S. Design Data For Footwear: Sweating Distribution On The Human Foot. *International Journal of Clothing Science and Technology* **2013**, *5*, 43-58. DOI: https://doi.org/10.1108/09556221311292200.
11. Puszkarz, A.K.; Usupov, A. The Study of Footwear Thermal Insulation Using Thermography and the Finite Volume Method. *International Journal of Thermophysics* **2019**, *40*, 45. DOI: https://doi.org/10.1007/s10765-019-2509-1.
12. Heus, R.; Schols, E.; Kistemaker, L. Frostbite in Ski Boots for Marines. *Prevention of Cold Injuries* **2005**, *7*, 1-8.
13. Bogerd, C.P.; Brühwiler, P.A.; Rossi, R.A. Heat Loss and Moisture Retention Variations of Boot Membranes and Sock Fabrics: A Foot Manikin Study. *International Journal of Industrial Ergonomics* **2012**, *42*, 212-218. DOI: https://doi.org/10.1016/j.ergon.2012.01.001.
14. Kalev Kuklane; Ingvar, H.; Giesbrecht, G. Change in Footwear Insulation at Various Sweating Rates. *Appl. Human Sci.* **1999**, *18*, 161-168. DOI: https://doi.org/10.2114/jpa.18.161.