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Thermal behaviour of ski-boot liners: effect of materials on thermal comfort in real and simulated skiing conditions.

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Abstract

The choice of the appropriate material for the construction of ski-boot liners is of fundamental importance in order to achieve ergonomic comfort and high thermal insulation. In this work the effect on thermal comfort of different materials used for commercial ski-boot liners has been analysed. The thermal insulation and the moisture management of liners made of different materials have been tested both in a climatic chamber and in outdoor conditions using wireless sensors combined with infrared thermography. The results obtained show substantial differences in terms of thermal comfort between the liners in the same environmental conditions, showing that closed cell ethylene vinyl acetate foams provide the best thermal comfort.

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Keywords: thermal insulation; ski-boots; polymeric foams; thermography; moisture management.

1. Introduction

Footwear thermal insulation is one of the most important factors for a proper protection against cold. Since hands and feet have a large surface area compared to their volume and a small muscle mass, they both tend to be much more sensitive to cold exposure with respect to other parts of the human body (Kuklane, 2009). It has also been reported (Kuklane, 2009) that the feeling of cold discomfort into the feet will dominate even if clothes with proper insulation are used on the rest of the body. The feet are comfortable when the skin temperature is about 33°C and the relative humidity next to the skin is about 60% (Oakley, 1984). The feeling of cold starts at temperatures around 25°C, while discomfort from cold is noted at temperatures below 20-21°C (Kuklane, 2009).

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It is well known how garments can affect performances in sport activities with stressful weather conditions (Pezzoli et al, 2012). The possibility to study, directly on the athlete, the benefits of a particular garment represents a new frontier in applied research in sport. Alpine skiing is performed in some of the coldest and harshest outdoor conditions of all sports and the effect of the external environment in terms of cold is therefore significant. Long exposures to cold temperatures are often the norm, since the best conditions are present at temperatures below 0°C. Kuklane (2009) has reported that, with the right amount of insulation, it is possible to keep the feet into the range of comfort and to avoid frostbite. The behaviour of ski-boots from a thermodynamic point of view is characterised by the heat transfer from the feet to the liner, which in turn interacts with the outer plastic shell and so with the environment. Inside the liner the heat transfer is ruled by the heat flow from the foot to the liner, by conduction and convection (Strijk et al, 2010). Since the factors that are responsible of heat transfer are function of the temperature gradient that is present between the foot and the environment, a significant decrease of foot temperature, due to the large temperature gradient, can be expected. Kuklane (2009) has reported that the insulation properties of shoes and boots are directly proportional to the amount of air trapped inside the fabric and between the foot and the shoe indicating that convection has a negative effect on heat insulation of boots. Another critical element among the characteristics of a boot is its ability to expel moisture from the inside to the outside. Recently, Hofer et al (2013) have measured the temperature and humidity inside a ski-boot liner during simulated and real skiing actions. They have concluded that the toe area is the most exposed to cooling. They have also found that ambient temperature and moisture inside the ski-boot strongly affect foot temperature and that a high water content in socks and liners reduces the thermal insulation properties. Moncalero et al (2013) have performed a pilot study, using wireless sensors, for the measure of temperature and humidity in outdoor conditions and concluded that different liners have different thermal insulation behaviours. However, in all previous studies the results have not been correlated with the composition of the liners. Moreover, a study of the temperature in the different points of the foot performed by thermo-graphic analysis was not performed. For these reasons, in this paper we present the results of a study conducted both in climatic chamber and in outdoor environment, using wireless sensors and thermo-graphic images, correlating the results obtained with the chemical and physical characteristics of the liners.

2. Materials and methods

Fourier Transform Infrared Analysis (FTIR) was performed directly on the liners using a Perkin Elmer Spectrum One instrument equipped with an Attenuated Total Reflectance (ATR) detector. Scanning Electron Microscopy (SEM) was performed with a JEOL JEM 2010 instrument in order to determine the cell morphology of the foams. The micrographs have been taken on fracture zones after cryogenic cut. Temperature and humidity tests have been performed by placing wireless sensors (Hygrochron - Maxim-Dallas) (Fig. 1) to record temperature and relative humidity inside the liner. The sensors did not interfere with the skiing action or caused pressures on skier's feet. Each boot was equipped with one sensor placed on the inner-sole (Fig. 1). All sensors have been placed in the toe area, considering this as the most critical part (Hofer et al, 2013). Proper slots have been obtained by removing small amounts of material from the liner inner-sole. The most sensitive part of the sensor has been directed towards the foot. The relative humidity resolution of the sensor is 0.04% while the temperature resolution is 0.0625°C working with 12-Bit and with a sensor sampling rate of 30 seconds.

Fig. 1. Sensor shape and size [mm] and position of the sensors on the liner sole.

Two testers have been used both in climatic chamber and in outdoor tests:

- Tester 1 (T1), male, 43 years old, 85 kg, ski-boot size 28,5 Mondopoint expert skier.
- Tester 2 (T2), male, 36 years old, 75 kg, ski-boot size 28,5 Mondopoint expert skier.

The ski-boot model used in all tests has been the Lupo from Calzaturificio Dalbello (size 28.5 Mondopoint). Three commercial liners with the same construction and thickness, made of different materials, have been tested (Fig. 2). During the measurements the testers wore the same type of socks (Dalbello ID socks - 95% of polypropylene fibres and 5% Elastane) and clothes they normally use in cold winter skiing conditions. This set-up has been kept constant both in indoor and outdoor tests.

Fig. 2. Liners used in this work. From left to right: liner 1, liner 2, liner 3

The ski-boots have been thermo-stated to 15°C before starting the indoor tests. The testers have performed 60 minutes of simulated skiing, with a continuous alternation of 5 minutes of flywheel half squat (YoYo Squat - YoYo Technology AB) and 5 minutes of rest in a climate chamber (Albafrigor srl) set to -10°C and with a relative humidity of 60%. At the beginning of each session (T0) and after 60 minutes (T60) the skin temperature maps of the feet were acquired by an infrared thermo-camera (NEC R300 - NEC Avio Infrared Technologies Co, Ltd., with a temperature resolution of 0.03°C). To describe the temperature in the different foot regions (tiptoe (Tt), instep (Ti), heel (Th), external (Te) and medial (Tm)) the punctual temperatures, collected as show in Fig. 3, have been averaged (Tt=(D1+D2+D3+L1+L2+L3+M2+S2+S2+S3)/10, Ti=(D4+D5+L4+L6+M2+M4+S4+S5)/8, Th=(L5+M3+S6)/3, Te=(D3+D5+L3+L4+L5+S3+S5)/7, Tm=(D1+D4+L1+M1+M2+M3+S1)/7). Every tester tested each liner at least two times. One test a day was performed, starting at 10.00 AM.

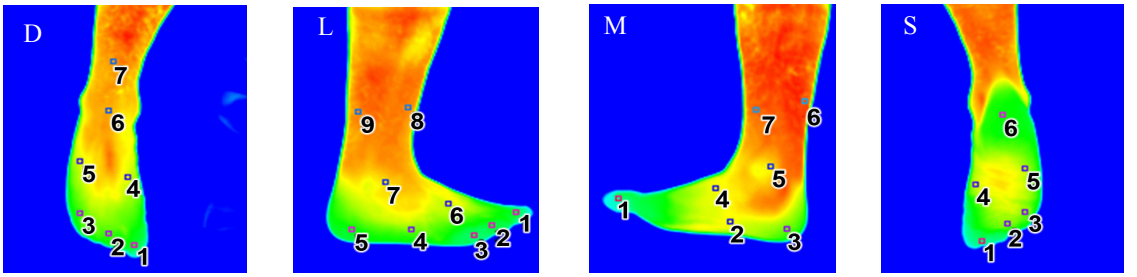

Fig. 3. Dorsal (D), lateral (L), medial (M) and sole (S) thermo camera view with punctual temperature collection

Outdoor tests have been carried out preforming standard recreational skiing sessions. Data has been recorded in continuous for 2 hours for each session. All tests have been performed in Val Senales (BZ, Italy) (Top: 3300 m; Bottom: 2000 m). A portable weather station (GEOS 11, Skywatch) has been used in outdoor tests to validate the results and measure the environmental conditions during each session. An additional on-board sensor (Hygrochron - Maxim-Dallas) was used to measure air temperature and relative humidity outside the ski-boots for all the duration of the test. The sensor has been installed outside the skier's jacket and, comparing its output with the data from the weather station, it has been verified that the body heating did not affect its records. Each on-snow test session has been performed by comparing simultaneously two liners made of different materials for each tester.

3. Results and discussion

The chemical composition of the 3 liners was analysed by FTIR analysis. The comparison with a database of polymeric foams permits to determine that the liners have the following compositions:

- Liner 1: cross-linked ethylene vinyl acetate (EVA) with 14% of vinyl acetate.
- Liner 2: sandwich made of a polyethylene (PE) based elastomer (external part) and EVA (internal part).
- Liner 3: sandwich made of polyvinyl chloride (PVC) (external part) and EVA (internal part).

Liner 2 and 3 also have an extra insulation in the front part made of Thinsulate, that is a mixture of non-woven fabrics made of PE (65%) and polyester (35%). The materials differ not only for the chemical composition, but also for the cell morphology, as evidenced by the SEM micrographs in Fig. 4. In particular, liner 1 is composed completely of EVA foam with a closed cell morphology with cell dimensions below 200µm and a wall thickness of 2-5µm. On the contrary the EVA material used for liners 2 and 3 presents a cell morphology with open and closed cells with a larger dimension up to 1 mm. Cracks and porosities are also present in the cell walls. The PE (liner 2) and PVC (liner 3) materials are both compact materials without the presence of gas cells.

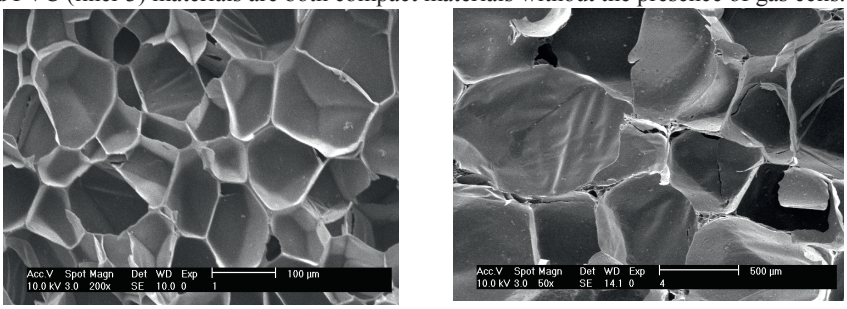

Fig. 4. SEM micrographs of the EVA materials used for the liner1 (left at 200x) and liners 2 and 3 (right at 50x).

According to Moncalero et al. (2013), the feet temperature and relative humidity with the same boot setup on both feet, showed minor differences (below 0.5°C) between left and right feet of the same skier in the same environmental conditions. For this reason, it has been assumed that the difference in terms of temperature and relative humidity between the two feet are negligible compared to those due to the effect of the liners.

The reproducibility of the method has been tested in a climatic chamber, comparing the same foot/liner setup in two different days, obtaining a good reproducibility (Fig. 5 (a)). As an example, in Fig. 5b the temperatures inside two different liners tested by the same tester in the same testing day are shown. A clear difference in term of thermal insulation of the liners can been observed; in particular, liner 1 not only has higher temperature values but its steady trend is very different if compared to that of liner 2, which is constantly decreasing. The average temperature difference (Average ΔT) between the beginning and the end of the tests (60 minutes) is reported in Table 1 along with the average ΔT measured by the thermo-camera in the toe area (were the sensor was installed) and the average relative humidity measured inside the liner (RH).

Table 1. Average sensors ΔT, average thermo-camera ΔT in the toe area and average relative humidity (RH).

Liner	Average ΔT Sensors [°C]	Average ΔT Thermo-camera (toe) [°C]	Average RH [%]	Average time to 80% RH [min]	Max RH [%]	Average time to max RH [min]
Liner 1	2.99 ± 1.10	1.94 ± 1.72	92.94 ± 2.15	3.00 ± 1.3	100.17 ± 0.56	57.2 ± 0.7
Liner 2	4.16 ± 1.11	4.61 ± 1.40	94.37 ± 2.27	2.88 ± 1.5	100.57 ± 0.72	54.2 ± 3.3
Liner 3	4.55 ± 1.34	5.70 ± 1.98	96.84 ± 2,49	1.00 ± 1.6	101.42 ± 0.58	57.0 ± 2.9

The results in Table 2 show the same temperature trend for the data acquired by the thermo-camera and by the sensor, indicating that liner 1 has a more efficient thermal insulation, followed by liner 2 and 3. The relative humidity reached the saturation limit for all liners before the end of the tests. No significant difference was observed among the three liners in the time needed to reach the maximum RH and 80% RH, indicating that all the liners tested are not able to manage the humidity exchange, at least in the part where the sensor is positioned (toe area).

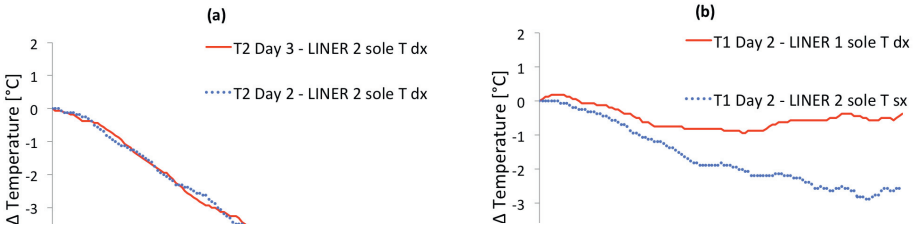

Fig. 5: a) reproducibility of the method (Tester 2 with the same liner in the same foot in two different days); b) comparison between liner 1 and liner 2 for tester 1 in the second day of tests.

Table 2. Average thermo-camera ΔT between the beginning and the finish of the test, for each part of the foot.

Part of the foot	Average initial Thermo-camera temperature [°C]	ΔT Thermo-camera [°C] LINER 1	ΔT Thermo-camera [°C] LINER 2	ΔT Thermo-camera [°C] LINER 3
Toe (Tt)	18.42 ± 2.25	1.94 ± 1.72	4.61 ± 1.40	5.70 ± 1.98
Instep (Ti)	26.31 ± 1.40	1.12 ± 2.61	2.21 ± 0.90	4.13 ± 0.87
Heel (Th)	19.99 ± 2.81	0.38 ± 2.30	3.33 ± 0.53	5.72 ± 0.09
External (Te)	20.98 ± 2.66	0.63 ± 4.01	3.38 ± 0.02	6.18 ± 1.73
Medial (Tm)	20.05 ± 2.16	1.21 ± 2.04	3.69 ± 0.77	5.11 ± 4.24

The thermo-graphic images (Fig. 6) show that the toe area is the coldest in agreement with the results previously reported in the literature (Hofer et al, 2013). The results reported in Table 2 show that the best insulation properties in the entire foot are observed for liner 1, in agreement with the results of the sensors.

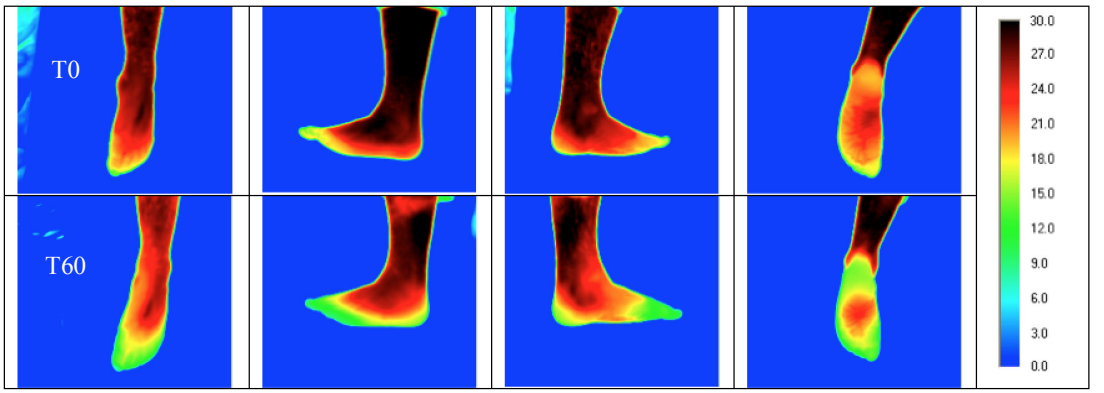

Fig. 6. Thermo-graphic camera images at T0 and T60 for liner 1, tester 1, second day of test.

For the on-snow tests it is not possible to average the data obtained in different testing sessions since the environmental conditions can be significantly different. Therefore, only comparative tests on two different liners used simultaneously by the same tester can be used to determine the thermal comfort of the liners. The results obtained (Table 3) show that liner 1 always had a more insulating behaviour compared to liner 3 and therefore the results of on-snow tests are in agreement with those obtained in the climatic chamber. The difference between the liners was more consistent in the coldest testing day (Test 1). In the warmest testing day, an increase in the final temperature using liner 1 was observed, indicating that the insulating behaviour of the material used for liner 1 can produce overheating in the liner in warm skiing conditions. No significant differences in humidity inside the liners have been observed also in this case, in agreement with the tests conducted in the climatic chamber.

Table 3. Temperature and humidity measured during two sessions of on-snow tests.

Liner	Average environmental T [°C]	ΔT Sensors [°C]	Average environmental RH [%]	Average Sensors RH [%]
Liner 1 Test 1	-4.65 ± 1.94	2.51	53.73 ± 5.61	101.45 ± 1.95
Liner 3 Test 1		7.53		99.53 ± 6.32
Liner 1 Test 2	0.95 ± 2.75	-0,50	68.75 ± 9.20	96.22 ± 4.54
Liner 3 Test 2		2,09		96.95 ± 3.63

4. Conclusions

Different materials used for the construction of ski-boot liners have been tested in order to determine their insulating behaviour and their moisture management. The tests have been conducted both in simulated indoor conditions and in outdoor skiing action. The results obtained using the thermo-camera and the wireless sensors are in good agreement, showing the same trends both in simulated indoor skiing and in outdoor real skiing action. The highest insulating behaviour of liner 1 can be explained on the bases of the morphology of the cells, since closed cells EVA has a more insulating behaviour with respect to the EVA material used for liners 2 and 3 that presents larger cells and cracks in the cell walls. The presence of the cracks and porosities in the cell walls permits the air movement inside the liner and allows moisture to fill up these spaces (Kuklane, 2009) therefore decreasing the thermal insulation. The chemical composition of the outer part of the liner (PE and PVC) seems not to have a fundamental effect on thermal insulation. On the basis of the thermo-graphic data and of the insulating behaviour of the materials it is possible to predict that new generations of liners should have the front part made of closed cell EVA foams since this material has the best insulating properties and the most cold parts are the front and the lower lateral sections of the foot. It is also important to optimize the insulation of the sole.

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