Frostbite in Ski Boots for Marines

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ABSTRACT

Previous research have showed that cold injuries of feet occur more often than cold injuries of hands. Recently, an unexpectedly large number of cold injuries were observed during military training in Norway and a relationship between cold injuries and the use of the Alico ski boot was suspected. The Marine Corps and the Defence Clothing agency asked TNO to investigate whether the Alico ski boot, in combination with the Berghaus gaiter, and the arctic sock would lead to an increased risk for cold injuries.

*Tests with several ski boot combinations were performed to measure the water vapour transport and the water tightness. Both worn and unworn ski boots were tested with and without a gaiter. The results were compared with the results of the Meindl climbing boot. The water vapour transport was measured using a thermal sweating foot model which was placed in a boot combination during three days for a couple of hours (indicate a more precise duration) a day. The water tightness was measured using a walking simulator where boots walked in a water tank. Both worn ski and climbing boots were tested by 8 marines in a climatic chamber of -18ºC. The subjects rested on a chair in the climatic chamber for the first half hour, walked on a treadmill for the second half hour and stood still for the last half hour. Several skin temperatures (**indicate the number of sites**) of the feet were measured. The subjects also provided regular information about their thermal sensations and comfort.*

A worn ski boot has higher water vapour absorption and lower water vapour transmission than an unworn ski boot. During water evaporation periods about half of the water absorption evaporated from both worn and unworn boots. Wearing a gaiter with the ski boot gives a lower water vapour transmission and a higher resistance to heat. The ski boots have higher water vapour absorption, a slightly lower water vapour desorption and a slightly lower water vapour transmission than the climbing boot. None of the tested boots are waterproof. More water leaks in a worn ski boot than in an unworn ski boot. The climbing boot gives the best results on water tightness. No significant differences were found between the different kind of boot combinations concerning temperature and comfort and thermal sensations.

Worn ski boots absorb more sweat and evaporate less sweat than unworn ski boots. By wearing a gaiter even less sweat can evaporate. The ski boots are not waterproof and water leaks in faster when shoes are worn. The climbing boots are not waterproof either, but water leaks in slower and the feet stay dry for longer periods. The boot combinations give equal temperatures and temperature decreases or increases. Also the comfort and thermal sensations are equal. The greatest problem is the ski boot not being waterproof which gives more leaking in of water and a faster cooling down of the feet. This could lead to earlier development of cold injuries.

1.0 INTRODUCTION

Marines suffer frequently from cold injuries during operations in arctic areas. Especially fingers and toes demonstrate frostbite injuries. Research in 2001 and 2002 (Daanen and Kistemaker, 2002) in the North of

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Norway showed a higher incidence of frostbite on the toes compared with fingers. This was starting point for an inventory (Van der Struijs, 2003) to examine the amount and indicators of cold injuries. A relation between the newly introduced ski boot (Alico) and the increased risk of cold injuries was suspected.

Therefore, the Dutch Marines initiated an inventory together with the TNO Logistic department to answer the following questions:

"Does a combination of the Alico ski boot and the Berghaus gaiter together with the use of an arctic sock increase the risk of cold injuries?" This study was carried out in two phases. In the first phase the product combination was tested with regards to thermal comfort, manifested by insulation measurements, water vapour transport and water tightness of the combination. In the second phase the combination was tested in a climatic chamber on a Marines specific drill (Figure 1).

Figure 1: Test drill on a treadmill in a climatic chamber at -18°C.

2.0 MATERIALS AND METHODS

The measurements were done with the following six foot protection combination:

- The Alico ski boot (new) with Berghaus gaiter and arctic sock (**combination 1**).
- The Alico ski boot (used) with Berghaus gaiter and arctic sock (combination 1a).
- The Alico ski boot (new), without the gaiter and arctic sock (**combination 2**).
- The Alico ski boot (used), without the gaiter and arctic sock (combination 2a).
- The Meindl Venediger hiking shoe with the arctic sock (**combination 3**).
- The combat boot M90 with arctic sock (combination 4).

2.1 Water Vapour Transport and Water Tightness

With the WSCR-method (whole shoe comfort rate), a thermal sweating foot model (Figure 2) (W8080 2002; Schols et.al. 2004), you can determine the water vapour transport and heat resistance as important parameters for thermal comfort.

On three subsequent days one shoe (no gaiter or sock were used) was tested in a climatic chamber of 5°C. The duration of the measurements was 8 hours and the following 16 hour period was used as a post conditioning period during which the shoe can evaporate the moisture to the environment. This means that all shoes were tested within a period of 18 days.

The following values were determined:

- WVA: Water vapour absorption (g); the amount of water vapour absorbed by the shoe during an 8 hours period.
- WVD: Water vapour desorption (%); the percentage of the water vapour take-up that is evaporated during the 16 hours period.
- WVP: Water vapour permeability ($g \cdot h^{-1}$).
- R: Heat resistance ($m^2 \cdot K \cdot W^{-1}$).

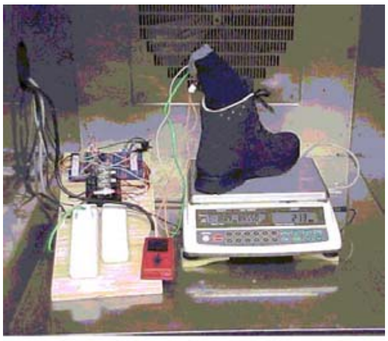

Figure 2: Hiking shoe with thermal sweating foot.

With the Geh-simulator (W8058), a walking simulator in a water tank (Figure 3), water tightness was determined of the five shoes (the M90 was not measured). During 8 hours all shoes were tested (17000 cycles). Two water levels were used:

- Just to the lasting margin, water level 3cm.
- Just above rubber edge, water level 5.5cm.

The hiking shoe was not measured at the high water level.

Figure 3: Geh-simulator.

2.2 Climatic Chamber Tests

Combination 1, 2 and 3 were tested in a -18°C climatic chamber with 8 Marines participating as test subjects. All tests were carried out with worn in boots. After an acclimatisation period of 30 minutes sitting on a chair, all subjects walked for 30 minutes on a treadmill with a speed of $5m \bullet s^{-1}$. After this a period of 30 minutes of guarding was simulated. Each subject underwent three sessions a day with a recovery phase of 75 minutes in a 25°C climate.

The following measurements were carried out:

- Temperatures on little toe, big toe, middle on the foot, middle under the foot, ankle.
- Subjective sensations of comfort and temperature of foot and whole body using a 9-point confort scale ranging from 0 (comfortable) to 8 (extremely unconfortable) and a 19-point temperature sensation scale ranging from –9 to +9 (–8 was very cold and +8 was very hot).
- Weight increase in socks (g).

To avoid cold injuries, the criteria for terminating the experiments were set at a foot temperature of 5°C. The results were tested with an Anova (Statistica 6.1, Statsoft). Significance was set at $p \leq 0.05$.

3.0 RESULTS

3.1 Water Vapour Transport and Water Tightness

In table I the results of the measurements of the water vapour transport are given.

Table I: Averaged scores for WVA (absorption), WVD (desorption), WVP (permeability) and R (heat resistance).

Boot	WVA [$g \bullet 8h^{-1}$]	WVD [$\% \bullet 16h^{-1}$]	WVP [$g \bullet h^{-1}$]	R [$m^2 \bullet K \bullet W^{-1}$]
Ski boot with gaiter, new	20	33	2.1	0.28
Ski boot with gaiter, used	35	40	1.9	0.29
Ski boot without gaiter, new	19	56	2.5	0.25
Ski boot without gaiter, used	28	41	2.3	0.26
Hiking shoe, new	16	60	2.6	0.23
M90 combat boot, new	40	46	1.6	0.21

In table II the results are given of the water tightness test. The results of the water absorption of the boots are given after the amount of water into the shoe was poured out.

Table II: Results of the water tightness with the Geh-simulator.

Ski boot without gaiter, test 1: Water just above lasting margin		
Cycles	**New boot**	**Used boot**
3360	Dry	water in the boot, test stopped
6260	Dry	
17270	water in the boot	
Water absorption	3.1%	9.6%
Ski boot without gaiter, test 2: Water just above rubber edge		
Cycles	**New boot**	**Used boot**
2260	Dry	feels wet
4375	Dry	water in the boot, test stopped
8500	Humid	
16600	water in the boot	
Water absorption	5.0%	8.5%
Hiking shoe water just above lasting margin		
Cycles	**New shoe**	
2380	Dry	
4750	Dry	
9500	humid, innersole	
16900	humid, innersole and liner	
Water absorption	4.3%	

3.2 Climatic Chamber Tests

During the acclimatisation period, the marching period, as well as the guarding period of 30 minutes none of the subjects showed significant differences in toe and or feet temperatures for the different foot protection combinations (Figure 4).

In the figures can be seen that the average temperatures of combination 1 are overall higher than the other combinations, but again this is not a significant result.

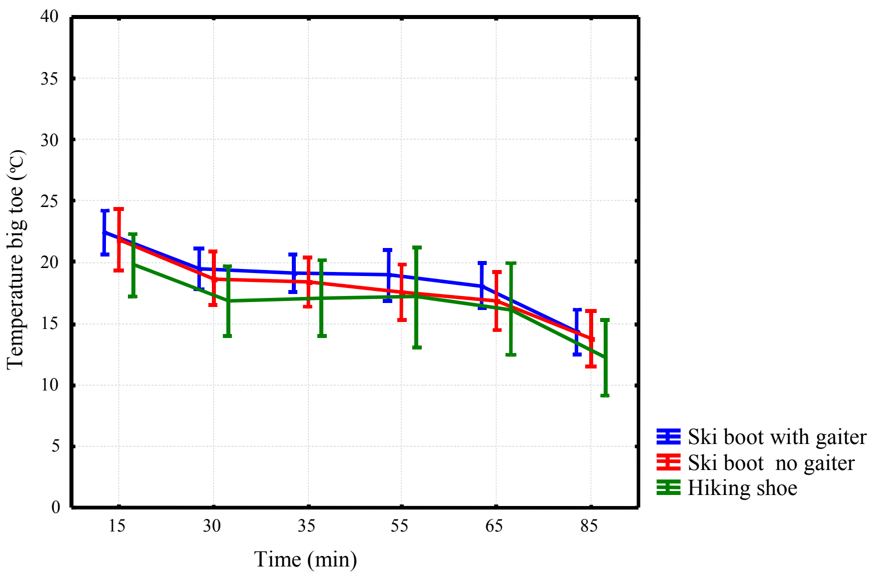

Figure 4: Average temperature of the big toe of all subjects in time.

One of the subjects had to finish one of the sessions of the experiment after 65 minutes due to a little toe temperature below 5ºC.

In table III all measured subjective sensations are given.

Table III: Average scores for perceived comfort- and temperature sensations.

	0 min.	15 min.	30 min.	45 min.	60 min.	75 min.	90 min.
Perceived Foot-comfort							
Ski boot with gaiter	0.4	0.5	0.9	0.5	0.5	1.3	1.5
Ski boot without gaiter	0.4	0.5	0.6	0.4	0.9	1.8	1.9
Hiking shoe	0.0	0.4	1.0	0.8	1.0	1.4	1.7
Perceived Body-comfort							
Ski boot with gaiter	0.4	0.4	0.8	0.5	0.6	1.1	1.1
Ski boot without gaiter	0.4	0.3	0.5	0.3	0.8	0.9	1.1
Hiking shoe	0.1	0.4	0.8	0.6	0.4	0.7	1.0
Perceived Foot-Temperature							
Ski boot with gaiter	1.4	1.0	0.1	0.9	0.5	-1.8	-2.3
Ski boot without gaiter	1.0	0.3	0.0	-0.3	-0.6	-2.1	-2.5
Hiking shoe	1.6	0.3	-0.4	-0.4	-0.5	-1.9	-2.7
Perceived Body-Temperature							
Ski boot with gaiter	1.5	1.0	0.3	0.9	1.0	-0.4	-0.6
Ski boot without gaiter	1.0	0.4	0.3	0.6	0.0	-0.6	-0.6
Hiking shoe	1.6	0.6	0.3	0.0	0.5	0.3	-0.3

4.0 DISCUSSION

Compared to the M90 combat boot, the ski boots have lower water vapour take-up, higher water vapour permeability and larger heat resistance. The used ski boots show higher water vapour take-up and lower water vapour permeability compared to the new ski boots. The heat resistance hardly varies between the boots. The water vapour desorption is an important parameter because in the course of a few days, a lot of water vapour can be taken up by the shoe. Applying the gaiter in the test demonstrates only minor differences, due to the fact that the test set-up makes it impossible to close the gaiter completely. The hiking shoes have lower water vapour take-up and higher water vapour permeability than the ski boot.

When testing the water tightness, the ski boot fails in both new and used conditions. It can not exactly be assessed where the water penetrates the shoe, but it can be expected that the construction of the boot causes a small slit between the sole and the upper in the ball-region. The hiking shoe, although not completely watertight, gives a much better score on this aspect.

The skin temperatures in shoe combination 1 (shoe with gaiter) are slightly higher than in the other shoe combinations. This is in line with the measured heat resistance. The differences are not significant, however. For all combinations tested, the feet feel ‘uncomfortable’, ‘cool’ to ‘cold’ at the end of the experiment. Again, no significant differences were found for perceived temperature and comfort-scores. The socks during the experiments took up hardly any moisture. This could possibly be due to the fact that the test period was too short or the workload was too low in order to get the feet sweating.

An important difference between the climatic chamber tests and use of boots in the field is that the subjects walked on a dry surface. In the field walking on snow or ice occurs frequently.

The test demonstrates that water vapour take-up is considerable, meaning that the shoes can get very damp or wet after a few days of consecutive use. The lack of water tightness provides another way for the shoes of getting wet. This means that in actual use, the shoes may get wet, giving a much lower heat resistance. This could possibly lead to an increased risk on frostbites.

5.0 CONCLUSIONS AND RECOMMENDATIONS

Used ski boots have a higher water vapour take-up and lower water vapour permeability than new boots. The heat resistance of the used ski boots remains the same. Wearing a gaiter reduces the water vapour permeability and increases the heat resistance. In a situation where the boots are worn for 8 hours and taken off for 16 hours, about 50 % of the water vapour taken up by the shoe can still be observed. The hiking shoe has a lower water vapour take-up and higher water vapour permeability and thus will keep the feet dryer.

The ski boots, new and used, are not watertight. Walking for a longer period will reduce the water tightness. The test does not show the exact place where the water enters the shoe. The construction of the shoe makes it likely that water enters between the sole and the upper in the ball region. When walking, this region is repeatedly bent and this creates a small slit giving a passage to the water. The hiking shoe is not 100% watertight but scores much better in this aspect.

The three shoe combinations tested in the climatic chamber, give no significant differences in temperatures, temperature-rise or –drop under the test conditions. No differences were found between the shoe combinations when used at -18ºC without wind, starting with a 30 minutes rest, followed by 30 minutes of walking with a speed of 5 m/s, again followed by 30 minutes of guarding. However, especially during low activity levels there is an increase in the risk of cold injuries reflected by the drop in toe temperatures at the end of the experiment.

Also the perceived temperature and comfort give no differences for the different shoe combinations.

Because the ski boots are not watertight and take up water sooner than the hiking shoes, the feet will decrease in temperature quicker and frostbite may appear earlier compared with wearing the dryer hiking boots.

It is advised to find a solution for the water tightness-issue of the ski boots or to buy a new type of watertight, but water vapour permeable boots and to retest used boots regularly.

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