U.S. Army Research Institute of Environmental Medicine

Natick, Massachusetts

TECHNICAL REPORT NO. T22-13
DATE July 2022

THERMAL MANIKIN AND THERMOREGULATORY MODELING EVALUATION OF FOOTWEAR SYSTEMS USING STANDARD TEST METHODS AND EMERGING WET FOOTWEAR TEST METHODS

United States Army
Medical Research & Development Command

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USARIEM TECHNICAL REPORT T22-13

THERMAL MANIKIN AND THERMOREGULATORY MODELING EVALUATION OF FOOTWEAR SYSTEMS USING STANDARD TEST METHODS AND EMERGING WET FOOTWEAR TEST METHODS

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July 2022

U.S. Army Research Institute of Environmental Medicine
Natick, MA 01760-5007

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*
07-20-2022

2. REPORT TYPE
Technical Report

3. DATES COVERED *(From - To)*
2021-2022

4. TITLE AND SUBTITLE
THERMAL MANIKIN AND THERMOREGULATORY MODELING EVALUATION OF FOOTWEAR SYSTEMS USING STANDARD TEST METHODS AND EMERGING WET FOOTWEAR TEST METHODS

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

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8. PERFORMING ORGANIZATION REPORT NUMBER
T22-13

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Medical Research and Development Command,
Fort Detrick, MD 21702

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
This report focuses on the biophysical evaluation of footwear through the use of standard thermal manikin testing methods and a new method that evaluates wet footwear. The Six Cylinder Thermoregulatory Model (SCTM) was used to determine foot endurance time, which is the amount of time Soldiers are able to function before a cold injury is likely to occur. The SCTM predicted foot endurance time of five dry footwear configurations to be between 34 and 49 minutes with the subject at rest, and between 43 and 99 minutes with the subject working at a total metabolic rate of 250 W. The predicted foot endurance time for two wet footwear configurations is between 28 and 36 minutes for a subject at rest and between 34 and 48 minutes for a subject working at a total metabolic rate of 250 W. The simulated air temperature was -51°C. The "wet thermal resistance" results showed between 7% and 22% decrease from the dry footwear thermal resistance. Water saturation in the footwear decreased thermal resistance and endurance times by approximately 5 minutes.

15. SUBJECT TERMS
Footwear; Thermal Manikin; Insulation; Wet Clothing; Cold weather; Biophysics; Heat transfer

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
Unclassified	Unclassified	Unclassified	Unclassified	20	Timothy P. Rioux
					19b. TELEPHONE NUMBER *(Include area code)* 508-206-2365

Reset

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ACKNOWLEDGMENTS

The authors extend a very special thank you to Russell Brill and Kossi Zonvide of WL Gore for performing thermal foot manikin experiments, particularly a new method with wet footwear, and providing data and documentation on the new methodologies. The authors also thank Chris Diaz from the Navy Clothing and Textile Research Facility for providing the wet boot data; James Filson III, Whitney Santee, and Lamar Palmer for providing testing samples; and Drs. Nisha Charkoudian and John Castellani for guidance and editorial comments.

EXECUTIVE SUMMARY

Introduction: During military cold weather operations, prevention of cold injury in the extremities is crucial to mission success and preventing casualties. This report focuses on the biophysical evaluation of footwear through the use of standard thermal manikin testing methods and a new method that evaluates wet footwear. The results of these evaluations are used as input to a thermoregulatory model that translates the footwear data into meaningful human outcomes, i.e., prediction time until cold injury in the foot. **Methods:** Thermal resistance and evaporative resistance measurements were completed for five footwear configurations using a sweating thermal foot manikin and following ASTM International standard test methods. The “wet thermal resistance” of two footwear configurations was also measured using a new method. Thermal resistance and evaporative resistance of full ensembles were calculated using previously collected clothing and equipment data along with the footwear data collected for this project. The Six Cylinder Thermoregulatory Model (SCTM) was used along with the clothing data input to determine the foot endurance time, which is the amount of time Soldiers are able to function before a cold injury is likely to occur. The analysis in this report was conducted for simulated environments with an air temperature of -60°F (-51°C) and various air velocities. **Results:** The intrinsic thermal resistance measurements of the five footwear configurations range from 0.84 to 1.02 clo in the toe region. The intrinsic evaporative resistance of the five footwear configurations range from 175 to 1121 $m^2{\cdot}Pa{\cdot}W^{-1}$ in the toe region. The “wet thermal resistance” of footwear testing results showed between 7% to 22% decrease from the dry footwear thermal resistance. The SCTM predicted foot endurance time of the five dry footwear configurations to be between 34 to 49 minutes with the subject at rest, and between 43 to 99 minutes with the subject working at a total metabolic rate of 250 W. The predicted foot endurance time for wet footwear configurations is between 28 to 36 minutes for a subject at rest and 34 to 48 minutes for a subject working at a total metabolic rate of 250 W. **Discussion:** Thermal resistance and evaporative resistance values vary within regions of the foot. Measurements from the toe region are used in this study for input to SCTM, due to cold injuries frequently occurring in this region first. The evaluation of wet footwear is a new method and discrepancies between laboratories still exist with more research needed to understand the cause of interlaboratory variation. The modeling results indicate that configurations including overboots provide the greatest environmental protection, and footwear configurations without overboots and saturated with water provide the lowest level of protection from cold injury. The analysis in this report focuses on the cold injury to the foot, but there are other factors to consider in extreme cold environments, such as cold injury to exposed skin and other health effects. **Conclusion:** The SCTM predicted foot endurance times at an air temperature of -51°C. The foot endurance times reduce as air velocity increases. Water saturation in the footwear decreased thermal resistance and endurance times by approximately 5 minutes.

INTRODUCTION

Prevention of cold injury to the extremities is one of the primary physiological concerns during military cold weather operations. Prolonged exposure to cold or cold-wet conditions may result in freezing or nonfreezing cold injury to the feet if footwear does not provide sufficient insulation or moisture protection. Field trials of military boots during cold exposure have indicated that toe skin temperatures fall rapidly, especially when subjects are at rest [1]. Since cold or pain sensations are usually associated with a specific foot region (often the heel, or more often the toes) during exposure to cold environments [2], it follows that toe temperature is an important parameter to measure or predict when evaluating the thermal protection provided by cold-weather footwear.

The development, validation, and refinement of biophysical testing and human thermoregulatory modeling processes are deeply ingrained into the history of the US Army Research Institute of Environmental Medicine (USARIEM). Currently, the typical biophysical testing and modeling cycle begins by using a sweating thermal manikin to collect measurements of thermal resistance and evaporative resistance (R_t and R_{et}) for clothing and individual equipment (CIE). Then, R_t and R_{et} measurements are used along with environment, anthropometry, and metabolic rate input parameters to run thermoregulatory models that provide quantifiable human outcomes. This biophysics and modeling method has been validated and used successfully for decades [3-11].

This report describes work that uses the standard thermal manikin and modeling paradigm to evaluate five cold-weather footwear configurations. Recently, a new method was developed jointly by the Navy Clothing and Textile Research Facility (NCTRF) and WL Gore & Associates, Inc. (Newark, DE, USA) to quantify the increased total heat loss in footwear due to water saturation. This report also describes a new approach of using data from the new wet footwear evaluation method and integrating the results with typical human thermoregulatory modeling to enhance footwear evaluations.

METHODS

MATERIALS

Five footwear configurations are examined in this study. The footwear configurations and items included in the configurations are coded with arbitrary numbers and letters. A matrix that breaks down the makeup of these configurations is shown in Figure 1. In Figure 1, the number associated with each ensemble configuration is listed in the top row, and individual items are listed in the leftmost column. Colored-in cells indicate that the item is included in the footwear configuration.

Figure 1. Matrix of items included in footwear configurations

	Footwear configuration number				
	1	2	3	4	5
Sock A	■	■	■	■	
Sock B					■
Boot A	■	■	■	■	
Boot B					■
Overboot A	■				
Overboot B		■			
Overboot C			■		

All five configurations were evaluated using standard test methods. Configurations 4 and 5 were also evaluated with the new wet footwear evaluation method outlined in this report. Pictures of the footwear configurations are shown in Figure 2 through Figure 6.

Figure 2. Footwear configuration 1

Figure 3. Footwear configuration 2

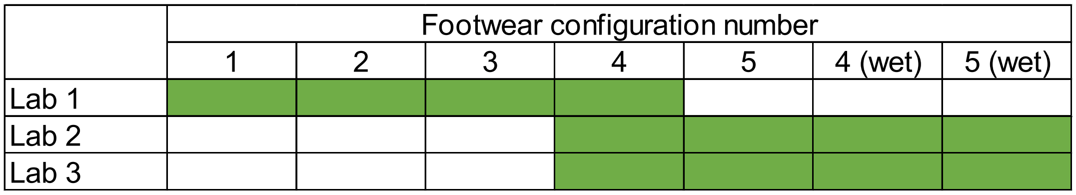
Figure 4. Footwear configuration 3

Figure 5. Footwear configuration 4

Figure 6. Footwear configuration 5

The biophysical testing was distributed between three separate laboratories. A breakdown of which laboratory performed each test is shown in Figure 7. In addition to standard testing, Configurations 4 and 5 were also tested using the new wet footwear method, which is indicated by the two right columns labeled “4 (wet)” and “5 (wet)”.

Figure 7. Matrix of laboratories performing experiments



Additional CIE data for a full clothing ensemble is required for thermoregulatory modeling input. In order to satisfy this clothing data requirement, previously collected biophysical properties for a heavy winter ensemble were used [12]. The clothing values were collected from the Generation III Extended Cold Weather Clothing System (Gen III ECWCS), the headwear was collected from a US Marine Corps (USMC) cold weather cap and balaclava, and the handwear was collected from the US Army Extreme Cold Weather Mitten Set. A full list of all garments included in the ensemble are shown in Table 1. Pictures of the ensemble components are shown in Figure 8 and Figure 9.

Table 1. List of clothing and equipment used for modeling

Clothing	Gen III ECWCS Lightweight Undershirt Gen III ECWCS Lightweight Drawers Gen III ECWCS Midweight Shirt Gen III ECWCS Midweight Drawers Gen III ECWCS Fleece Jacket Gen III ECWCS Soft Shell Jacket Gen III ECWCS Soft Shell Trouser Gen III ECWCS Extreme Cold Weather Parka Gen III ECWCS Extreme Cold Weather Trouser
Handwear	Extreme Cold Weather Mitten Set (insert, liner, and shell)
Headwear	Cold weather cap Balaclava

Figure 8. Headwear configuration used for modeling

Figure 9. Clothing configuration used for modeling (headwear and footwear tested separately)

BIOPHYSICAL EVALUATIONS

Standard methods

Thermal resistance and evaporative resistance measurements of five footwear configurations were collected on a sweating thermal foot manikin (Thermetrics, Seattle, Washington, USA) according to ASTM Standard Test Methods F3426-20, F1291-16 and F2370-16 [13-15]. Thermal resistance and evaporative resistance measurements for clothing, handwear, and headwear were collected previously on a whole-body manikin, thermal hand manikin, and thermal head manikin [12, 16].

Body part manikins such as the thermal head manikin, thermal hand manikin, and thermal foot manikin include partial neck, partial wrist, and partial leg sections, respectively. For data collected on head and hand manikins, resistances of the neck, and wrist zones were not included in the data used for modeling. The thermal foot data used for modeling is calculated from the parallel weighted average of the upper and lower toe zones [8]. USARIEM consistently uses this region of zone groupings because the toe section is the most vulnerable part of the foot and where a cold injury would likely occur first.

Thermal resistance and evaporative resistance values measured on a thermal manikin are values of total resistance (R_t, R_{et}). That is, the resistance of air in between the manikin surface and CIE, the resistance of CIE components, the resistance of air layers between additional layers of CIE, and the resistance of the boundary air layer that surrounds the CIE (R_a, R_{ea}). Intrinsic thermal resistance (R_{cl}) and intrinsic evaporative resistance (R_{ecl}) values differ from total resistance values by not including the boundary air layer that surrounds the CIE. The intrinsic resistances are calculated by Eq. 1 for thermal resistance and Eq. 2 for evaporative resistance:

$$R_{cl} = R_t - \left(\frac{R_a}{f_{cl}}\right) \quad \text{(Eq. 1)}$$

$$R_{ecl} = R_{et} - \left(\frac{R_{ea}}{f_{cl}}\right) \quad \text{(Eq. 2)}$$

where R_{cl}, R_t, and R_a may be in units of $m^2 \cdot °C \cdot W^{-1}$ or clo, with the caveat that the same units are used consistently throughout the calculation; R_{ecl}, R_{et}, and R_{ea} are in SI units of $m^2 \cdot Pa \cdot W^{-1}$; and f_{cl} is the dimensionless clothing area factor, which represents the increase of body surface area due to CIE worn on the body or manikin. When calculating intrinsic resistance values for this study, an f_{cl} of 1 was used. Using an f_{cl} of 1 and using data from the toe section of the thermal foot manikin will result in conservative prediction times from thermoregulatory modeling, i.e., the model will err on the side of predicting a cold injury early.

<u>Method for wet footwear test</u>

A new method of using a thermal foot manikin to measure the “wet thermal resistance” of a boot saturated with water was developed collaboratively by NCTRF and WL Gore. These experiments were completed using a thermal foot manikin and were designed and executed by both labs. A summary of the method is as follows:

1. Flex boots in a dry state for 100,000 cycles to simulate wear, using a SATRA (Kettering, North Northhamptonshire, United Kingdom) STM 505 Dynamic footwear water resistance tester.
2. Weigh dry boots and record measurement.
3. Place (3) 1255 ± 5 g weights in boot.
4. Mark the submersion water level at 75% of the height of the waterproof lining of the boot.

5. Submerge the boot in tap water to the pre-marked level for 45 minutes.
6. Remove boot from the water bath and allow excess water to drain from boot for 10 minutes. The inside of the boot should be dry. If inside of boot is wet, the procedure should be attempted again, either with the same boot after returning to dry weight or using a different boot sample.
7. Use a paper towel to wipe off any excess water from the exterior of the boot.
8. Weigh boot and record measurement.
9. Fit an anti–microbial boot sock (2.5% silver-plated nylon, 82% cotton, 10% nylon, 5.5% spandex) on the thermal foot manikin.
10. Fit a boot on the thermal foot manikin, which shall be enclosed in an environmental chamber.
11. Lace boot snug on foot manikin form.
12. Collect data for 2 hours with manikin surface temperature = 35°C, air temperature = 5°C, relative humidity = 65% RH, and air velocity = 0.4 $m \cdot s^{-1}$.
13. Record thermal resistance and heat flux value at 2 hours elapsed time.
14. Weigh boot immediately after test completion and record measurement.
15. Place boot on boot dryer until boot returns to initial weight.

THERMOREGULATORY MODELING

The Six Cylinder Thermoregulatory Model (SCTM) was used to simulate human thermal responses to cold while wearing different footwear configurations. SCTM is a rational model, and is based on principles of heat transfer and physiology [5, 6, 17]. The human body is divided into six regions representing the head, torso, arms, legs, hands, and feet. The model simulates the thermoregulatory actions of shivering heat production, vasodilation/vasoconstriction and sweat production. The model is validated for exposure to heat and cold (45°C to -40°C) and cold water immersion. Additionally, SCTM inputs include individual anthropometric characteristics, intensity of human activity, environmental conditions and clothing properties (i.e., thermal resistance and evaporative resistance) for each of the six body regions. Predicted outputs from SCTM include core temperatures and skin temperatures. In this project, the SCTM output was used to determine the foot endurance time. Foot endurance time is defined as the time until the skin temperature of the foot decreases to 5°C, at which point extreme pain and numbness are expected in the foot and the probability of cold injury increases significantly. Additional symptoms of loss of manual dexterity, pain and significant loss of manual performance, and intolerable pain, begin to occur as hands and feet skin temperature reach 20°C, 15°C, and 10°C respectively [18].

Simulations were run for five standard footwear configurations, two of which include wet footwear data. The model also was run to simulate exposed skin. The environmental conditions for SCTM were set to an air temperature (T_a) of -51°C (-60°F) and a relative humidity of 75% RH for all simulations. The simulations were run at four separate air velocities to demonstrate the effect on prediction times: 1 $m \cdot s^{-1}$, 7 $m \cdot s^{-1}$, 15 $m \cdot s^{-1}$, and 22 $m \cdot s^{-1}$ (2.2 mph, 15.7 mph, 33.6 mph, and 49.2 mph). For each of these environmental conditions, the model was also run at two metabolic rates: sedentary and light activity (250 W). The active simulations assume the activity is performed constantly at 250 W for the entire simulation time period. The anthropometric modeling input was based on a standard western male: 175 cm height, 83.5 kg mass, and 25% body fat.

The clothing input for SCTM requires clothing data in the form of intrinsic thermal resistance and intrinsic evaporative resistance for six regions (head, torso, arm, hand, leg, and foot). For the footwear data collected using standard test methods, the parallel weighted average of the upper and lower toe zones was calculated. Then, the intrinsic resistances were calculated using Equations 1 and 2. The data used for the other five regions (head, torso, arm, hand, and leg) were collected from previous thermal manikin measurements of cold-weather clothing and the intrinsic resistance values were calculated using Equations 1 and 2. All ensemble configurations used for modeling maintained the same clothing data for the head, torso, arm, hand, and leg regions, but changed the foot region value based on each footwear configuration.

RESULTS

BIOPHYSICS

The results of the thermal foot manikin testing in accordance with ASTM International standard test methods F3426-20, F1291-16 and F2370-16 are shown in Table 2. The results shown are intrinsic thermal resistance and intrinsic evaporative resistance, which is the required form for input into the SCTM. The toe is typically the section used for SCTM input, however the data for all thermal foot zones (including calf zones) and the foot section (excluding calf zones) are also shown in Table 2. The results presented for configurations 1 through 4 were from Lab 1 and the results presented for configuration 5 were from Lab 2. Evaporative resistance values were not collected for configuration 5.

Table 2. Intrinsic thermal resistance and evaporative resistance of five footwear configurations

Footwear Configuration	R_{cl} (clo)			R_{ecl} ($m^2 \cdot Pa \cdot W^{-1}$)		
	All Zones	Foot	Toe	All Zones	Foot	Toe
1	1.64	2.03	1.18	321.7	403.6	718.8
2	1.36	2.14	1.35	169.8	403.9	1120.7
3	1.44	2.07	1.34	142.1	257.3	665.4
4	0.76	1.37	0.84	45.19	92.66	174.5
5	0.74	1.11	1.02	-	-	-

The total thermal resistance of dry and wet footwear for configurations 4 and 5 at Lab 2 and Lab 3 are shown in Table 3. The dry configurations were tested according to standard test methods and the wet configurations were tested according to the wet footwear method outlined in the methods section. The “wet thermal resistance” values for configuration 4 and configuration 5 were recorded at 2 hours elapsed time of the test trial. The results are presented as total thermal resistance for direct comparison of the dry and wet boot methods. Additionally, the results are from the toe section (parallel average of upper toe zone and lower toe zone). It is worth noting that the combined toe sections of each thermal foot manikin are not equal. The foot manikin toe sections at Labs 1 and 2 have a surface area of 0.0072 m^2 and the foot manikin toe sections at Lab 3 have a surface area of 0.0092 m^2. For configuration 4 (wet), Lab 2 measured a 7% decrease in R_t relative to the dry boot, and Lab 3 measure a 22% decrease in R_t. For configuration 5 (wet), both Lab 2 and Lab 3 measured a decrease of 10% in R_t.

Table 3. Total thermal resistance of wet and dry configurations 4 and 5 at Labs 2 and 3

Footwear Configuration	Toe R_t (clo)	
	Lab 2	Lab 3
4	1.20	1.48
4 (wet)	1.11	1.15
5	1.39	1.66
5 (wet)	1.25	1.48

The R_{cl} and R_{ecl} input for the SCTM foot region are listed in Table 4. Since the wet footwear method produced varying results between Lab 2 and Lab 3, two separate values were used for each laboratory. Configuration 4 (wet) Lab 2 was calculated by decreasing the dry R_{cl} value by 7% and configuration 4 (wet) Lab 3 was calculated by decreasing the dry R_{cl} value by 22%. The R_{cl} and R_{ecl} input for the other five regions of SCTM are shown in Table 5.

Table 4. SCTM clothing property input for the foot region

Configuration	SCTM foot region input	
	R_{cl} (clo)	R_{ecl} ($m^2 \cdot Pa \cdot W^{-1}$)
1	1.18	718.8
2	1.35	1120.7
3	1.34	665.4
4	0.84	174.5
4 (wet) Lab 2	0.77	174.5
4 (wet) Lab 3	0.65	174.5
5	1.02	191.8
5 (wet)	0.92	191.8

Table 5. SCTM clothing property input for five body regions

Region	R_{cl} (clo)	R_{ecl} ($m^2 \cdot Pa \cdot W^{-1}$)
Head	0.66	12.54
Torso	7.52	238.9
Arm	4.41	124.0
Hand	2.28	150.0
Leg	4.06	139.7

PREDICTED HUMAN THERMAL RESPONSES

The results of the simulation at four air velocities (v_a) of 1 m·s^{-1}, 7 m·s^{-1}, 15 m·s^{-1}, and 22 m·s^{-1} for a subject at rest are shown in Table 6. The values presented are foot endurance times, with the exception of configuration ES (Exposed Skin), which is an endurance time of exposed skin anywhere on the body. It is worth noting that the ES prediction times were the same regardless of which footwear was selected.

Table 6. Endurance time (time to 5°C) of the foot at T_a = -51°C for sedentary condition and various air velocities

v_a (m·s^{-1})	Time (minutes)				
	Configuration				
	1	2	3	4	ES
1	44	49	48	34	13
7	37	42	42	28	7
15	35	40	40	26	6
22	35	39	39	25	5

The results of the simulation at four air velocities (1 m·s^{-1}, 7 m·s^{-1}, 15 m·s^{-1}, and 22 m·s^{-1}) for an active subject working at a constant rate of 250 W are shown in Table 7. The values presented are foot endurance times, with the exception of configuration ES (Exposed Skin), which is an endurance time of exposed skin anywhere on the body. Configuration ES was included in Table 6 and Table 7 for context and reference. If the skin is exposed in these extremely cold environmental conditions, a cold injury would occur in exposed areas prior to a cold injury in the foot, even when considering the decreased environmental protection of wet footwear.

Table 7. Endurance time of the foot at T_a = -51°C for active condition (250 W) and various air velocities

v_a (m·s^{-1})	Time (minutes)				
	Configuration				
	1	2	3	4	ES
1	70	99	96	43	14
7	50	63	62	32	8
15	46	58	57	30	6
22	45	56	55	29	5

Simulation results for configurations 4 and 5 with wet footwear are shown in Table 8. The results of configurations 4 and 5 with dry footwear are included in this table for convenience. As the wet footwear evaluation is a new method, some discrepancies are to be expected. Results from both labs are presented here to demonstrate the potential variability in simulation results due to differences in footwear data.

Configuration 5 (wet) had the same percent decrease in thermal resistance at both Lab 2 and Lab 3, therefore only a single value was used.

Table 8. Endurance time for dry and wet footwear configurations at T_a = -51°C and v_a = 1 m·s^{-1}

Configuration	Time (minutes)	
	Rest	Active, 250 W
4	34	43
4 (wet) Lab 2	32	39
4 (wet) Lab 3	28	34
5	39	55
5 (wet)	36	48

Foot skin temperature (T_s) vs. time plots for dry footwear are shown in Figure 10 and Figure 11. The horizontal red line at 5°C was added to visualize the foot endurance time, which occurs at the time when the foot skin temperature curves intersect with the red line. Figure 10 shows the results for a sedentary subject and Figure 11 shows results for a subject performing a light activity (250 W), such as walking on a hard surface at 1 m·s^{-1} with a 20 kg load. During the active simulations, it is assumed the work rate is constant, and therefore a 4 hour time limit is applied to the simulation. Configuration 2 and configuration 3 virtually have the same foot skin temperature prediction, therefore it may be difficult to differentiate between those two footwear configurations on the plots.

Figure 10. Simulated foot skin temperature for a sedentary subject at T_a = -51°C, 1 m·s^{-1} air velocity, with dry footwear

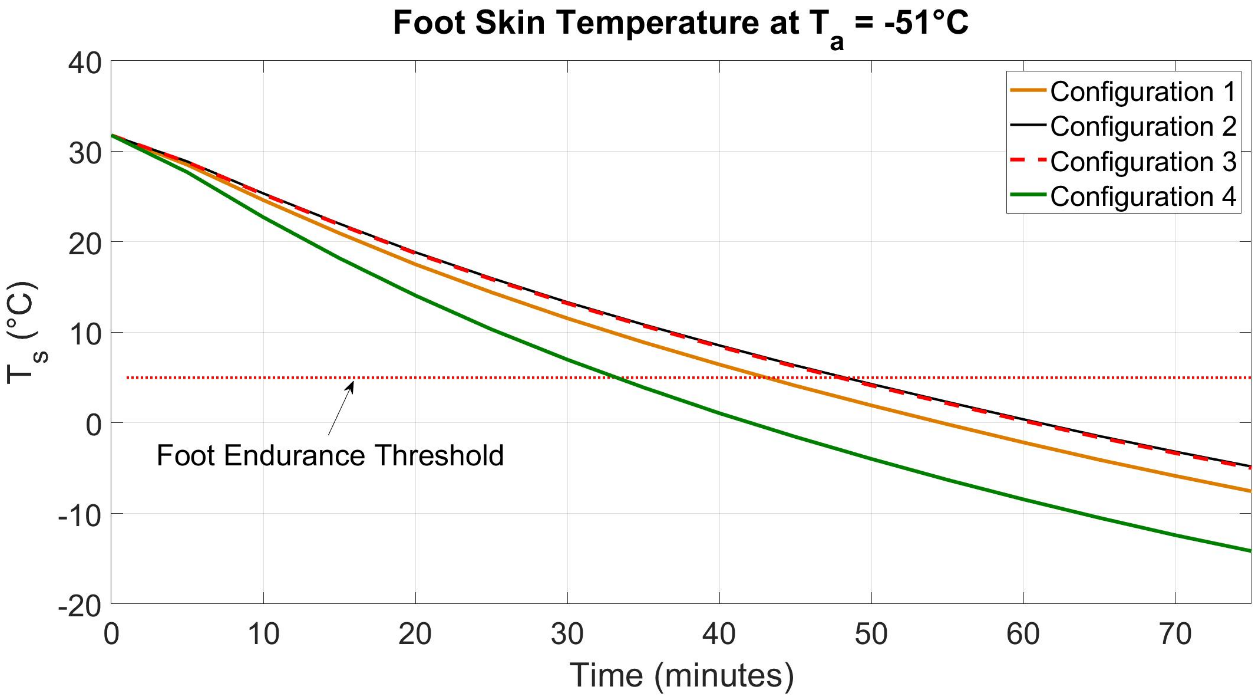
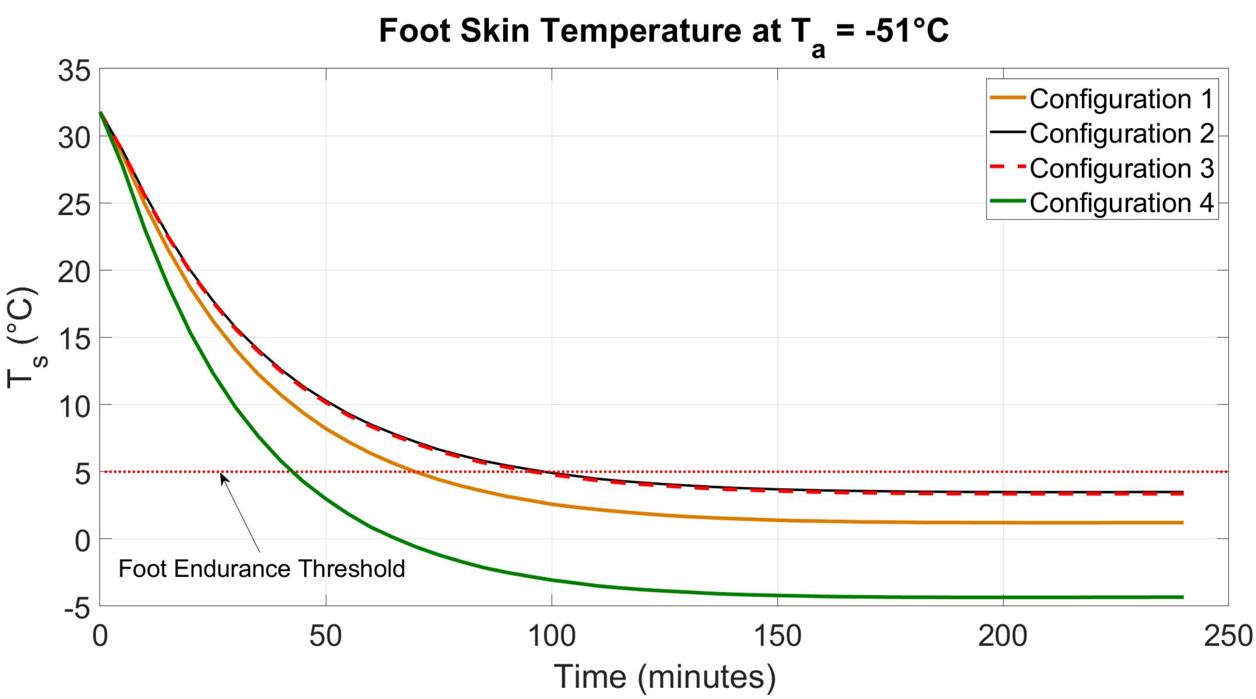


Figure 11. Simulated foot skin temperature for an active subject (250 W) at T_a = -51°C, 1 m·s^{-1} air velocity, with dry footwear



Foot skin temperature (T_s) vs. time plots that focus on wet footwear data are shown in Figure 12 and Figure 13. Modeling results for dry footwear are included for comparison and are represented with dashed lines. Figure 12 shows the results for a sedentary subject and Figure 13 shows results for a subject performing a light activity (250 W), such as walking on a hard surface at 1 m·s^{-1} with a 20 kg load. During the active simulations, it is assumed the work rate is constant, and therefore a 4 hour time limit is applied to the simulation.

Figure 12. Simulated foot skin temperature for a sedentary subject at T_a = -51°C, 1 m·s^{-1} air velocity, with dry and wet footwear

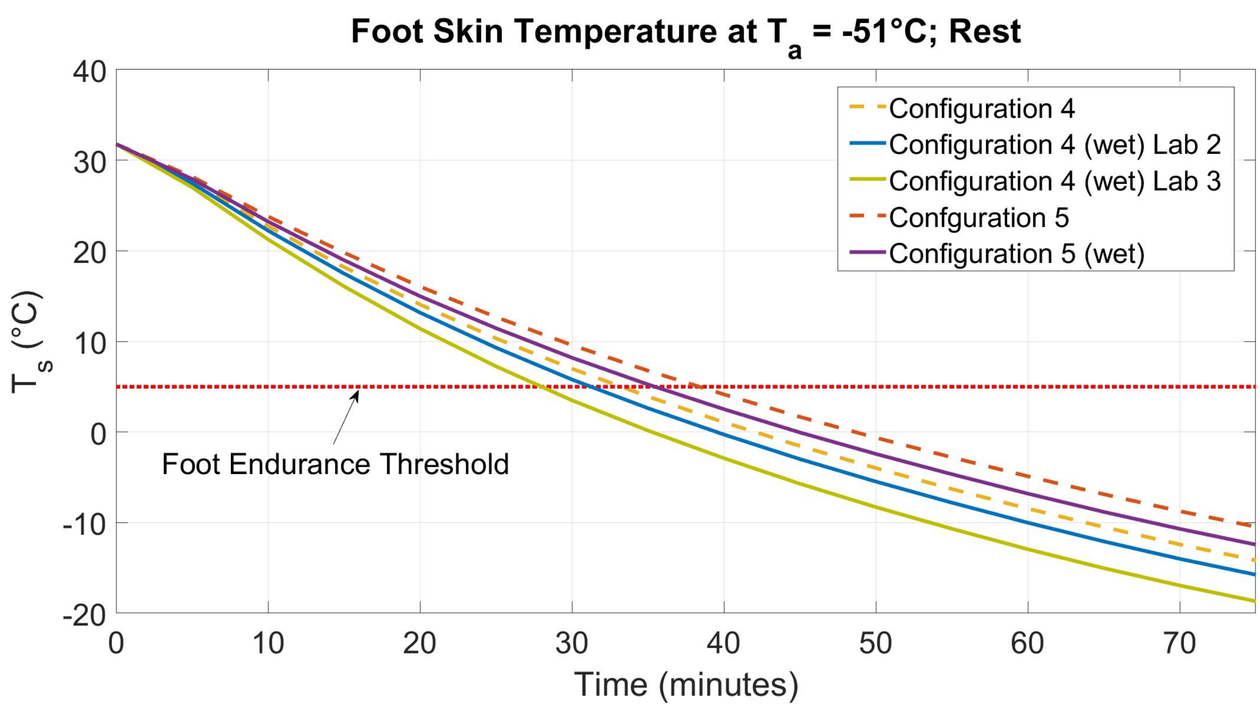
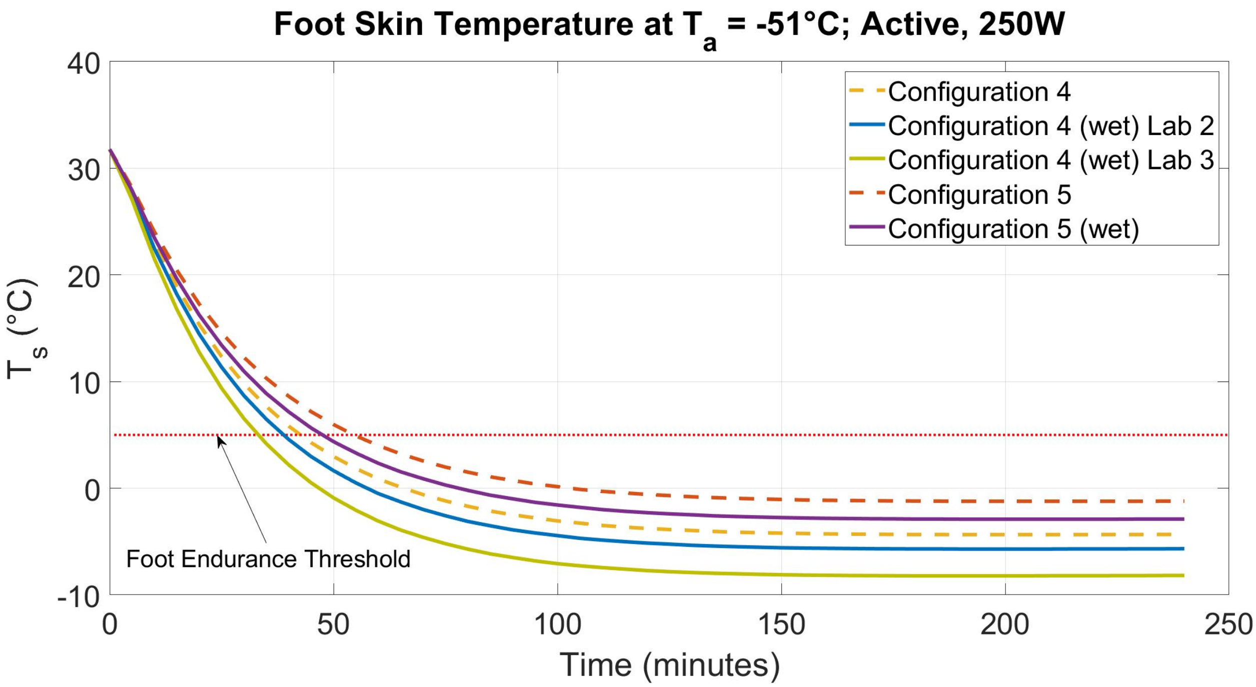


Figure 13. Simulated foot skin temperature with an active subject (250 W) at T_a = -51°C, 1 m·s^{-1} air velocity, with dry and wet footwear



DISCUSSION

Thermal resistance and evaporative resistance measurements often vary between body regions. The results in Table 2 from this study are an example of this behavior where R_{cl} and R_{ecl} values vary in different foot regions. Since the toes are typically the most vulnerable part of the foot for cold injury, the resistance values of the thermal foot manikin's toe section are typically used for SCTM foot region input. In addition, the toe thermal resistance is usually the lowest, which results in simulations that err on the side of predicting cold injury early. However, it is worth noting that using data from a different region may alter modeling results. For example, when comparing the regional thermal foot manikin data of the overboot configurations (configurations 1 - 3), configuration 1 has the lowest R_{cl} for the toe region and the highest R_{cl} value for all zones. The higher R_{cl} value for all zones of configuration 1 can be attributed to the greater thermal resistance in the partial leg section of the thermal foot. Since this higher thermal resistance is approximately half the value of the R_{cl} from the leg section of the ECWCS clothing ensemble and covers approximately 10% of the leg surface area, the contribution of this partial-leg thermal resistance is likely negligible. Therefore, using all zones of the thermal foot manikin data for input to SCTM modeling may lead to an interpretation of modeling results that indicate the configuration 1 footwear provides superior environmental protection. Our analysis focuses on the part of the foot which is most vulnerable to cold injury and therefore predicts longer endurance times for configurations 2 and 3, when compared to configuration 1.

This is the first time that the effects of wet footwear on human thermal responses were analyzed and simulated. Due to the evaluation method and the footwear design, the water absorbed is exclusively in the exterior layers of the footwear and does not include water saturation inside the footwear. Quantifying total heat loss of wet footwear on a thermal foot manikin is currently an emerging method. At present, the simplest and most logical way to integrate the wet footwear data is to use a reduced thermal resistance value, "wet thermal resistance". The percent reduction of the thermal resistance of a wet boot (relative to a dry boot) was calculated for the wet footwear configurations (configurations 4 and 5 with a saturated boot) and the testing results were used as modeling input. In this study, the smallest percent decrease of R_t for wet footwear was 7%. To understand the relevance of this percent difference, the current version of the thermal manikin standard test methods consider anything less than 10% difference to be acceptable when repeating trials for the same CIE configuration [14, 15]. Using that constraint, the 7% decrease due to water saturation may be considered negligible. However, the larger percent decrease in R_t for configuration 4 (wet) was 22%, which demonstrates a more significant impact of moisture saturation of footwear. Further research is required to understand the differences in results between laboratories, but that is beyond the scope of this project.

The modeling results of dry footwear show that configuration 2 and configuration 3 have similar performance and provide the best environmental protection in the toe region of the foot. The endurance times for those configurations are 39 to 49 minutes during rest and 55 to 99 minutes during exercise. As expected, a footwear configuration that does not include an overboot (configuration 4) provides the lowest level of protection, with endurance times from 25 to 34 minutes during rest and 29 to 43 minutes during exercise. When the footwear is saturated with water, e.g., configuration 4 (wet), the performance reduces even further. However, the 7% (Lab 2) and 22% (Lab 3) reduction in thermal resistance due to water saturation is relatively small. This is perhaps due to the experiment design of the wet footwear testing method, which states that the inside of the boot must be dry and therefore the sock is also likely to be dry.

USARIEM's manikin and modeling approach is an efficient way to assist in the research and development of footwear. Human studies are time consuming and can be conducted only for a small subset of all the possible combinations of temperature, wind, clothing and activities. Under extreme conditions, human studies are even impossible to conduct due to ethical restrictions and high risk of injury. An alternative way to evaluate footwear effectiveness and predict the risk of discomfort and cold injury over the actual range of conditions experienced during cold exposure is to use a mathematical model that utilizes input for clothing properties measured on a physical model. The SCTM predictions are limited to thermal responses. However, there may be other health-related issues during exposure to extreme cold environments, such as complications from asthma and cardiovascular issues [18]. Furthermore, SCTM is validated to -40°C, but is still a rational model that is expected to provide a rational prediction at -51°C.

CONCLUSIONS

The thermal performance of five footwear configurations was evaluated. The thermal foot manikin was used to determine the thermal resistances and evaporative resistances using standard methodologies. The SCTM was used to predict foot endurance times of five dry footwear configurations and two wet footwear configurations during rest and exercise at an air temperature of -51°C. The biophysical evaluations show that footwear configuration 2 and footwear configuration 3 provide the greatest environmental protection in the toe region with an R_{cl} value of 1.3 clo. At 1 $m \cdot s^{-1}$, the foot endurance times of the five configurations ranged from 34 to 49 min during rest and from 43 to 99 min during exercise. The foot endurance times reduce as air velocity increases. Water saturation in the footwear decreased thermal resistance and endurance times by approximately 5 minutes, but further studies are required a more in-depth understanding of the effects of wet footwear.

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