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DETERMINING ENERGY REQUIREMENTS FOR HEATED CLOTHING AND INDIVIDUAL EQUIPMENT USING MANIKIN AND MODELING METHODS

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USARIEM TECHNICAL REPORT T22-14

DETERMINING ENERGY REQUIREMENTS FOR HEATED CLOTHING AND INDIVIDUAL EQUIPMENT USING MANIKIN AND MODELING METHODS

Timothy P. Rioux[1]
Paola D'Angelo[2]
Elizabeth Hirst[2]
Michael P. Castellani[1]
Xiaojiang Xu[1]

[1]Thermal and Mountain Medicine Division, U.S. Army Research Institute of Environmental Medicine
[2]Combat Capabilities Development Command - Soldier Center

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Timothy P. Rioux
Paola D'Angelo
Elizabeth Hirst
Michael P. Castellani
Xiaojiang Xu

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14. ABSTRACT
This study determines the energy requirements of silver nanowire heated CIE through the use of thermal manikin measurements and thermoregulatory modeling. The biophysical properties (thermal resistance and evaporative resistance) of the five configurations were measured on thermal manikins. A thermoregulatory model was modified to include input that considers the heat flux from the heated CIE to the skin. Modeling conditions included -40°C air temperature, 1 m/s wind speed, and sedentary activity. The model predicted skin temperatures (Ts) of the hand, foot, and torso. The predicted power requirements for heated CIE are 20 W, 40 W, and 55 W for the hand, foot, and torso regions, respectively. Providing 55 W of heating to the torso does not show an improvement in the hand or foot Ts when compared to the unheated configuration. However, 100 W of heating to the torso predicts longer endurance time and tissue freeze time. Heating the hand, foot, and torso simultaneously does not appear to provide a benefit to the hand Ts, but indicates a potential benefit to the foot Ts.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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EXECUTIVE SUMMARY

Introduction: Heated clothing and individual equipment (CIE) are being developed with silver nanowire coated textiles as the active heating element. The goal of developing heated CIE is to provide a target level of thermal protection in extreme cold with fewer CIE items or lighter weight CIE than currently required. This study determined the energy requirements of silver nanowire heated CIE through the use of thermal manikin measurements and thermoregulatory modeling. **Methods:** Five ensemble configurations were used in the analysis: a Target ensemble and four ensemble configurations with heated CIE in the 1) hand, 2) foot, 3) torso, and 4) hand, foot, and torso. Configurations 1 through 4 also have two modes: unheated (U) and heated (H). The biophysical properties (thermal resistance and evaporative resistance) of the five configurations were measured on thermal manikins. Intrinsic thermal resistance and intrinsic evaporative resistances were calculated for the six body regions required for modeling input. The thermoregulatory model was modified to include input that considers the heat flux from the heated CIE to the skin. Environmental conditions of -40°C air temperature and 1 $m \cdot s^{-1}$ wind speed along with a sedentary activity condition were used for modeling input. The model predicted skin temperatures (T_s) of the hand, foot, and torso. In general, the T_s curves of heated CIE configurations were compared with that of the Target configuration to determine the required heating power. When possible, the T_s was used in conjunction with three threshold values to compare the performance of heated CIE to the Target configuration: functional time (t_{func}: time until T_s = 15°C), endurance time (t_{endur}: time until T_s = 5°C), and tissue freezing time (t_{freeze}: time until T_s = -1°C). **Results:** The predicted power requirements for heated CIE to provide equivalent thermal protection to the Target configuration are 20 W, 40 W, and 55 W for the hand, foot, and torso regions, respectively. **Discussion:** The predicted T_s curves did not always align between the heated configurations and the Target configuration. Therefore, depending on whether parameters such as t_{endur} or another metric of determining similarity was used, there may exist a degree of subjectivity in determining energy requirements of heated CIE. The thermal protection provided by heated CIE is dependent on environmental conditions and having a properly functioning energy source. **Conclusion:** The modeling results show 20 W of power to the hand produces a similar equilibrium phase of hand T_s to the Target configuration, 40 W of power to the foot with configuration 2H predicts comparable foot t_{endur} to the Target configuration, and 55 W of power to the torso results in a similar torso T_s curve of the Target configuration. Providing 55 W of heating to the torso does not show an improvement in the hand or foot T_s from the unheated configuration. However, 100 W of heating to the torso predicts longer t_{endur} and t_{freeze}. Heating the hand, foot, and torso simultaneously does not appear to provide a benefit to the hand T_s, but indicates a potential benefit to the foot T_s.

INTRODUCTION

The Emergent Materials Development Team at the Combat Capabilities Development Command Soldier Center (CCDC SC) is developing a novel silver nanowire coating that can be applied to textiles. Actively heated clothing and individual equipment (CIE) can be created when these coated textiles are implemented into CIE and interfaced with an energy source. CCDC SC has identified a set of standard issue cold-weather clothing items as candidates to apply the silver nanowire coating. The ultimate goal of creating these heated CIE items is to eliminate underutilized, heavy, or bulky layers of CIE systems by supplementing the remaining CIE items with active heating. Achieving this goal will reduce the overall weight and number of items required for Soldiers. An additional benefit for heated gloves is the potential to maintain manual dexterity in cold environments with less cumbersome handwear, and an additional benefit of heated footwear is the potential to reduce the metabolic cost by using lighter weight footwear. The United States Army Research Institute of Environmental Medicine (USARIEM) used expertise in biophysical evaluations and human thermoregulation modeling to conduct the theoretical analysis of planned prototypes [1-5]. This report describes a method to determine the energy required for actively heated CIE to maintain a target level of thermal protection, which is represented by a target ensemble with relatively high passive insulation. The analysis focuses on three regions of body heating (torso, hand, and foot) using a modified thermoregulatory model to determine the human effect of applying heat to each of the three body regions.

METHODS

MATERIALS

All CIE used for this analysis are listed in Table 1. The garments are part of the U.S. Army's Generation III Extended Cold Weather Clothing System (ECWCS). The Extreme Cold Weather Mitten Set (ECWMS) consists of 3 pieces: an outer mitten, a mitten liner, and a wool 5 finger insert. The Trigger Finger Mitten Set (TFMS) consists of 2 pieces: an outer “trigger finger” mitten and a wool 5 finger insert. Both the Vapor Barrier (VB) Boot and the Intermediate Cold Wet Boot (ICWB) measurements were completed with the Darn Tough T4050 sock. The ICWB included a separate quilted liner, which is the layer between the sock and the boot.

Table 1. Clothing and Individual Equipment for heated clothing analysis

Clothing	Layer 1: Lightweight Undershirt and Drawers Layer 2: Midweight Shirt and Drawers Layer 3: Fleece Jacket Layer 5: Soft Shell Jacket and Trousers Layer 7: Extreme Cold Weather Parka and Trousers
Handwear	Army Extreme Cold Weather Mitten Set Trigger Finger Mitten Set
Footwear	Darn Tough T4050 Sock Vapor Barrier Boots Intermediate Cold Wet Boot (ICWB) with quilted liner
Headwear	Cold-weather Cap and balaclava

Clothing ensemble configurations

The analysis performed in this study is based on a target level of thermal protection, which is represented by the passive insulation of a single cold-weather clothing ensemble, pictured on the thermal manikin in Figure 1. The headwear is pictured separately in Figure 2. In addition to the Target configuration, four ensemble configurations were selected to determine the energy requirements of heated CIE. Three configurations focused on the analysis of heating specific body regions: the hand (configuration 1), the foot (configuration 2), and the torso (configuration 3). Configuration 4 was selected to analyze simultaneous heating in the hand, foot, and torso. Configurations 1 through 4 will replace the higher passive insulation of the Target configuration with lighter weight CIE that is supplemented with active heating in each of their respective body regions of focus.

Figure 1. Target configuration dressed on the thermal manikin.

Figure 2. Cold-weather Cap and balaclava

Utilizing active heating, configurations 1 through 4 are intended to provide the same level of thermal protection as the Target configuration's passive insulation. The matrix shown in Figure 3 illustrates which CIE items were included in each configuration as well as the location of the heated layers. The arbitrary number associated with each configuration is listed in the top row and the individual garments are listed in the leftmost column. A colored-in cell indicates that the CIE item is included in the ensemble configuration. The CIE items that include heating functionality are indicated by a red-colored cell and the text "U/H", which represents the two modes of heated CIE (U = Unheated or H = Heated). Therefore, configurations 1 through 4 will have two modes: an unheated mode with passive insulation less than the Target configuration and an active heating mode that is intended to provide thermal protection equivalent to the Target configuration. In other words, the ensemble configurations with the same number (e.g., 1U and 1H) will consist of the same clothing items, but the thermal protection will differ based on whether or not the heating is active. The unheated configurations are included in this analysis to demonstrate the reduced thermal protection if the heating functionality is not operational. In summary, the intention of configuration 1H is to replace the Extreme Cold Weather Mitten Set with lighter weight handwear by adding active heating to the 5 Finger Wool Insert; the intention of configuration 2H is to replace the Vapor Barrier Boot with the Intermediate Cold Wet Boot by adding active heating to the sock; the intention of configuration 3H is to eliminate the Fleece Jacket by adding active heating to the torso of the Lightweight Undershirt; configuration 4H is the combination of the above three.

Figure 3. Configuration Matrix

	Configuration				
	Target	1U/1H	2U/2H	3U/3H	4U/4H
Lightweight Undershirt				U/H	U/H
Lightweight Drawers					
Midweight Shirt					
Midweight Drawers					
Fleece Jacket					
Soft Shell Jacket					
Soft Shell Trouser					
Extreme Cold Weather Parka					
Extreme Cold Weather Trouser					
Cold-weather Cap					
Balaclava					
5 Finger Wool Insert		U/H			U/H
Extreme Cold Weather Mitten Outer					
Extreme Cold Weather Mitten Liner					
Trigger Finger Mitten Outer					
T4050 Sock			U/H		U/H
Vapor Barrier Boot					
Quilted Boot Liner					
Intermediate Cold Wet Boot					

BIOPHYSICAL CLOTHING PROPERTIES

The biophysical properties of thermal resistance (also known as insulation) and evaporative resistance were measured using ASTM standard test methods F1291-16, F2370-16, and F3426-20 [6-8]. A whole-body sweating thermal manikin (20-zone Newton model, Thermetrics, Seattle, WA) was used to measure the properties of clothing. A thermal head manikin, thermal hand manikin, and thermal foot manikin (Thermetrics, Seattle, WA) were used to measure the properties of CIE worn on the head, hand, and foot, respectively. The biophysical properties of the ECWCS clothing system and the headwear used in this study were measured previously [9-11]. Testing of the footwear and handwear were completed for this study on USARIEM's thermal foot manikin and thermal hand manikin.

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 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:

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

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

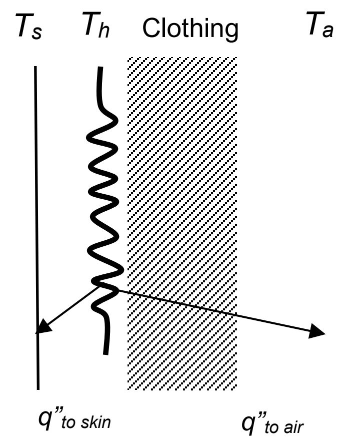
where R_{cl}, R_t, and R_a may be in units of $m^2 \cdot °C \cdot W^{-1}$ or clo, with the caveat that the same units are used consistently throughout the calculation; R_{ecl}, R_{et}, and R_{ea} are in units of $m^2 \cdot Pa \cdot W^{-1}$; and f_{cl} is the dimensionless clothing area factor, which represents the increase of body surface area due to CIE worn on the manikin. When calculating R_{cl} values for this study, an f_{cl} of 1 was used in all cases except for the footwear. The foot f_{cl} values were estimated using the following equation from McCullough et al. [12]:

$$f_{cl} = 1.0 + 0.3 \cdot R_{cl} \quad \text{(Eq. 3)}$$

It was necessary to calculate regional resistance values for the simulation and analysis in this study. USARIEM typically separates thermal manikin data into six regions (head, torso, arm, hand, leg, and foot) for cold thermoregulatory modeling [3]. The full configurations in Figure 3 were not tested directly on the whole-body thermal manikin. Headwear, handwear, and footwear CIE were tested on the thermal head manikin, thermal hand manikin, and thermal foot manikin, respectively. These body part manikins include partial neck, partial wrist, and partial leg sections. For data collected on the head and hand manikins, resistances of the neck, and wrist zones were not included in the data used for modeling. An even smaller region was used from the thermal foot manikin data, which was calculated from the parallel weighted average of the upper and lower toe zones [13]. USARIEM typically uses this toe 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. Diagrams that illustrate the zone locations of USARIEM's suite of thermal manikins were documented in a previous report [14]. Since the biophysics data used in this study were not collected from testing an entire ensemble on the whole-body sweating thermal manikin, data from 4 thermal manikins (whole-body, head, hand, foot) were compiled to create a full ensemble with data separated into the 6 body regions.

HEAT TRANSFER ANALYSIS

Figure 4. Diagram of the equilibrium state of a heated garment system



The equilibrium state of a heated garment system is illustrated in Figure 4. Shown from left to right are the skin at temperature T_s, the heated garment at a temperature of T_h, the clothing, and the environment at temperature T_a. The total heat flux (q'') from the heated garment is dispersed partially to the skin ($q''_{to\ skin}$) and partially through the clothing and into the environment ($q''_{to\ air}$). Thus, the heat balance of the system is described as:

$$q'' = \frac{T_h - T_s}{R_{sh}} + \frac{T_h - T_a}{R_t} \qquad \text{(Eq. 4)}$$

where:
q'': the total heat flux from the heated garment in W·m^{-2}; an input parameter
R_t: total thermal resistance in m^2·°C·W^{-1}, (the clothing resistance measured on the thermal manikin for this region), from the skin to the environment and including the boundary air layer resistance at the surface of the clothing.
R_{sh}: thermal resistance from the skin to the heated garment in m^2·°C·W^{-1}, which is approximately 0.024 m^2·C·W^{-1} per mm of still air (0.154 clo per mm of still air)
T_s: the skin temperature in °C.
T_a: the air temperature of the ambient environment in °C.
T_h: the temperature of the heated garments in °C.

The equation is rewritten as:

$$T_h = \frac{\frac{T_s}{R_{sh}} + \frac{T_a}{R_t} + q''}{\frac{1}{R_{sh}} + \frac{1}{R_t}} \qquad \text{(Eq. 5)}$$

In this study, it is assumed the CIE layer that includes the heating element is next to the skin (~ 1 mm distance) and therefore R_{sh} is 0.154 clo. The total thermal resistance (R_t) of CIE is measured on thermal manikins for each heated region. The heat flux (q'') of the heated clothing is selected experimentally to match the thermal protection of the Target configuration. The surface temperature (T_s) of the skin is assumed to be 35°C, as that is the standard for biophysics evaluations. And the air temperature (T_a) was selected to be -40°C for this analysis. Once T_h has been calculated, the heat flux to the skin can be calculated by:

$$q''_{to\ skin} = \frac{T_h - T_s}{R_{sh}} \qquad \text{(Eq. 6)}$$

where $q''_{to\ skin} \geq 0$, in W·m^{-2}. When $T_h < T_s$, the heated clothing system behaves as an unheated clothing system and provides no heat to the body.

SIMULATION

An existing thermoregulatory model was modified to include input parameters that simulate heated clothing at specific regions of the body. Using previous research as a guide, various values of heating power were applied until the modeled thermal protection of heated ensemble configurations produced similar results to the passive insulation of the Target configuration [15-19].

The six cylinder thermoregulation model (SCTM) was used for the modeling analysis [3]. SCTM is a rational model and is based on first principles of physiology and the physical laws of heat transfer. The human body is divided into six cylinders representing the head, torso, arms, legs, hands, feet (cylinders i = 1…6). Each cylinder is further subdivided into four concentric layers representing the core, muscle, fat, and skin tissues (layers j = 1…4). A one-loop circulatory system is assumed, the central blood pool delivers the arterial blood to the tissues and the blood flows back to the pool through the veins. Temperature regulation is based on an integrated thermal signal, which is composed of the weighted input from thermal receptors at various sites distributed throughout the body. The difference between this signal and its threshold is the afferent signal that activates the thermoregulatory mechanisms including sweat production, vasomotor function, and metabolic heat production. Selected equations from SCTM are summarized below.

The energy balance equation for each cylinder in one-dimensional cylindrical coordinates is:

$$\rho_i c_i \frac{\partial T_i}{\partial t} = \dot{M}_i - W_{ex,i} + \lambda_i \left\{ \frac{\partial^2 T_i}{\partial r^2} + \frac{1}{r} \cdot \frac{\partial T_i}{\partial r} \right\} + \beta_i Q_i \rho_b c_b (T_b - T_i) \qquad \text{(Eq. 7)}$$

where ρ_i is the density (kg·m^{-3}), c_i is the specific heat (J·kg^{-1}°C^{-1}), i is the cylinder number, T_i is the temperature (°C) of the tissue, t is the time (s), $\dot{M}_i$ is the total metabolic rate ($W \cdot m^{-3}$), $W_{ex,i}$ is external work ($W \cdot m^{-3}$), λ is the thermal conductivity ($W \cdot m^{-1} \cdot °C^{-1}$) of the tissue, r is the cylinder radius (m), β is the countercurrent factor by which the heat exchange between arterial blood and venous blood is approximated (dimensionless), $Q_i(r,t)$ is the blood flow rate per volumetric unit of the tissue ($m^3 \cdot s^{-1} \cdot m^{-3}$), ρ_b is the density of the blood ($kg \cdot m^{-3}$), c_b is the specific heat of the blood ($J \cdot kg^{-1} °C^{-1}$), and $T_b(t)$ is the temperature of the blood pool (°C).

The afferent signal for the thermoregulation system is calculated by the equation:

$$a(t) = \sum_{i=1}^{6} \sum_{j=1}^{4} g_{ij} T_{ij}(r,t) - a_0 \qquad \text{(Eq. 8)}$$

where $a(t)$ is the afferent signal for the thermoregulation system (°C), g_{ij} is the weighting factor (dimensionless), j is the layer number, and a_0 is the threshold (°C). The integrated afferent signal is then transformed into efferent signals using distribution factors, which have different values for sweat production and for blood flow. The sweat production, for example, is calculated as:

$$E_i = E_{i0} + \varepsilon_{Ei} a \qquad \text{(Eq. 9)}$$

where E_i is the evaporative heat loss ($W \cdot m^{-2}$), ε_{Ei} is the distribution factor for evaporation ($W \cdot m^{-2} \cdot °C^{-1}$), and E_{i0} is the basal evaporation value ($W \cdot m^{-2}$).

The heat transferred to skin was incorporated into the boundary equations of the model to adjust for effects of the heated garments. The modified boundary equation is:

$$-\lambda \frac{\partial T}{\partial r} = R + C + E + q''_{to\ skin} \qquad \text{(Eq. 10)}$$

where λ is the thermal conductivity of the tissue ($W \cdot m^{-1} \cdot °C^{-1}$), T is the tissue temperature (°C), r is the radius (m), R is the irradiative heat exchange ($W \cdot m^{-2}$), C is the convective heat exchange ($W \cdot m^{-2}$), and E is the evaporative heat exchange ($W \cdot m^{-2}$). This revised boundary equation considers not only the heat exchange between the body, skin and environment but also the heat exchange between the skin and the heated clothing.

The SCTM has been validated for a broad range of conditions, including heat, cold and water immersion [3, 20-23]. SCTM has been used to evaluate heat strain in personal protective equipment [24, 25] and to design personal cooling systems [26, 27]. It has been used to develop user-friendly tools for operational use, the Probability of Survival Decision Aid (PSDA) [23, 28, 29] and the Cold Weather Ensemble Decision Aid (CoWEDA) [4, 30]. The SCTM inputs include individual characteristics, intensity of activity, environmental conditions and clothing properties (i.e., thermal resistance and evaporative resistance) for each of the six body regions. The SCTM predicts physiological responses, e.g., core temperatures, skin temperatures, and sweat rates for six body regions. The individual characteristic, intensity of activity, and environmental conditions selected for this study are shown in Table 2.

Table 2. Modeling input parameters

Individual Characteristics	Height	1.75 m
	Mass	83.5 kg
	Body Fat	22 %
Activity (sedentary)	External Work	0 W
	Total Metabolic Rate	100 W
Environmental Conditions	Air Temperature	-40°C
	Relative Humidity	40 %RH
	Wind Speed	1 $m \cdot s^{-1}$

The simulated skin temperature (T_s) predicted by SCTM was used as a basis to determine three thresholds: functional time (t_{func}), endurance time (t_{endur}), and tissue freezing time (t_{freeze}). The functional time is defined as the time until T_s decreases to 15°C, at which point significant loss of motor skills are expected. Endurance time is defined as the time until T_s decreases to 5°C, at which point extreme pain and numbness are expected and the probability of cold injury increases significantly. Tissue freezing time is defined as the time until T_s decreases to -1°C, indicating that the body tissue has frozen. These thresholds will vary among individuals, but the general guidelines have been determined through human subject studies [31].

Using previous research as a guide, the power of the heated garments was determined through systematic experimentation with SCTM. Simulation results vary with the power inputs, and thus simulations were run several times with different power inputs to find the T_s profiles of the heated configurations that match the Target T_s profiles. If the T_s profile of the heated and Target configurations did not align well, other methods of equivalency were used. In some cases, it was more appropriate to use similar t_{endur} to determine similar levels of thermal protection. In other instances, it was more appropriate to determine equivalent levels of thermal protection by finding similar T_s equilibrium states (approximately the final 200 minutes of the simulation period). Once the power values were ultimately determined, the heat flux (q'') was calculated by dividing the power to the heated garments, in W, by the surface area (m^2) of each heated region. The regional surface areas were obtained from the SCTM body region distribution with a standard western male that has a total body surface area of 1.81 m^2.

RESULTS

BIOPHYSICAL CLOTHING DATA

The intrinsic thermal resistance (R_{cl}) and intrinsic evaporative resistance (R_{ecl}) of five clothing ensembles are shown in Table 3 and Table 4, respectively. The intrinsic resistance values for the six regions of clothing ensembles are required input for SCTM.

Table 3. Intrinsic thermal resistance of ensemble configurations

	R_{cl} (clo)					
Configuration	Head	Torso	Arm	Hand	Leg	Foot
Target	1.83	6.90	5.06	2.85	4.36	1.55
1	1.83	6.90	5.06	1.82	4.36	1.55
2	1.83	6.90	5.06	2.85	4.36	1.05
3	1.83	5.99	4.04	2.85	4.36	1.55
4	1.83	5.99	4.04	1.82	4.36	1.05

Table 4. Intrinsic evaporative resistance of ensemble configurations

	R_{ecl} ($m^2 \cdot Pa \cdot W^{-1}$)					
Configuration	Head	Torso	Arm	Hand	Leg	Foot
Target	47.8	224	129	89.3	137	104
1	47.8	224	129	57.0	137	104
2	47.8	224	129	89.3	137	82.3
3	47.8	209	115	89.3	137	104
4	47.8	209	115	57.0	137	82.3

ENERGY REQUIREMENTS

The simulated power (P) and heat flux required for the heated CIE to provide similar thermal protection to the Target configuration are shown in Table 5. The heating powers were selected for the following reasons. For the hand region, 20 W of power was determined to match the equilibrium phase of the Target configuration. For the foot region, 40 W of power was determined to produce comparable t_{endur} to the Target configuration. For the torso region, 55 W of power was determined to produce a similar torso T_s curve to the Target configuration. The heat flux was also provided in Table 5 to account for different surface areas of heated clothing. The heat flux was calculated using the surface area from a standard male (1.75 m, 84 kg, and 25 % body fat).

Table 5. Predicted power and heat flux required for heated CIE to have similar performance to the Target configuration

Region	P (W)	q'' ($W \cdot m^{-2}$)
Hand	20	220
Foot	40	320
Torso	55	85

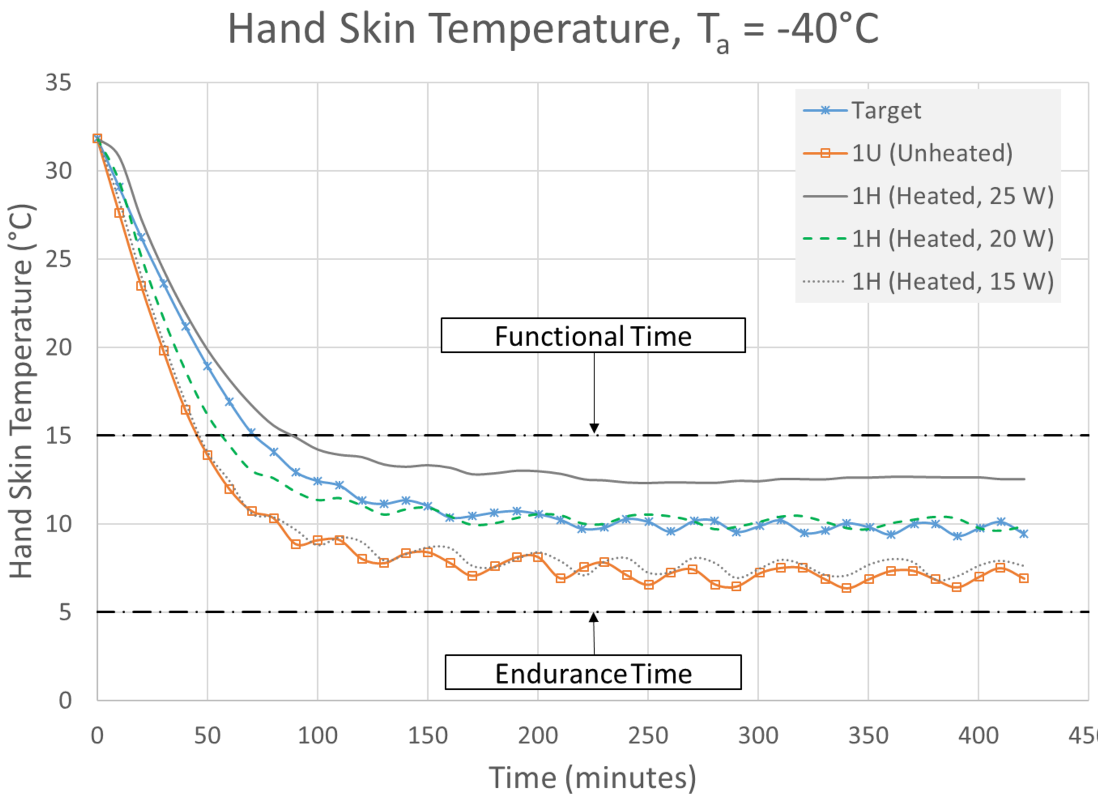
The functional times (t_{func}) for the hand while wearing the Target configuration, configuration 1U, and configuration 1H with various power levels at T_a = -40°C are listed in Table 6. All prediction times are in 5-minute increments. The time for each threshold is determined from the T_s output of SCTM for the hand.

Table 6. Functional time of the hand for Target configuration and configuration 1 with and without heating

Configuration	t_{func} (min)
Target	70
1U	45
1H (15 W)	45
1H (20 W)	55
1H (25 W)	90

The skin temperature predictions from the SCTM are plotted in Figure 5 through Figure 11. Each figure contains the skin temperature prediction for the Target configuration, an unheated configuration and a heated configuration with distinct power values. Figure 5 shows configuration 1H with 25 W, 20 W, and 15 W of power applied to the hand. Up to 15 W of heating power can be applied to the hand without a predicted improvement from the unheated configuration. With 20 W applied to the hand, the equilibrium phase of T_s is similar to that of the Target configuration.

Figure 5. Hand skin temperature of configuration 1 with and without heating at -40°C



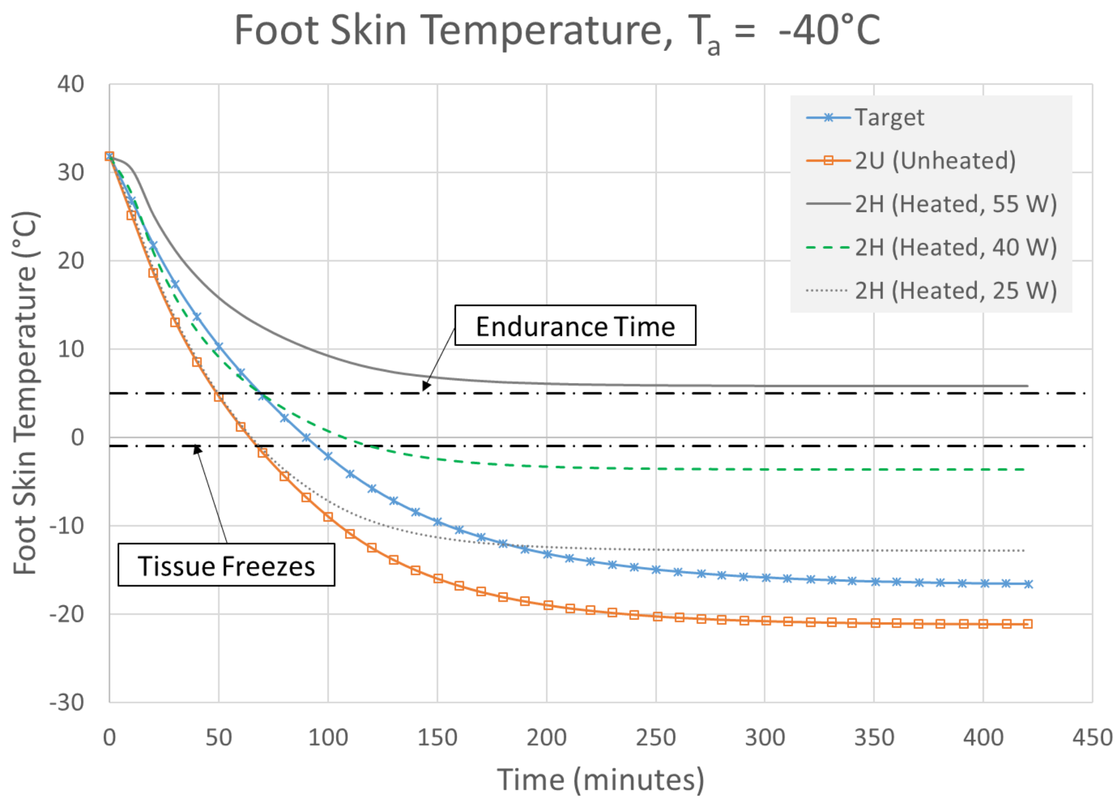
The endurance time (t_{endur}) and tissue freezing time (t_{freeze}) for the foot while wearing the Target configuration, configuration 2U, and configuration 2H with various power levels at T_a = -40°C are listed in Table 7. The predicted T_s for configuration 2H with 55 W of heating did not decrease below the t_{endur} of t_{freeze} thresholds during the simulation period.

Table 7. Endurance time and tissue freezing time of the foot for Target configuration and configuration 2 with and without heating

Configuration	t_{endur} (min)	t_{freeze} (min)
Target	70	95
2U	50	65
2H (25 W)	50	70
2H (40 W)	70	120
2H (55 W)	-	-

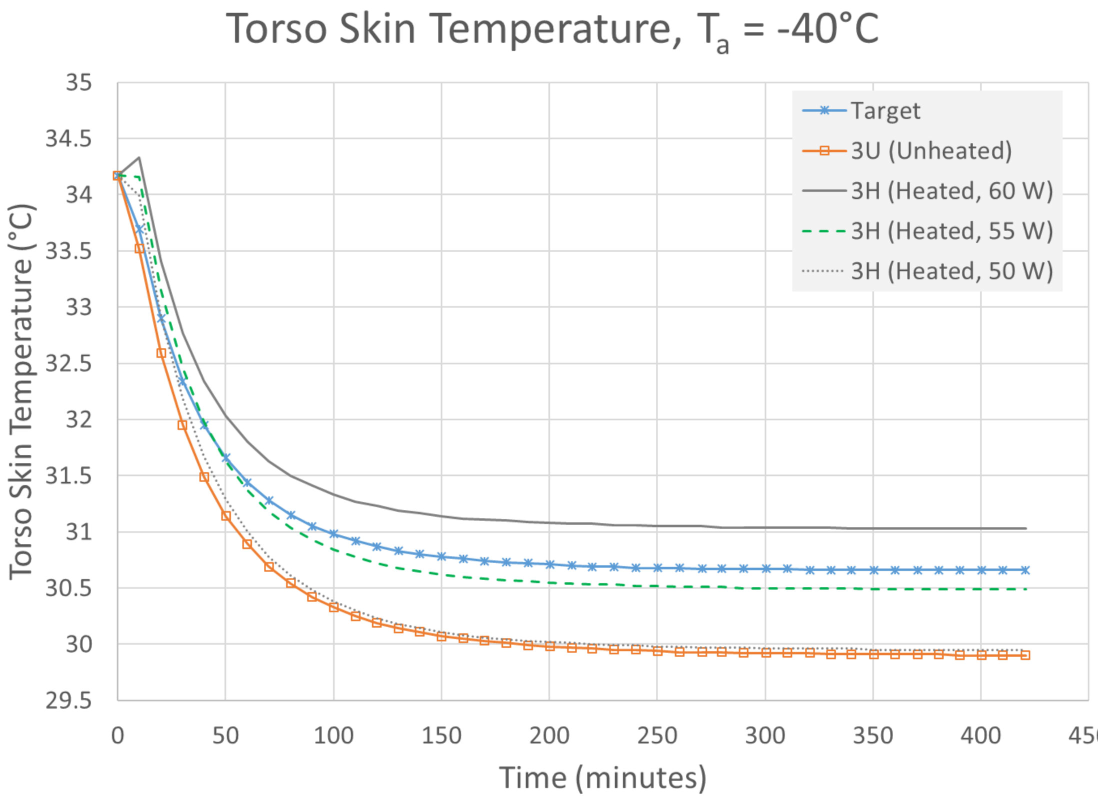
The foot skin temperatures from the SCTM results are shown in Figure 6 for the Target configuration, configuration 2U, and configuration 2H with 55 W, 40 W, and 25 W of power applied to the footwear. With as much as 25 W of heating to the foot, the foot T_s essentially does not improve upon the unheated configuration, as the temperature curves align until T_s decreases approximately 5°C lower than t_{freeze}. Once the t_{freeze} threshold has been surpassed, the tissue is frozen and there will be no predicted benefit to the user regardless of whether the T_s stabilizes at 12°C or -20°C. With 40W of heating to the foot, the foot t_{endur} is predicted to be the same as the Target configuration. Providing 55 W of heating power to the foot is predicted to maintain the foot T_s above the t_{endur} threshold for 420 minutes.

Figure 6. Foot skin temperature of configuration 2 with and without heating at -40°C



The torso T_s from the SCTM results are shown in Figure 7. When providing up to 50 W of heating to the torso, the simulation predicts no difference from the unheated configuration with regards to torso T_s. With 55 W provided to the torso, the torso T_s is similar to that of the target configuration.

Figure 7. Torso skin temperature of configuration 3 with and without heating at -40°C



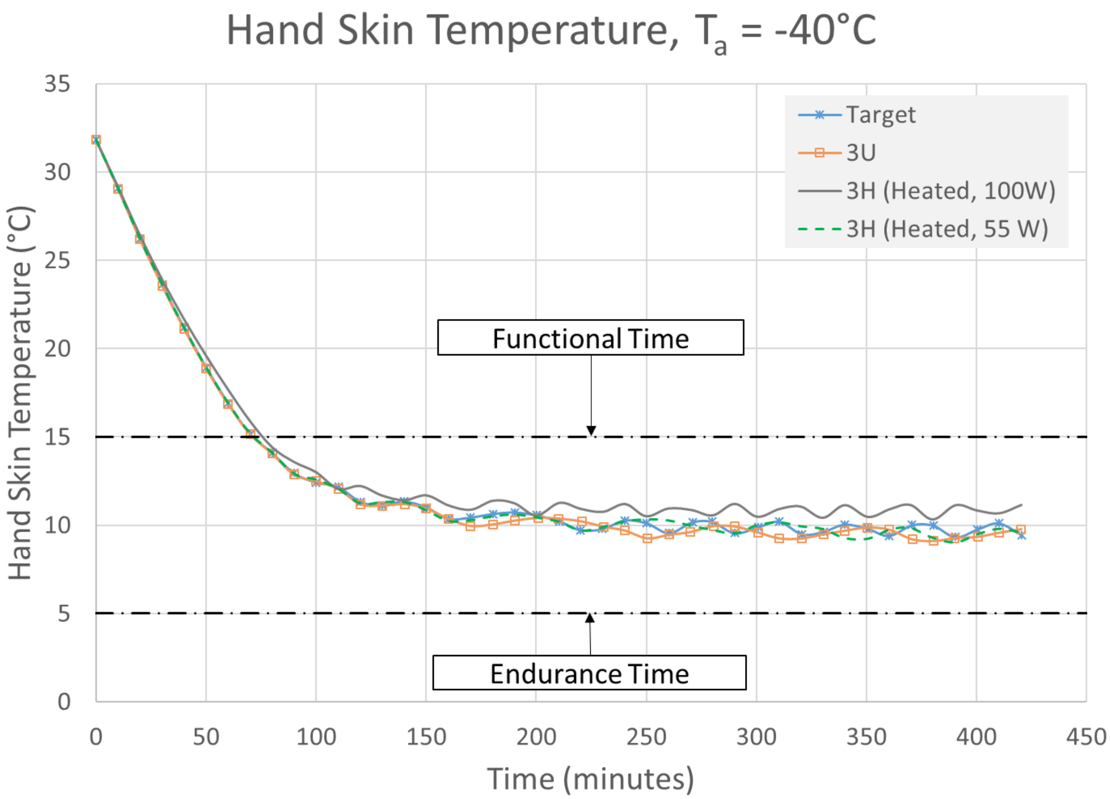
The torso T_s does not decrease below any of the three thresholds used in this study and therefore the results are less definitive. Thus, it is worthwhile to examine the effect of torso heating on the hand T_s and the foot T_s with Figure 8 and Figure 9. Figure 8 shows that 100 W heating to the torso has a minimal impact on the hand T_s. In Figure 9, 100 W of heating to the torso has an impact on the foot T_s. The functional times (t_{func}) for the hand while wearing the Target configuration, configuration 3U, and configuration 3H with various power levels at T_a = -40°C are listed in Table 8. All prediction times are in 5-minute increments. The time for each threshold is determined from the T_s output of SCTM for the hand.

Table 8. Functional time of the hand for Target configurations and configuration 3 with and without heating

Configuration	t_{func} (min)
Target	70
3U	70
3H (55 W)	70
3H (100 W)	75

The hand T_s from the SCTM results are shown in Figure 8 for the Target configuration, configuration 3U and configuration 3H with 55 W and 100 W of power applied to the torso area of the base layer garment.

Figure 8. Hand skin temperature of configuration 3 with and without heating at -40°C



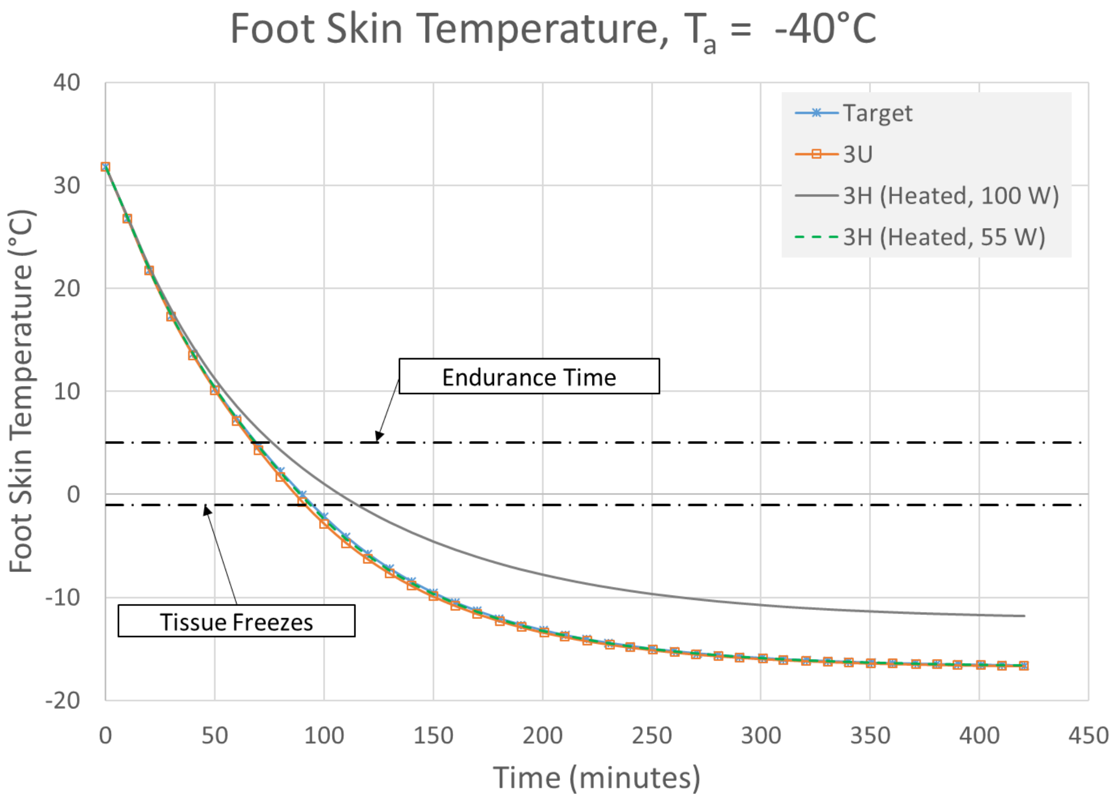
The endurance time (t_{endur}) and tissue freezing time (t_{freeze}) for the foot while wearing the Target configuration, configuration 3U, and configuration 3H at various power levels with T_a = -40°C are listed in Table 9.

Table 9. Endurance time and tissue freezing time of the foot for Target configuration and configuration 3 with and without heating

Configuration	t_{endur} (min)	t_{freeze} (min)
Target	70	95
3U	70	90
3H (55 W)	70	95
3H (100 W)	75	115

The foot skin temperatures from the SCTM results are shown in Figure 9 for the Target configuration, configuration 3U, configuration 3H with 55 W and 100 W of power applied to the torso area of the base layer garment.

Figure 9. Foot skin temperature of configuration 3 with and without heating at -40°C



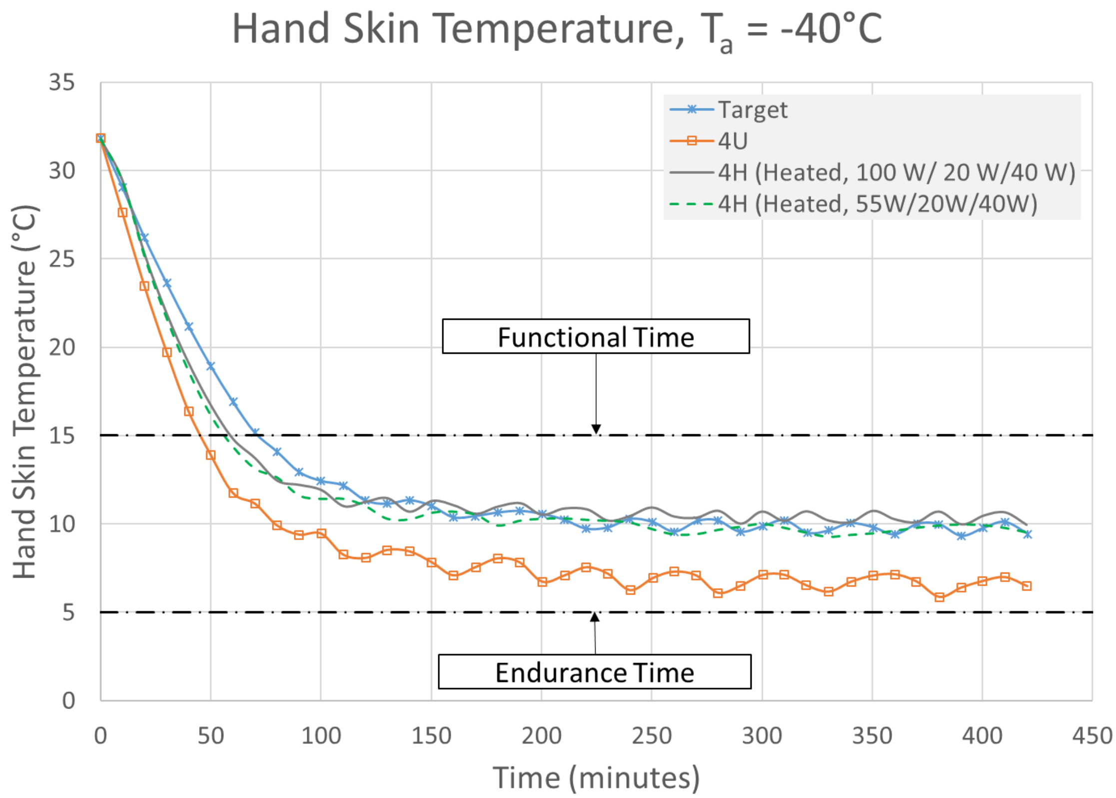
The functional times (t_{func}) for the hand while wearing the Target configuration, configuration 4U, and configuration 4H with various power levels at T_a = -40°C are listed in Table 10. Configuration 4H has two distinct heating power distributions: 55 W for the torso, 20 W for the hand, and 40 W for the foot (55W / 20W / 40W) and 100 W for the torso, 20 W for the hand, and 40 W for the foot (100W / 20W / 40W). All prediction times are in 5-minute increments. The times until each threshold are determined from the T_s output of SCTM for the hand. Increasing the torso heating power by an additional 45 W has a limited effect on hand t_{func}.

Table 10. Functional time of the hand for Target configurations and configuration 4 with and without heating

Configuration	t_{func} (min)
Target	70
4U	45
4H (55W / 20W / 40W)	55
4H (100W / 20W / 40W)	60

The hand T_s from the SCTM results are shown in Figure 10 for the Target configuration, configuration 4U and configuration 4H with various heating powers applied to the torso, hand, and foot.

Figure 10. Hand skin temperature of configuration 4 with and without heating -40°C



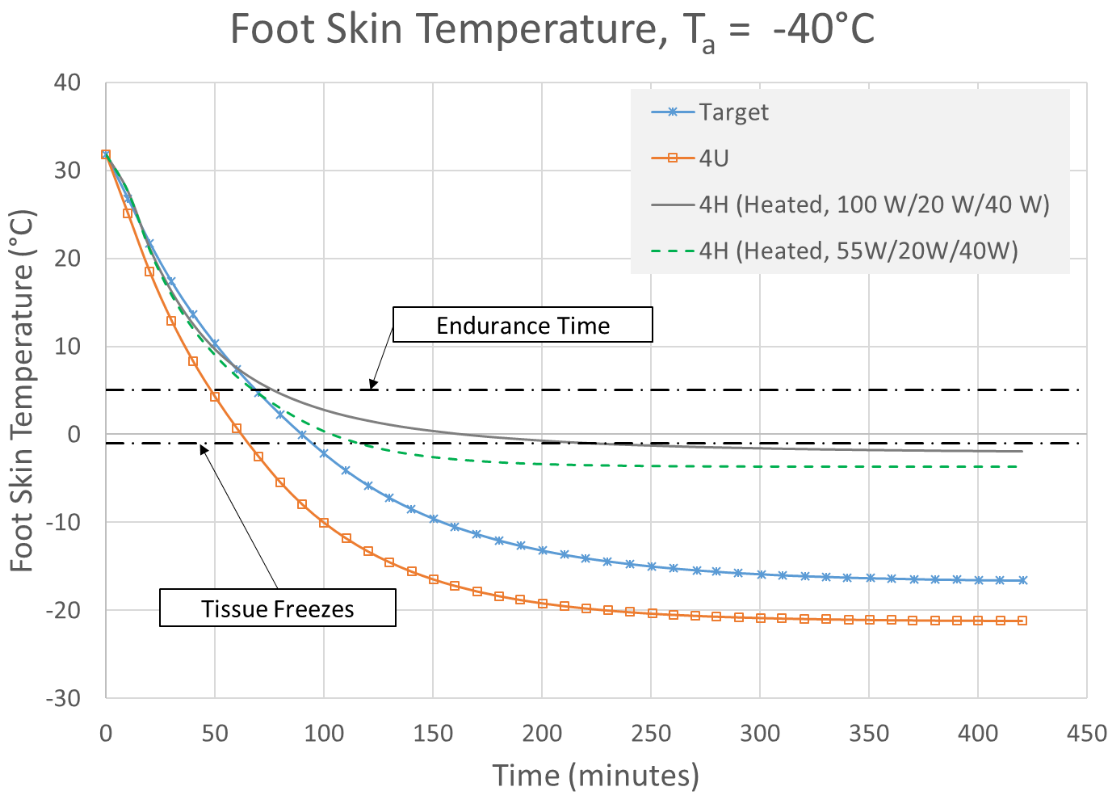
The endurance time (t_{endur}) and tissue freezing time (t_{freeze}) for the foot while wearing the Target configuration, configuration 4U, and configuration 4H at various power levels with T_a = -40°C are listed in Table 11. Increasing the torso heating power by an additional 45 W has a limited effect on foot t_{endur}, but doubles t_{freeze}.

Table 11. Endurance time and tissue freezing time of the foot for Target configuration and configuration 4 with and without heating

Configuration	t_{endur} (min)	t_{freeze} (min)
Target	70	95
4U	50	65
4H (55W / 20W / 40W)	70	115
4H (100W / 20W / 40W)	75	225

The foot skin temperatures from the SCTM results are shown in Figure 11 for the Target configuration, configuration 4U, configuration 4H with various levels of power applied to the torso, hand, and foot.

Figure 11. Foot skin temperature of configuration 4 with and without heating at -40°C



DISCUSSION

The power and heat flux values to heat each region were determined using a thermal manikin and modeling approach. The power requirements were based on providing equivalent thermal protection between heated configurations (H) and the Target configuration. The modeled T_s vs. time plot profiles may not match exactly, so there is a degree of subjectivity in determining the equivalency of thermal protection and the equivalency criteria may vary depending on the modeling conditions and the parameter being examined. For the hand T_s predictions in Figure 5 and Figure 10, the t_{func} are not identical and the t_{endur} are not approached in the 420 minutes of simulation. However, the equilibrium phase occurring between 120 - 420 minutes of the simulation aligns well and therefore it is determined that the heated (H) configurations provide similar levels of thermal protection to the Target configuration. This equilibrium criteria is reasonable in these scenarios as t_{func} is not as damaging to the exposed individual as t_{endur} and t_{freeze}. For the foot T_s predictions in Figure 6 and Figure 9, equivalency between H configurations and the Target configuration was determined based on comparable t_{endur} values. Although the foot T_s curves diverged as time elapsed, it is reasonable to use the intersection of t_{endur}, as this is the time when probability of cold injury significantly increases.

The heat balance equation, Eq. 4, shows that the efficacy of heated clothing is influenced by the heating power and environmental conditions. Two previous studies provide seemingly inconsistent conclusions about whether or not heating the torso in addition to heating the extremities is beneficial. A 1993 study by Hickey et al. concluded that introducing heated body garments in addition to heated handwear and footwear was not effective in a -40°C environment when supplying approximately 54 W of heating power to the torso [15]. While a 1998 study by Brajkovic et al. concluded that providing 111 W of heating power to the torso significantly increases hand and foot temperatures in a -25°C environemnt [17]. Different magnitudes of heating power provided to the torso and the difference of environmental air temperatures are likely the source of this discrepancy between the two studies. Additionally, the effects of torso heating on the extremities are also dependent on whole body or local physiology responses. If sufficient heat is applied, vasoconstriction will be relaxed, and heat carried by the blood will rewarm the extremities. Our modeling results show that increasing the heating power to the torso from 55 W to 100 W increases the foot T_s at -40°C environment (Figure 11), but does not increase the hand T_s (Figure 10). Thus, the differences are likely due to local physiological responses. In general, at lower environmental air temperatures, more heat from heated clothing is lost to the environment and thus the effectiveness is reduced.

Relatively low heating power values do not appear to improve upon unheated clothing configurations up until a certain threshold. The exact value of these thresholds varies with each body region and CIE type. When T_h in Eq.5 is lower than the corresponding clothing temperatures, the heated clothing will have no impact. In Figure 5 for example, 15 W of heating power does not show an improvement in hand T_s when compared to the same unheated clothing configuration. However, an incremental increase to 20 W of heating power shows a similar steady state hand T_s to the Target clothing configuration. This is likely due to the insufficient heating power not increasing the temperature of the clothing system adequately and therefore not improving upon unheated clothing configurations. In this case, the heat supplied to the heated clothing is lost almost entirely to the environment. It was observed in a manikin study that the efficiency of a heated vest reduces as the air tempeature reduces [32].

Quantifying the energy required for heated CIE is an important step to identify an appropriate energy source. This is especially important in military applications, where mobile energy sources (e.g., batteries) may be necessary and any added mass to the dismounted Soldier is not viewed favorably. Since mobile energy sources have a finite time of providing energy, predicting energy requirements for heated CIE can assist in planning mission exposure length in extreme cold environments. Energy predictions can also assist in determining the technical specifications and mass of a mobile energy sources. Thus, this report provides useful information to material developers.

The energy required to heat the CIE effectively will be dependent on the environmental conditions. A single set of environmental conditions (T_a = -40°C; wind speed = 1 $m \cdot s^{-1}$; Activity = sedentary) was chosen for this analysis as a single extreme cold case, but variations in these conditions will result in different energy requirements for heated CIE. For instance, if the air temperature decreases or the wind speed increases from the modeled conditions in this study, more energy will be required to provide thermal protection. Another dynamic element to the analysis is that "equivalent thermal protection" is only an adequate comparison as long as there is an energy source. Without an energy source (e.g., malfunction, depleted battery), thermal protection will be significantly degraded in certain cases due to the lower passive insulation of the clothing ensemble. Modeling results from the unheated configurations were provided for this reason. More work is necessary in order to expand the modeling analysis to how energy requirements of heated CIE vary with changes in environmental conditions, mainly ambient temperature and wind speed. Furthermore, the modifications made to SCTM for this study allow for the heating element to be placed within any layer of the clothing ensemble. This provides the capability for additional work to focus on the effect of heating element placement within different layers of CIE. Finally, since there were no functional prototypes available for testing at the time of the analysis, the energy calculations are theoretical and may be verified through physical experiments and human subject studies when prototypes are available.

CONCLUSIONS

The modeling results indicate that in order to provide thermal protection equivalent to the Target configuration, 20 W of heating power to the hand is required while wearing configuration 1H, 40 W of heating power to the foot is required while wearing configuration 2H, and 55 W of heating to the torso is required while wearing configuration 3H. Providing 55 W of heating to the torso does not show an improvement in the hand or foot T_s compared to the unheated configuration. However, increasing the heating power to 100 W to the torso predicts longer t_{endur} and t_{freeze}. Heating all three regions does not appear to provide a benefit for the hand T_s, but does show an improvement for the foot T_s. The performance of the heated configurations is based on the assumption that the heated CIE is energized and functioning properly.

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