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**DEVELOPMENT OF A COLD INJURY PREVENTION TOOL:
THE COLD WEATHER ENSEMBLE DECISION AID (COWEDA)**

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**United States Army
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USARIEM TECHNICAL REPORT T19-06

**DEVELOPMENT OF A COLD INJURY PREVENTION TOOL:
THE COLD WEATHER ENSEMBLE DECISION AID (CoWEDA)**

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EXECUTIVE SUMMARY

A state-of-the-art decision aid, the Cold Weather Ensemble Decision Aid (CoWEDA), has been developed to optimize readiness for cold weather operations, prevent cold injury, and provide guidance for mission planning and clothing selection. CoWEDA is an interactive decision aid that supplements information found in Army Technical Bulletin – Medical 508 (TB MED 508) “Prevention and Management of Cold-Weather Injuries”.

A new approach was developed to define the thermal performance of cold weather ensembles using physiological criteria (i.e., safety limits). Thermal performance is defined by endurance times, which are the durations before the physiological safety limits, corresponding to when the onset of frostbite, and hypothermia are reached, either for the extremities or the whole body. This novel human-centric approach ensures that the selected ensemble will provide adequate protection to prevent degradation of performance, nonfreezing cold injury (NFCI), frostbite, and hypothermia while avoiding excessive sweating.

New algorithms have been developed to predict thermal properties of multi-layer configurations. A database of thermal properties of individual military clothing item have been established. The ensemble performance metrics, new algorithms, clothing database and the USARIEM six-cylinder thermoregulatory model (SCTM) have been integrated into CoWEDA.

The CoWEDA is an innovative knowledge-based decision aid. It is the first tool available that allows users to build their own ensembles from the clothing inventory for each body region (i.e., underwear, pants, jackets, handwear, footwear and headgear), and then interpret their selection in the context of physiological responses to cold exposure. It is also the first tool that uses a human-centric approach, which evaluates the thermal performance of cold ensembles using physiological criteria.

INTRODUCTION

“Cold Still Kills: Cold-Related Illnesses in Military Practice Freezing and Non-Freezing Cold Injury” (1), the title of a review article, clearly indicates the persisting danger of cold weather during outdoor activities, such as military and emergency personnel, as well as other outdoor workers and winter sports enthusiasts. In the high Arctic, the extreme cold remains the persistent and capable enemy of Armed Forces, with temperatures as low as -60°C (2). Cold stress has deleterious effects on health, tolerance, and performance (3, 4). Despite advancement in personal protective equipment, cold injuries continue to afflict active duty members of the U.S. Armed Forces. From 2012 through 2017, a total of 2,717 members had at least one medical encounter for cold injury with a primary diagnosis of frostbite as the most common cold injury (5). Cold injuries have wide-ranging impacts on military readiness (1, 6). During “Exercise Arctic Ram” in February 2017, the environmental conditions were extremely cold, with an air temperature of -21°C and wind chill index of -44°C . Of the 126 Soldiers in this exercise, 21% developed frostbite (7). The extremities have the highest risk, with hands and feet the most susceptible, followed by the face and ears (7). Civilian populations are also at risk, with cold weather injury often seen in outdoor winter sports (8). An analysis of weather related deaths in the U.S. between 2006 and 2010 showed the incidences of weather related deaths to be approximately 2,000 annually, and 63% of them attributed to exposure to excessive natural cold, hypothermia, or both (9).

Cold stress degrades physical performance, results in lost duty days and non-combat casualties, and ultimately impacts the viability of military operations in extreme cold environments. Generally, cold weather injuries refer to whole body injuries such as hypothermia and local injuries such as nonfreezing cold injury (NFCI) and frostbite (1, 8, 10). When the skin temperature of an extremity is low, it causes discomfort, pain, numbness, performance deterioration and eventually local cold injury. In general, local pain is present when hand or foot temperature drops to below 15°C , and the pain become intolerable when the temperature drops to below 10°C . Numbness develops when the temperatures drop to about 5°C and risk of cold injury increases significantly

(10-12). Manual hand performance deteriorates as hand skin temperatures decrease. (12, 13, 14). Hand cooling begins to affect performance, at about 20-22°C, with an initial drop in manual dexterity. Below skin temperatures of 13-16°C, there is a significant decrease in finger dexterity, and at 6-8°C there is a rapid decline in tactile sensitivity (12, 14). Cold feet affect balance and walking, and may increase the risk of slipping (4). When whole body temperature is falls there is discomfort, which has negative effects on mental and physical performance, and can eventually lead to life-threatening hypothermia. Therefore, cold protection must address all of these related concerns.

Clothing is considered the primary deterrent to cold injury (8). Thus, proper selection of cold weather ensembles is the primary mitigation strategy for preventing cold injury, and is expected to provide protection against all cold injuries. At present, most methods of cold weather ensemble evaluation are mainly based on simple whole body heat balance equations. One such method is the required clothing insulation (IREQ) which was developed by Holmer (15, 16). It is the basis for the International Standard, ISO 11079: Ergonomics of the thermal environment – Determination and interpretation of cold stress when using required clothing insulation (IREQ) and local cooling effects (17). As the name implies, IREQ determines the required insulation of cold weather ensemble to maintain thermal comfort, taking into account environmental conditions and work intensity. When the insulation is low for a set of given conditions, IREQ also predicts an acceptable exposure time, i.e., duration limited exposure. ISO 11079 was also the basis for a computer program, PREDICTOL, which determines cold exposure limits (18). Another standard method, from the American Society of Testing and Materials (ASTM), is ASTM F2732-16, Standard Practice for Determining the Temperature Ratings for Cold Weather Protective Clothing (19). This ASTM standard predicts the temperature rating for comfort at two activity levels (2 or 4 MET; 1 MET = 58.2 W·m⁻²) using simple whole-body heat loss models. ASTM F2732-16 does not provide any guidance or evaluation for extremity (hands and feet) protection, and ISO 11079 only provides general guidance and directs readers to standard EN 511, Protective gloves against cold, for more information on glove protection. In addition, both methods use ensemble insulation as the major index, which is difficult for end

users to understand and how to interpret its meaning in terms of equivalence to clothing items, operation duration and potential risks of cold injury.

The Department of Defense clothing community, materiel developers, purchasers, and users have significant interests in how long a specific ensemble allows Soldiers to function in a given set of environmental conditions or which ensemble configuration are needed for specific mission profiles. In the civilian world, outdoor workers such as Arctic open-pit miners select their winter clothing for operations in a cold environment, taking into account task duration and environmental conditions (20). It is clear that the two existing methods of cold weather ensemble evaluation, ASTM F2732-16 and ISO 11079, are insufficient, particularly for evaluating clothing items on the extremities.

The objective of this project was to develop a method or tool that addresses complicated requirements of cold protection, and specify/evaluate the thermal performance of cold weather ensembles. This project has four specific goals: 1) develop an innovative approach for quantifying thermal performance of cold weather ensembles using physiological criteria or safety limits; 2) develop a new approach to express ensemble thermal properties as a function of the thermal properties of individual clothing items; 3) develop an approach for translating the ensemble thermal properties into meaningful criteria of safe operation limits using thermoregulatory modeling; and 4) develop a user-friendly software application on mobile and desktop platforms, the Cold Weather Ensemble Decision Aid (CoWEDA), to enable Commanders and individual Soldiers use of this new science and knowledge in operational settings.

METHODS

HUMAN-CENTRIC THERMAL PERFORMANCE OF COLD WEATHER ENSEMBLE

Thermal performance of cold weather ensembles can be quantified using measurable physiological criteria. The specific metrics include endurance times, which

are the times predicted for selected physiological parameters (i.e., core temperature, toe and finger skin temperatures, and skin wettedness) to reach a significant risk level. The physiological criteria in Table 1 are used to define endurance times and to evaluate and quantify the thermal performance of cold weather ensembles. The potential for frostbite increases significantly when local skin temperatures drop below the safety limit of 5°C. The risk of hypothermic injury increases when the core temperature falls below the physiologically based threshold of 36°C for mild hypothermia. The endurance times are the safe period for operation before local surface or core body temperatures drop below the physiologically based safety criteria (Table 1).

Exercise increases body heat production, and therefore less insulation is required to maintain body heat balance in cold conditions. On the other hand, exercise also causes sweat and sweat accumulation in the clothing (usually in the underwear layer), if the rate of heat production exceeds the rate of heat loss, wet clothing which reduces the effective insulation (i.e., protection level) may increase the risk of cold injury. Thus, the selection of appropriate ensembles is complicated by exercise and complex work patterns related to resting conditions. The objectives of selecting an appropriate clothing ensemble for exercise are not only to control heat loss in order to maintain a heat balance to prevent cold injuries and to optimize endurance time for the mission, but also to avoid overheating and excessive sweating. Thus, the thermal performance of cold weather ensembles is also defined by the time it takes for skin wettedness, caused by accumulation of sweat on the skin, to increase to the critical value. An optional criterion is that the skin temperature should be maintained within the range of thermal comfort, i.e. between the minimum and maximum skin temperatures. Table 2 shows the additional or optional physiological criteria that are used to evaluate the thermal performance of cold weather ensembles relative to comfort while exercising.

Table 1 Physiological criteria for thermal performance of cold weather ensembles

Thermal performance	Physiological parameters	Criteria	Physiological symptoms
Functional time	Core temperature	36°C	<ul style="list-style-type: none"> • Mild hypothermia
Hand endurance time	Hand skin temperature	5°C	<ul style="list-style-type: none"> • Extreme pain or numbness • Cold injury • Significant impairment in manual dexterity
Foot endurance time	Foot skin temperature	5°C	<ul style="list-style-type: none"> • Extreme pain or numbness • Cold injury
Exposed skin	Skin temperature	5°C	<ul style="list-style-type: none"> • Extreme pain or numbness • Cold injury

Table 2 Additional physiological criteria for thermal performance of cold weather ensembles during exercise

Thermal Performance	Physiological parameters	Criteria	Physiological symptoms
Sweat time	Skin wettedness	0.5	Skin & underwear getting wet
Thermal comfort	Minimum skin temperature Maximum skin temperature	$T_{s,min}$ $T_{s,max}$	<ul style="list-style-type: none"> • $T_{s,min} < T_s < T_{s,max}$ Comfortable • $T_s < T_{s,min}$ Limited duration Uncomfortable cold • $T_s > T_{s,max}$ Unlimited duration Overheating Underwear getting wet

The minimal and maximal skin temperatures for thermal comfort are calculated using the following equations (17, 21, 22):

$$T_{s,min} = 33.34 - 0.035 \cdot M \quad (\text{Eq. 1})$$

$$T_{s,max} = 35.7 - 0.0285 \cdot M \quad (\text{Eq. 2})$$

where M is the rate of metabolic heat production in $\text{W}\cdot\text{m}^{-2}$.

Temperature thresholds for the sedentary and active phases in Table 1 and Table 2 are based on ISO standard 11079 and published values in the literature (17, 23-26) as well as information from the expertise of USARIEM investigators conducting human thermal physiology research. The temperature thresholds may be refined or revised when new results from relevant human research studies become available.

Ensemble requirements during rest and during exercise differ. Based on observations, a cold ensemble that was suitable for guard duty, is often inappropriate for hiking (27). CoWEDA addresses this issue by separating the ensemble selection process into two distinct categories: ensembles for rest and for exercise. For the rest condition, the maximum simulation duration is set for 24 hours. The duration of exercise and other physically challenging activities is limited by the intensity of the activity and cannot be sustained indefinitely. U.S. Army load carriage guidelines (Field manual 21-18) suggest that the duration is less than 4 hours when exercise intensity is moderate i.e., $\sim 360 \text{ W}$ (28). Thus, for the exercise condition, the simulation duration is set to a maximum time limit of four hours and the work intensity during this period is assumed to be constant (i.e. continuous, with no work/rest cycles) for a selected activity intensity. If the ensemble meets the physiological criteria for a 4 hour period, the ensemble would be considered acceptable.

THERMOREGULATORY MODEL

The thermoregulatory model used for CoWEDA is the six cylinder

thermoregulatory model (SCTM). SCTM predicts human thermal responses during heat exposure and prolonged cold exposure in air or water. It takes into account physiological mechanisms, including metabolic heat production, sweating heat loss, respiratory heat loss, and blood circulation. It is able to predict both core and regional temperatures, and evaporative water loss through the skin and lungs, which can then be used to estimate time until dehydration occurs.

SCTM was derived from an earlier version of a thermoregulatory model developed by Werner and Webb (29) which was, in turn, based on the pioneering work of Stolwijk and Hardy (30). The original model consisted of six two layer cylinders, an outer shell and a core layer. In the the current version of SCTM, muscle, fat, and clothing layers were added (31) and a conceptual model for shivering intensity and fatigue was incorporated (32). These additions improved the model prediction of human responses to long-term cold exposure. Each cylinder is now divided into concentric compartments representing the core, muscle, fat, and skin. Circulation is represented as a one-loop circulatory system and is an independent compartment, which is not treated as a layer. Thus, the human body is represented by 25 compartments; i.e., six cylinders with four layers and one blood pool. The size of each compartment is derived using height, weight, and body fat percentage (33). Those SCTM compartments represent the biological components of SCTM. There is an optional outer cylinder which may be used to represent the clothing layer, which is a key element in CoWEDA.

In the active or control system of the model, an integrated thermal signal is sent to the thermoregulatory controller, consisting of the weighted thermal inputs from thermal receptors at various sites distributed throughout the body. The integrated body temperature is weighted using different values for the core, muscle, and skin compartment temperatures. The afferent signal is the difference between this body temperature and its threshold, which activates various thermoregulatory responses, including vasomotor changes, sweat production, and metabolic heat production (31). Shivering thermogenesis (i.e., part of metabolic heat production) is a function of core and mean skin temperatures, and includes adjustments for intensity, maximal capability,

shivering exhaustion, and inhibition due to a low core temperature (32). The maximal shivering intensity was estimated from the height, weight, and age (34).

The SCTM has been validated for a broad range of conditions, including heat and cold air exposures (31), prolonged cold exposure to air and water (32), exercise during cold water immersion (35-37), and prolonged exposure to cold water immersion for up to 75 hours (38). The SCTM has been used to assess heat strain in protective ensembles (39, 40) and liquid cooling garments in the heat (41), including the design of controllers for the cooling garments (42, 43). The SCTM also underpins USARIEM's Probability of Survival Decision Aid (PSDA) (38, 44, 45) which has been incorporated into the United States Coast Guard (USCG) Search and Rescue (SAR) operations since June 2010 (38, 46). USCG has mandated PSDA use in SAR cases where victims are at risk of hypothermia or dehydration.

SCTM inputs include individual characteristics (i.e., height, weight, body fat percentage, age) and level of activity, as well as environmental (i.e., air temperature, humidity, and air velocity) and clothing (i.e., thermal resistance and evaporative resistance) properties for each of the six cylinders.

DATABASE OF CLOTHING BIOPHYSICAL PROPERTIES

A paradigm of testing all individual layers of a multi-layer clothing system was developed and used to test all of the layers or components of military clothing systems (47, 48). Table 3 lists thermal and evaporative resistance of 13 individual clothing items. In addition, new algorithms were developed to predict thermal and evaporative resistances for multi-layer configurations based on thermal and evaporative resistances of individual layers or items. These regional thermal and evaporative resistances of ensembles are inputs for the SCTM. The US Army cold weather ensemble inventory has more than 50 items, including clothing, headgear, handwear, and footwear. Thermal and evaporative resistances of these items are included in the database.

Table 3 Thermal and evaporative resistances of individual clothing items

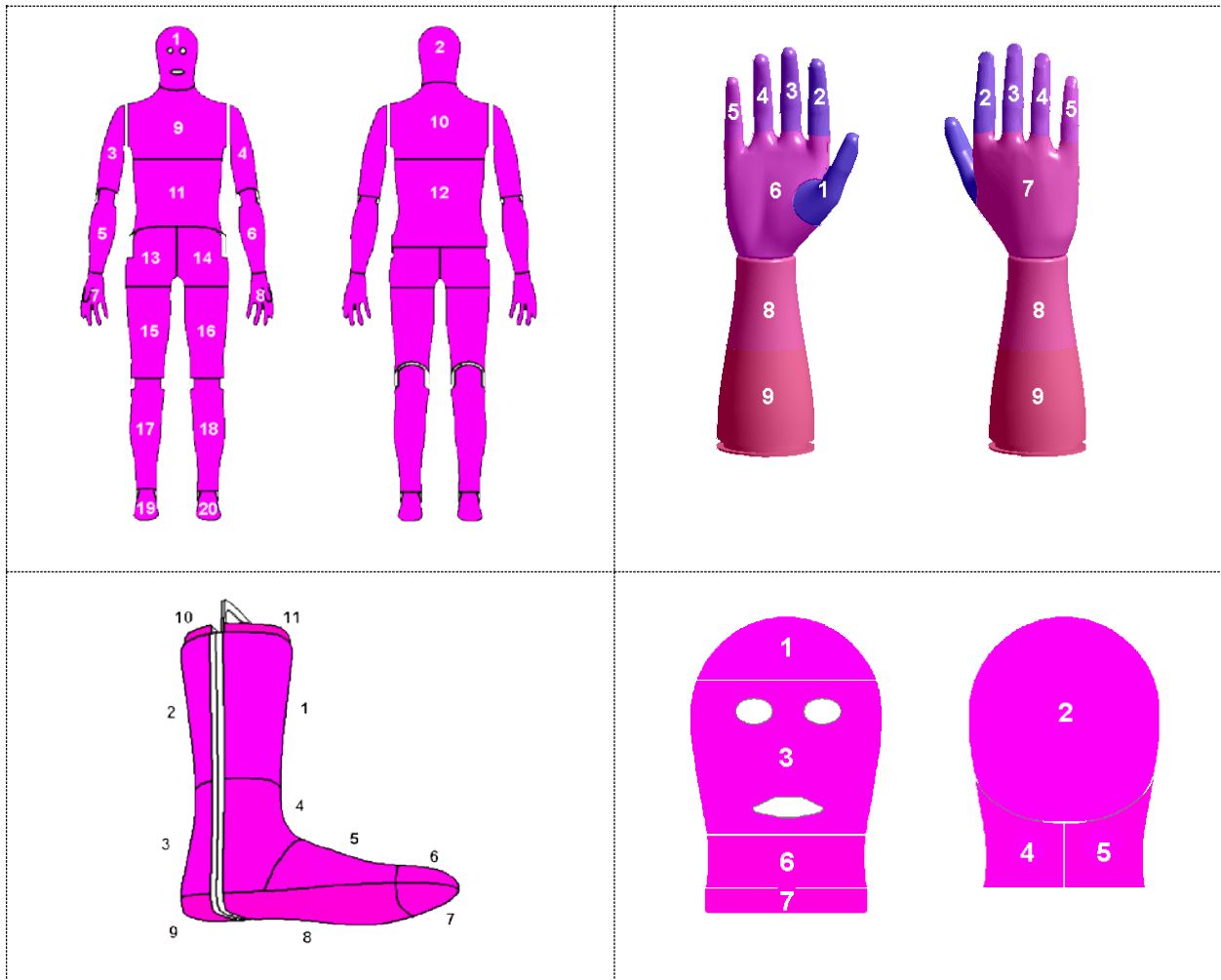
Item Name	Thermal Resistance						Evaporative Resistance					
	head	torso	arm	hand	leg	foot	head	torso	arm	hand	leg	foot
Gen III ECWCS Lightweight Cold Weather Undershirt	0.000	0.086	0.064	0.014	0.002	0.002	0.00	9.86	6.52	0.00	1.02	0.00
Gen III ECWCS Lightweight Cold Weather Drawers	0.000	0.022	0.000	0.000	0.052	0.004	0.00	3.31	1.03	0.00	6.81	1.04
Gen III ECWCS Midweight Cold Weather Shirt	0.004	0.107	0.105	0.025	0.000	0.000	0.32	12.96	13.33	0.46	0.00	0.00
Gen III ECWCS Midweight Cold Weather Drawers	0.000	0.026	0.000	0.002	0.092	0.005	0.00	3.41	0.01	0.00	10.08	0.00
Gen III ECWCS Fleece Cold Weather Jacket	0.008	0.163	0.204	0.009	0.001	0.003	0.47	14.20	21.70	0.00	0.03	0.00
Gen III ECWCS Cold Weather Wind Jacket	0.000	0.109	0.085	0.004	0.001	0.003	0.00	13.63	16.27	0.00	0.00	0.00
Gen III ECWCS Soft Shell Jacket	0.005	0.147	0.101	0.004	0.001	0.003	0.09	46.13	55.94	0.00	0.00	0.00
Gen III ECWCS Soft Shell Trouser	0.000	0.045	0.000	0.004	0.117	0.000	0.00	8.06	0.95	2.20	70.57	0.00
Gen III ECWCS Cold Wet Weather Jacket	0.003	0.136	0.107	0.006	0.001	0.002	0.00	34.25	31.81	0.00	0.00	0.11
Gen III ECWCS Cold Wet Weather Trouser	0.000	0.031	0.000	0.008	0.109	0.003	0.00	5.58	0.00	0.00	39.38	0.00
Gen III ECWCS Extreme Cold Weather Parka (stowed hood)	0.000	0.572	0.456	0.021	0.002	0.000	0.00	65.91	65.41	0.46	0.00	0.00
Gen III ECWCS Extreme Cold Weather Trouser	0.000	0.052	0.000	0.009	0.387	0.000	0.00	7.41	0.60	0.00	69.06	0.00
Gen III ECWCS Extreme Cold Weather Parka (freed hood)	0.141	0.572	0.456	0.021	0.002	0.000	29.87	65.91	65.41	0.46	0.00	0.00

A more detailed description of the measurement method, database details, and algorithms will be detailed in a separate report. The thermal and evaporative properties of clothing were measured with thermal manikins. Figure 1 shows the whole-body, hand, foot, and head sweating thermal manikins (Thermetrics, Seattle, WA; www.Thermetrics.com). USARIEM's whole-body manikins are Newton models consisting of 20 independently heated and controlled zones, which includes one zone in each hand or foot and two zones in the head. To obtain more accurate values for hand, foot and head clothing items, clothing items are tested separately on sectional "parts" manikins. The thermal hand manikin is used to test handwear and effectively has eight zones with an additional guard zone beginning around the middle of the forearm. The thermal foot manikin is used to test boots and other footwear systems, including socks. It has nine effective zones and two additional guard zones at the top of the foot, zones 10 and 11. The head thermal manikin is used to test headgear and effectively has six independently heated and controlled zones that make up the measurement area. There is an additional guard zone at the neck to prevent heat loss downward through the neck. The manikin systems are controlled, and all parameters are recorded and processed, by ThermDAC software.

All manikin testing was conducted according to ASTM International standards F1291-16 and F2370-16 (49, 50). Thermal resistance (1 clo = 0.155 m²·K·W⁻¹) was

measured at an air velocity of $0.4 \text{ m}\cdot\text{s}^{-1}$ with the air temperature (T_a) and relative humidity (RH) inside the environmental chamber at 20°C and $50\%\text{RH}$, respectively. Evaporative resistance ($\text{m}^2\cdot\text{Pa}\cdot\text{W}^{-1}$) was measured at an air velocity of $0.4 \text{ m}\cdot\text{s}^{-1}$ with a T_a of 35°C and an RH of 40% . Three test replications were completed for each clothing configuration.

Figure 1 Zone diagrams from ThermDAC software of the whole-body, hand, foot and head thermal manikin



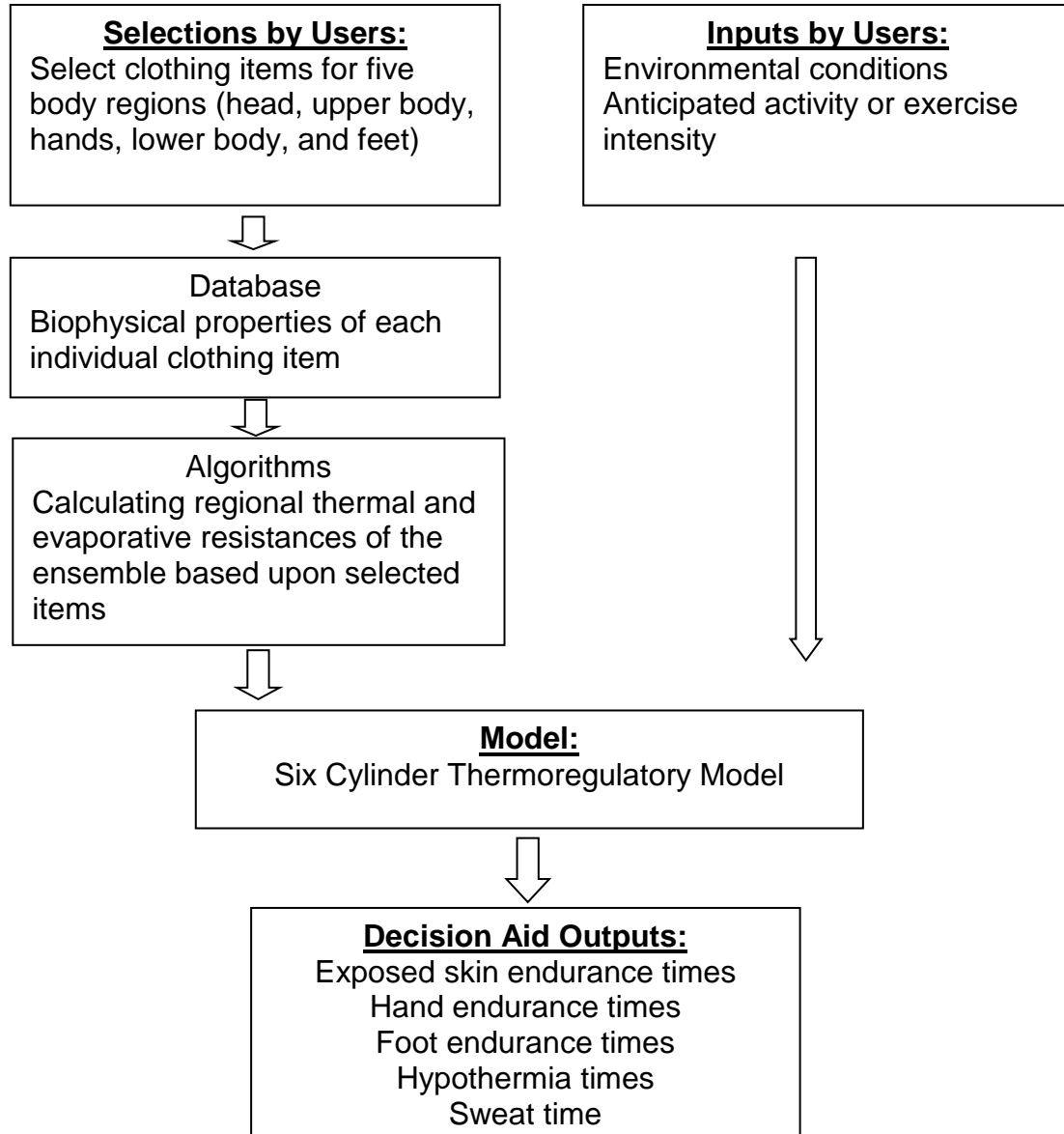
SYSTEM FLOWCHART

Figure 2 shows a software flow chart for of CoWEDA and Figure 3 shows a prototype user interface. As shown in Figure 3, users will select clothing items by body regions (e.g., head, torso, hands), enter environmental conditions, select activity or enter activity levels, and then CoWEDA will display endurance times (i.e., safe exposure times to avoid hypothermia and extremity injuries). The database of biophysical properties includes intrinsic thermal and evaporative resistance values for individual clothing items

of the US Army and USMC Cold Weather Clothing Systems. The newly developed USARIEM algorithms will calculate the regional thermal and evaporative resistances of ensembles based upon the values of the selected individual clothing items. The regional thermal and evaporative resistances of the ensemble are SCTM inputs.

CoWEDA integrates physiological criteria, SCTM, the database of clothing biophysical properties, and algorithms for calculating biophysical properties of the selected ensemble into a user-friendly software application. It has been developed to translate the research outcomes and knowledge, clothing science, and the new algorithms into actionable information for end users, such as military leadership, Soldiers, planners, clothing designers, and materiel developers.

Figure 2 Cold Weather Ensemble Decision Aid Flowchart



COLD WEATHER ENSEMBLE DECISION AID (CoWEDA)

Figure 3 shows the CoWEDA user interface. The inputs for CoWEDA are environmental conditions, activity or work intensity, and clothing items selected by users. The CoWEDA results are presented as:

- 1) Endurance time of the exposed body area, i.e. uncovered body area, the time it takes for the temperature of skin exposed to air to drop to 5 °C, indicating frostbite is likely to occur;
- 2) Hand endurance time is the time for the predicted hand skin temperature to reach 5 °C (46 or 41 °F), indicating that frostbite is likely to occur; below the threshold, the probability or risk of a cold injury increases significantly;
- 3) Foot endurance time is the time until the predicted foot skin temperature reaches 5 °C or 41 °F, indicating that NFCl is likely to occur; below the threshold, the probability or risk of an injury increases significantly;
- 4) Body endurance time is the time until the predicted core temperature reaches 36°C or 96.8 °F, indicating hypothermia is likely to occur, which can be lethal;
- 5) Sweat time is the time until the predicted skin wettedness reaches 0.5, indicating underwear starts to get uncomfortably wet and reduction of insulation can be expected.

The information above is human-centric and provide useful guidance for military users, such as Commanders and Soldiers, which will enable them to select the most appropriate cold weather ensemble(s) relative to anticipated mission physical activities and environmental conditions. CoWEDA translates the properties of the clothing ensemble chosen by users into safe operating limits, based on human physiology, to help users understand what their selection means in terms of operational time restraints and risks of cold injury. The ultimate goal of the CoWEDA is to optimize readiness, reduce the risk of cold injury, and ensure operational success.

The CoWEDA was designed to be simple to use, clear and user-friendly. The input of environmental conditions is simple, as in Figure 3. Activities for common tasks can be selected through a pull down menu, as shown in Figure 4. The clothing selection panel provides options to select clothing for five body regions: head, upper body, hand, lower body and foot, as shown in Figure 3. When the cursor is hovered over the body zone, it shows the selected clothing for the zone, as shown in Figure 5. When clicking the dropdown icon “v” on the right, the panel displays the menu of clothing options for each zone, as shown in Figure 6. After clicking the box next to a

specific clothing item, a “✓” will now be displayed indicating the item is included in the ensemble. Clicking the “✓” in the box next to the clothing items will remove this item from the ensemble.

Figure 3 Cold Weather Ensemble Decision Aid (CoWEDA)

Cold Weather Ensemble Decision Aid [0.4.2.15892 (3/3/2018 8:49:44 AM)]

Menu Help

USARIEM Cold Weather Ensemble Decision Aid

Environment

Air Temperature: -10.9 °C

Relative Humidity: 35.6 %

Wind Speed: 7 m/s

Activity

Avg Watts: 0.0

Command Buttons

Reset All Details

Results

Body Section: Number of Hours Until Critical Temperature

Exposed(Frostbite)	0.4 Hrs	Inadequate
Feet(Frostbite)	1.2 Hrs	Limited
Hands(Frostbite)	1 Hrs	Inadequate
Body(Hypothermia)	22 Hrs	Ideal
Comfort (Until Sweating)	24 Hrs	

Preset Clothing Selections

Mild Cold Weather Gear Save

Clothing Selection

Head

Upper Body

Gloves

Lower Body

Boots

Figure 4 Activity panel pull down menu

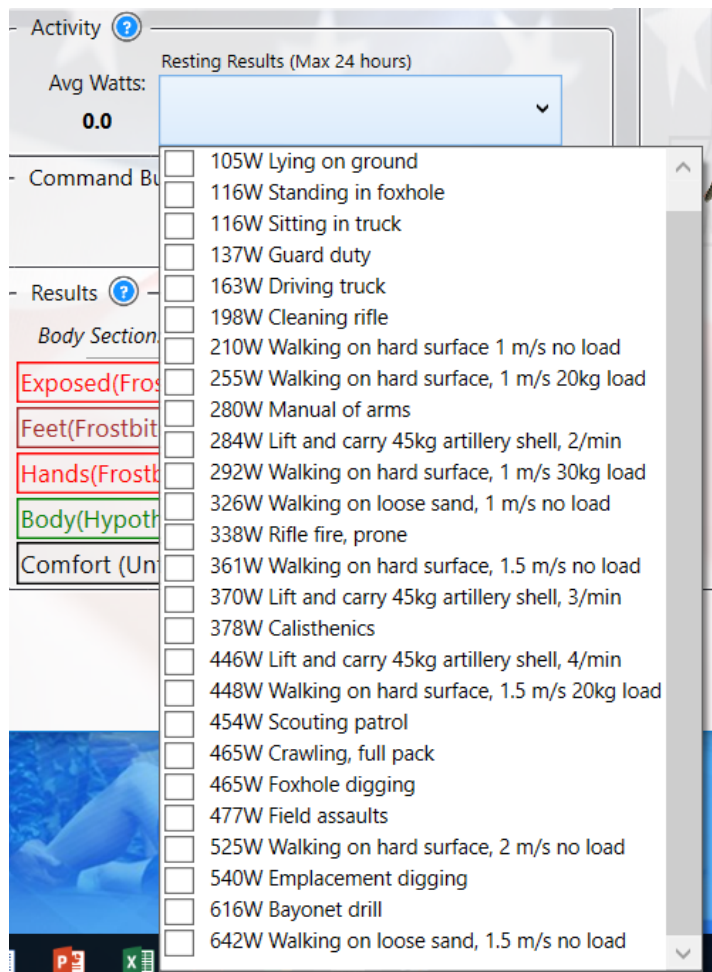


Figure 5 Selected clothing for the region

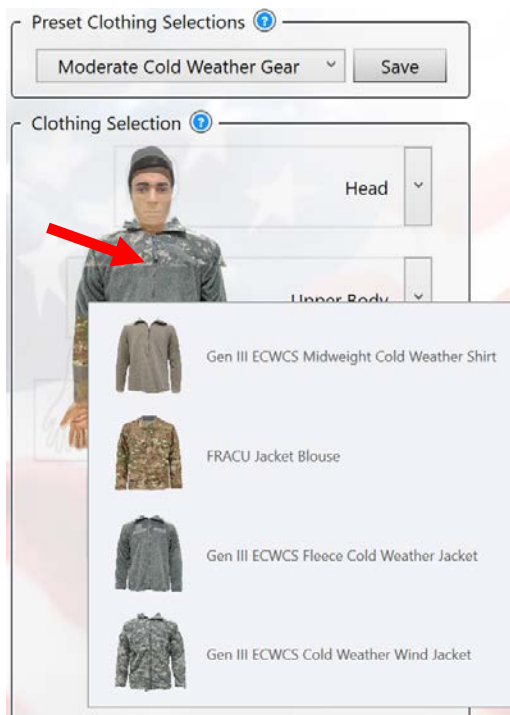
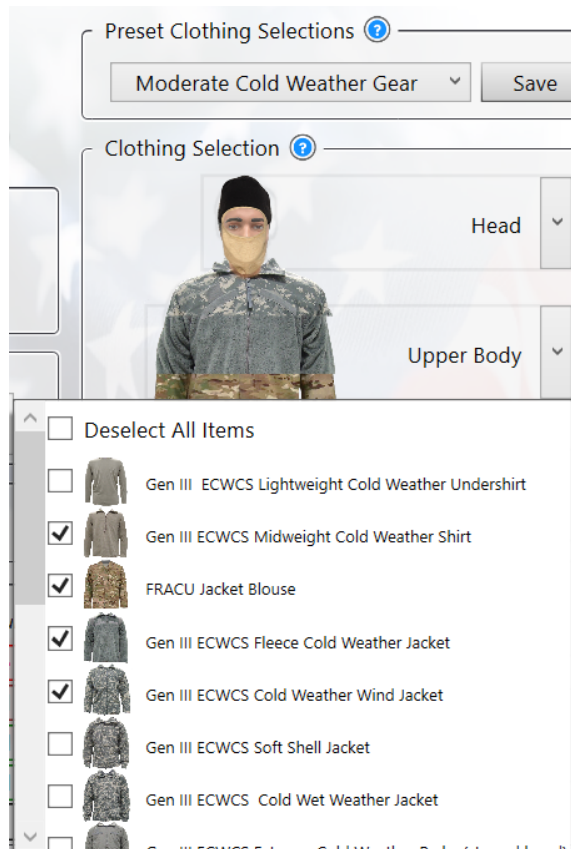


Figure 6 Menu of clothing options for each body region



VALIDATION WITH HUMAN STUDIES

2017 Human study with Generation III Extended Cold Weather Clothing System

Eight volunteers (2 women; 6 men) sat quietly at an ambient temperature of $0.48 \pm 0.53^{\circ}\text{C}$ and relative humidity of $51 \pm 3\%$ with a wind velocity of $1.34 \text{ m}\cdot\text{s}^{-1}$ for 120 minutes (51). They wore 3 layers of the Army Extended Cold Weather Clothing Ensemble on the torso (silk weight underwear, fleece mid-layer, and soft shell outer layer) and 2 layers on the legs (silk weight underwear, and soft shell outer layer) as well as wool socks, the Army Improved Intermediate Cold-Wet Boot and an Army fleece hat, but were bare-handed throughout the exposures. Skin temperature and heat flux (HF) of the volunteers' non-dominant side were measured at 13 sites (forehead, cheek, chest, anterior thigh, triceps, subscapula, abdomen, ventral aspect of forearm, dorsal aspect of hand, dorsal aspect of 4th finger on the middle phalanx, calf, dorsal aspect of foot, and dorsal aspect of the 1st toe) every minute throughout the baseline and cold experimental time periods. An 11-site formula was used for calculating mean weighted T_{sk} . Mean T_{sk} was calculated using a weighted, 11-site formula.

CoWEDA was used to simulate the thermal responses. The ensembles used in the study are the same as the ones which are included in the CoWEDA database. The clothing was selected as described above. Measured (mean \pm SD) and CoWEDA predicted temperatures are shown in Table 4. Most of the predicted values are within the range of measured \pm SD.

Table 4 Measured skin temperatures (mean \pm SD) and predicted skin temperatures at min 90 during the trial

	Measured $^{\circ}\text{C}$	Predicted $^{\circ}\text{C}$
Hand	15.44 ± 1.43	
Finger	9.15 ± 2.59	10.5
Foot	23.25 ± 1.39	
Toe	16.14 ± 1.93	15.4
Forearm	28.03 ± 1.90	28.1
Cheek	21.06 ± 2.02	
Forehead	30.84 ± 1.84	27.2
Mean skin	27.10 ± 1.00	27.3

1989 Human study with Extended Cold Weather Clothing System

In 1989, a human study was conducted to evaluate the human thermoregulatory responses of wearing the original Extended Cold Weather Clothing System (ECWCS I) at rest or during exercise (24). The ECWCS ensemble tested (insulation: 3.6 clo, weight: 10.1 kg) consisted of skin-tight polypropylene underwear, polyester/cotton fatigues, polyester-insulated liners, balaclava, vapor-barrier boots, and polytetrafluorethylene-lined outer garments plus handwear. ECWCS includes three different handwear options; the light duty glove (LD, total insulation 0.86 clo), a heavy duty glove (HD, insulation 1.05 clo), and an Arctic mitten (AM, insulation 1.46 clo). Six fit males both rested ($M = 71 \text{ W}\cdot\text{m}^{-2}$) and did treadmill exercise (speed $0.98 \text{ m}\cdot\text{s}^{-1}$, $M = 171 \text{ W}\cdot\text{m}^{-2}$) during exposure to -0°C , -20°C , and -30°C , RH 20% and air velocity $1.34 \text{ m}\cdot\text{s}^{-1}$ for a maximum exposure time of 120 min (2 hours) after a 15 min baseline period. Rectal (T_{core}), middle finger (T_{mf}), and mean weighted skin (T_{sk} , 10 sites) temperatures were recorded continuously. As Table 5 indicates, not all clothing was tested.

The finger temperatures and mean skin temperatures predicted by CoWEDA were compared with the measured values, as show in Table 5 and Table 6. Due to changes in the ECWCS system, over time, it was necessary to select clothing items from the ECWCS III database that were similar to the original ECWCS clothing items. The selected clothing items were the balaclava, lightweight undershirt and drawers, soft shell jacket and trouser, the extreme cold weather parka and trousers, and the vapor-barrier boots. The handwear items selected for input into CoWEDA were essentially equivalent to the handwear used in the study. During the exercise in the study, the metabolic rate was $\sim 326 \text{ W}$, and that value was used in the CoWEDA prediction.

Table 5 Measured and CoWEDA predicted finger temperatures at the end of rest and exercise at 0, -20 and -30°C wearing three different gloves and Extended Cold Weather Clothing System (ECWCS)

Conditions	Ta °C	M (W·m ⁻²)	Duration min	Measured finger °C	Predicted finger °C
LD Rest	0	67	116	12.5 ± 0.5	14.29
LD Rest	-20	69	62	7.9 ± 1.9	9.30
LD Rest	-30	88	37	6.9 ± 2.7	9.10
LD Ex	0	169	115	31.5 ± 2.4	25.37
LD Ex	-20	169	111	21.1 ± 8.1	19.80
HD Rest	0	60	108	11.3 ± 2.3	14.71
HD Rest	-20	60	62	8.7 ± 2.8	9.47
HD Rest	-30	64	46	7.0 ± 1.8	7.26
HD Ex	0	164	120	29.0 ± 3.4	25.76
HD Ex	-20	174	120	28.2 ± 3.4	20.41
HD Ex	-30	169	71	16.2 ± 9.4	15.81
AM Rest	0	64	120	18.9 ± 6.0	17.15
AM Rest	-20	65	81	7.6 ± 1.5	10.96
AM Ex	0	168	120	33.8 ± 1.8	28.15
AM Ex	-30	171	79	16.1 ± 10.5	19.84

Table 6 Measured and CoWEDA predicted mean skin temperatures at the end of rest and exercise at 0, -20 and -30°C wearing three different gloves and Extended Cold Weather Clothing System (ECWCS)

Conditions	Ta °C	M (W·m ⁻²)	Duration min	Measured mean skin °C	Predicted mean skin °C
LD Rest	0	67	116	31.1 ± 0.9	30.21
LD Rest	-20	69	62	29.3 ± 1.8	28.16
LD Rest	-30	88	37	29.2 ± 0.7	27.99
LD Ex	0	169	115	32.7 ± 0.5	34.65
LD Ex	-20	169	111	31.0 ± 0.8	31.19
HD Rest	0	60	108	30.9 ± 1.0	30.27
HD Rest	-20	60	62	28.9 ± 1.1	28.18
HD Rest	-30	64	46	29.2 ± 2.1	27.19
HD Ex	0	164	120	32.7 ± 1.0	34.69
HD Ex	-20	174	120	30.5 ± 0.9	31.28
HD Ex	-30	169	71	28.9 ± 2.2	29.69
AM Rest	0	64	120	31.2 ± 0.8	30.37
AM Rest	-20	65	81	29.1 ± 1.6	27.80
AM Ex	0	168	120	32.7 ± 1.4	34.93
AM Ex	-30	171	79	29.8 ± 1.0	29.97

1993 Human study with Extended Cold Weather Clothing System

Four Soldiers wore an ECWCS clothing ensemble during 2-hour exposures to a -40°C environmental condition (52). The Soldiers' temperatures were monitored with thermistors placed on the tip of the middle finger, inside the large toes, and below the scapula; and a rectal thermistor was inserted to a depth of 10 cm. These thermistors were hardwired to a data logger, and the temperatures were recorded at 5-minute intervals during each trial. One of the criteria for termination of an exposure session was if and when a skin temperature fell below 10°C.

Table 7 Measured skin temperatures (mean \pm SD) and predicted skin temperatures at 100 min. (termination time) during the trial

	Measured °C	Predicted °C
Finger	10.3 \pm 1.0	11.3
Toe	13.2 \pm 1.3	-4.3
Back	30.6 \pm 1.2	30.6

Validation summary

Figure 7 summarizes the measured and predicted finger or toe temperatures from these three studies. Among nineteen comparisons, twelve predicted temperatures were within the range of measured values \pm SD. Figure 8 summarizes the measured and predicted mean skin, forearm and back temperatures from the three studies. Among nineteen comparisons, fourteen predicted temperatures were within the range of measured \pm SD. Of thirty eight comparisons, twenty six predicted temperatures were within the range of measured \pm SD. This indicates that prediction accuracy is 68%. Given individual differences observed in experiments, the predictions were considered acceptable.

Figure 7 Comparison of measured and CoWEDA predicted finger or toe temperatures at the end of rest and exercise at 0, -20, -30 and -40°C wearing three different gloves and Extended Cold Weather Clothing System (ECWCS)

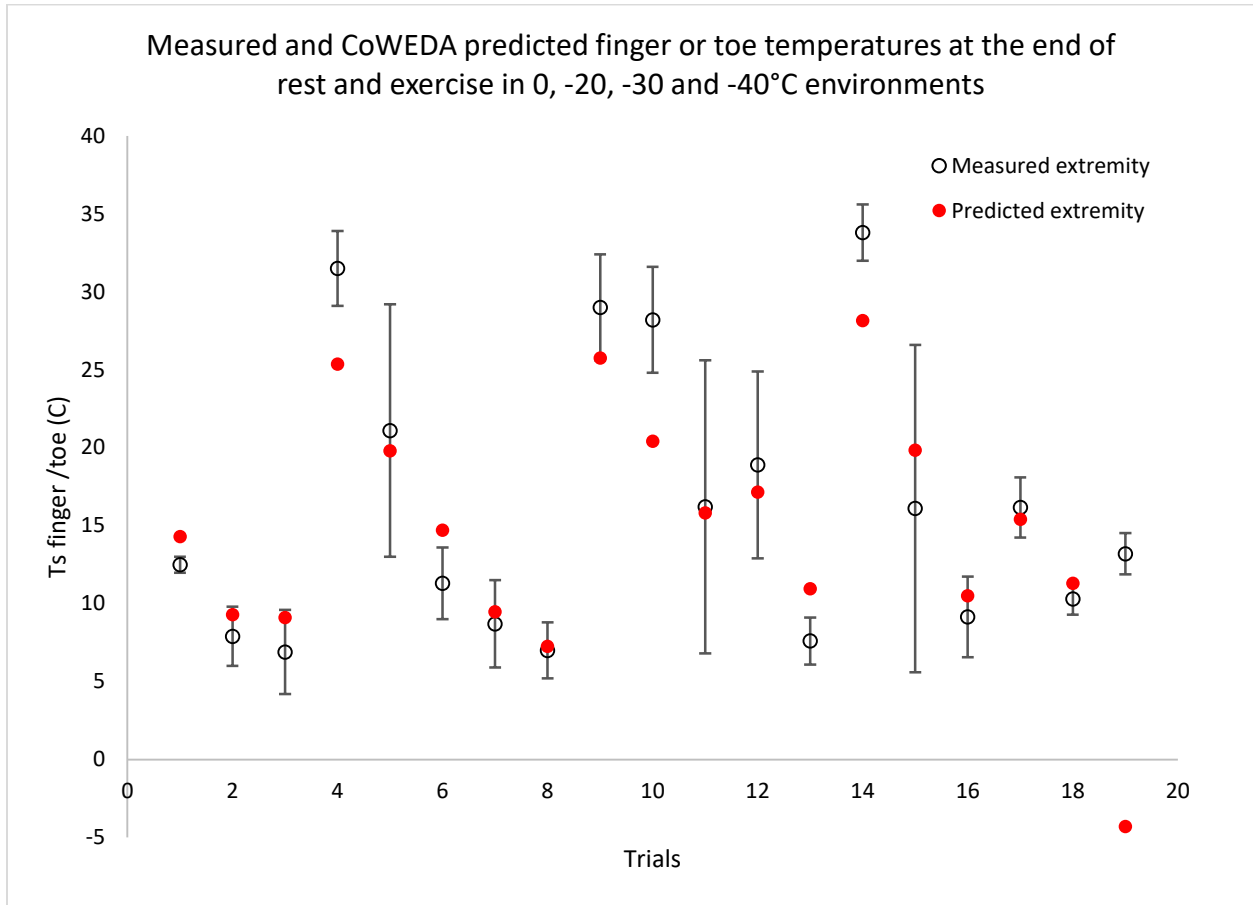
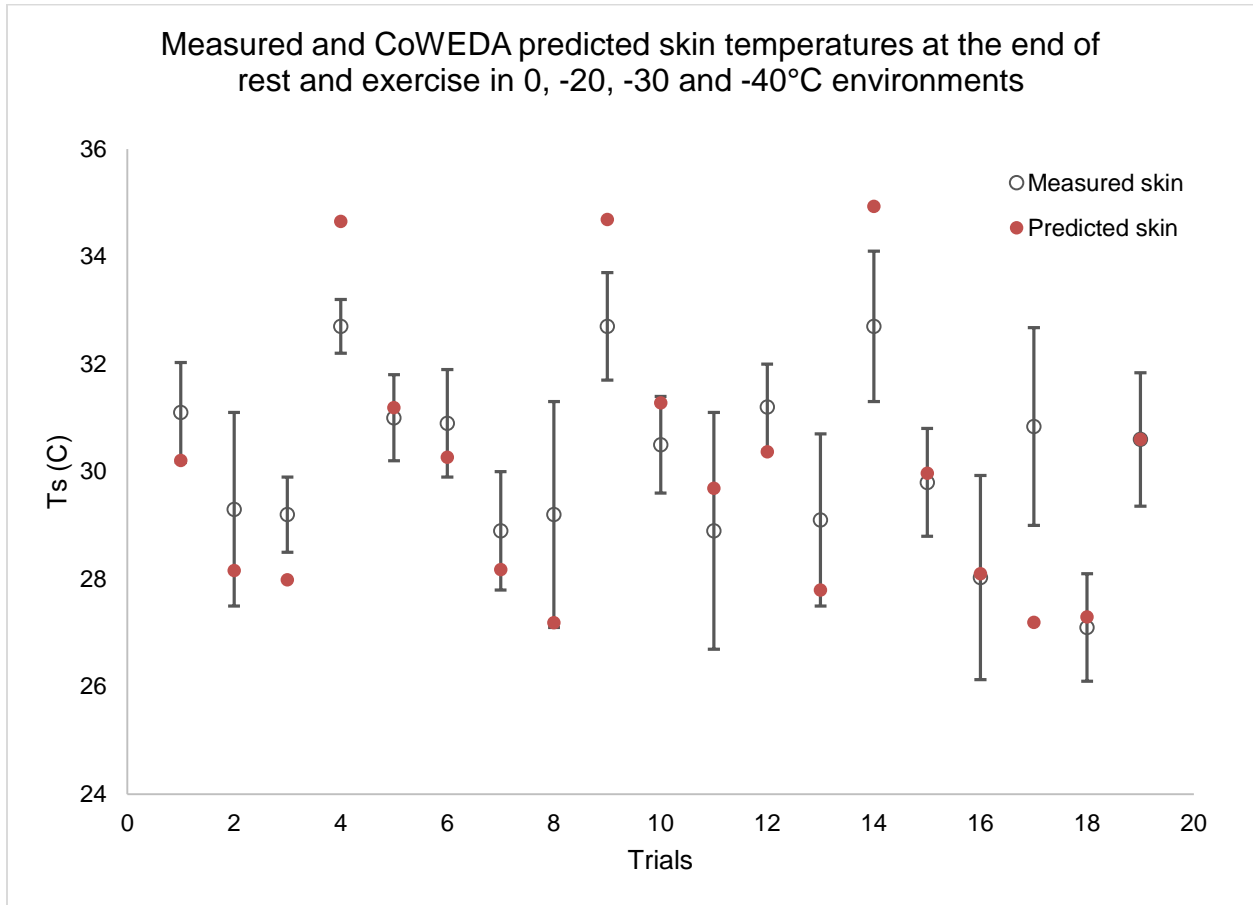


Figure 8 Comparison of measured and CoWEDA predicted mean skin temperatures at the end of rest and exercise at 0, -20, -30 and -40°C wearing three different gloves and Extended Cold Weather Clothing System (ECWCS)



DISCUSSION

CoWEDA is an innovative knowledge-based decision aid that can be used by users, such as Commanders and Soldiers, to guide selection of the most appropriate cold weather ensemble(s) relative to anticipated activities and environmental conditions. The novel feature of the CoWEDA is the integration of the USARIEM six-cylinder thermoregulatory model (SCTM), physiological criteria, a database of clothing biophysical properties, and new algorithms for calculating ensemble thermal and evaporative resistances into a single user-friendly software application. CoWEDA is the first tool that uses a human-centric approach, focuses on human performance and safety, and evaluates the thermal performances of cold ensemble using physiological criteria (i.e., safety limits). It is the first tool that allows users to build their own ensembles from the inventory, and interpret the selection using physiological terms and consequences. The CoWEDA is the first interactive tool for cold weather ensemble selection that can be used to supplement information found in Army Technical Bulletin – Medical 508 (TB MED 508) “Prevention and Management of Cold-Weather Injuries”. Comparison with measured skin temperatures during exposure to 0 to -40°C environments shows that the current accuracy of CoWEDA prediction is ~68%. CoWEDA is a state-of-the-art tool for cold readiness optimization, cold injury prevention, mission planning, and clothing selection.

CoWEDA is human-centric and aims to prevent cold injury and ensure optimal human performance. Two current international standards, ISO 11079 and ASTM F2732-16, focus on the clothing insulation values instead of human performance (17, 19). ISO 11079 estimates the clothing insulation required to maintain body heat balance at given environmental conditions and work rate, and expresses cold stress in terms of IREQ. When the clothing insulation is low and not able to maintain heat balance, ISO 11079 estimates the maximal exposure time from the limit value of body heat loss (i.e., heat content loss) and the rate of body heat storage. ASTM F2732-16 estimates the lowest environmental temperature for comfort at two fixed metabolic rates (58.2 and 116.4 W·m²), using insulation values and a simple heat loss model. Both of the standard methods are for whole body applications only and do not address the critical need for

hand, foot and face protection. In comparison, CoWEDA outcomes are presented as human endurance times that indicate if the selected ensembles meet operation requirements, are easy to understand, and can be directly incorporated into mission planning and risk assessments.

CoWEDA is, to our best knowledge, the first successful attempt to use physiological criteria or safety limits to define thermal performance of cold weather ensembles. Cold stress may result in a temporary and/or permanent loss of manpower, and ultimately impacts military operations. Cold injury, whether local injury (e.g., frostbite, non-freezing injury) or injury encompassing the whole body (e.g., hypothermia), can be life-changing and life-threatening. As selecting appropriate cold weather ensembles is one of the most important measures to counter cold stress and prevent cold injury, it is practical to define the thermal performance according to the protective role an ensemble provides. Frostbite occurs when extremity skin temperatures are reduced below the thresholds in Table 1. Hypothermia occurs when the core temperature falls below the software threshold in Table 1. Therefore, extremity and body endurance times are used as metrics to define the thermal performance of cold weather ensembles. These endurance times illustrate the level of protection against injury provided by the selected clothing. On other hand, more clothing means more protection, which, from the perspective of thermal comfort during exposure to cold, is more desirable. However, this increases the logistical burden, adds to the weight and bulk carried by the soldier, and may cause overheating during exercise. It is possible to have heat strain during exercise at high intensity even during exposure to cold (53). Furthermore, moisture from sweat absorbed into the inner layers, may significantly reduce clothing insulation (54, 55). Thus, sweat time accumulation is used to indicate potential problems with sweat accumulation in underwear and overheating. Our approach, which incorporates all of these factors, is more comprehensive than any existing methods. CoWEDA is designed to address the complex requirements of cold weather ensembles: adequate protection to prevent both frostbite (face, hand and feet) and hypothermia while avoiding excessive sweating.

CoWEDA is the first tool that allows users to select from an inventory of available individual clothing items and accessories to build an ensemble. Published clothing databases are available in the literature which provide thermal and evaporative resistances of specific ensembles and/or a few individual clothing items (17, 26, 56, 57). Too often it is not convenient to use the insulation values from these databases, because it lacks the the ensembles that a user has available. Furthermore, due to lack of standard procedures or calculation methods, it is hard to use thermal and evaporative resistance of individual clothing items to determine the total thermal and evaporative resistance of an ensemble. It is also extremely difficult for end users to build an ensemble that provides a required insulation value. The CoWEDA should avoid use of insulation values as inputs for ensemble selection, instead an algorithm summing the individual layers of a multi-layer clothing system was developed and has been used to test all layers or components of military clothing system (47, 48). Our new approach, including the testing paradigm, data process and format, and new algorithms, makes it possible to determine the regional thermal and evaporative resistances from values of the individual clothing items. Our approach significantly enhances the ability to incorporate/use the insulation values for individual clothing items found in clothing databases into [human] thermal models to meet various needs of end users. This innovative approach underpins the CoWEDA, enabling users to just select clothing items from menus without the need to use insulation values directly, thus making CoWEDA truly user friendly.

CoWEDA is an interactive supplement to US Army Technical Bulletin – Medical 508 (TB MED 508) “Prevention and Management of Cold-Weather Injuries” (58). TB MED 508 includes tables for clothing insulation and charts for clothing insulation requirements relative to metabolic rates and environmental conditions. However, the tables alone are not particularly useful to make clothing decisions. TB MED 508 includes Wind Chill Temperature (WCT) for cold injury risk assessment. The risk of injury is presented as a look-up table. Frostbite times of exposed cheek skin in the WCT tables are a function of ambient temperature and air velocity, and is limited to four time categories: unlimited, 30 min, 10 min and 5 min (58, 60). One CoWEDA output, the endurance time of exposed skin, captures basically the same information, but presents it as a single value rather than as a look-up table. This exposure time is a function of ambient temperature, air velocity,

ensemble worn and activity, and incorporates more of the factors that actually determine the safe exposure time. For example, in air temperatures of -25°F temperature with a 5 mph air velocity (-32°C and $2.2\text{ m}\cdot\text{s}^{-1}$), frostbite time is calculated at about 30 min according to the WCT table (58). CoWEDA predicts the endurance time of exposed skin to be about 0.6 hours (36 min) or 1.0 hours (60 min) when the Moderate Cold Weather Gear or Extreme Cold Weather Gear (a preset ensemble) is worn, respectively. At the condition of -40°F temperature and 10 mph air velocity (-40°C and $4.5\text{ m}\cdot\text{s}^{-1}$), frostbite time is about 10 min according to WCT table (58). CoWEDA predicts endurance times of exposed skin to be about 0.3 hours (18 min) or 0.2 hours (12 min) when the Extreme Cold Weather Gear or the Moderate Cold Weather Gear (a preset ensemble) are worn, respectively. In addition, CoWEDA provides endurance times for frostbite of the hands and feet, and hypothermia. Therefore, CoWEDA provides more comprehensive information than WCT. In addition, improved awareness among medical staff, command, trainers, and those at risk is a critical element to local cold injury prevention efforts (1).

The selection of physiological criteria for evaluation of ensemble thermal performance is also dependent on the application. A threshold temperature of 5°C for the extremity skin safety limit was selected to represent the temperature below which cold injury, i.e. frostbite and nonfreezing injury, is likely to occur. Frostbite occurs when tissue temperatures fall below 0°C while nonfreezing cold injuries typically occur when tissues are exposed to temperatures between 0 and 15°C for prolonged periods of time, i.e. for several hours or days (8, 10). The freezing point of human tissue are not absolute and can be conditional. It has been observed that tissue freezes at -0.6°C in a salt water bath (61) and surface temperature would be super-cooled to an average of -10°C prior to frostbite (62, 63). Skin frostbite temperatures appears to be around -6.3°C and the risk of tissue freezing increases from 5 to 95% as the finger surface temperature falls from -4.8 to -7.8°C (64). Thus, the freezing point of skin varies with rate of heat loss (63) and likely ranges from -0.6°C to -10°C . In other words, local cold injuries may occur at skin temperatures of 15°C to -10°C . However, if, for example, the purpose of the application is to ensure manual performance to complete certain tasks, the physiological criteria would be different and a skin temperature of 15°C would be appropriate. Hand manual

performance reduces as its temperature drops, the performance drops initially at finger temperatures of 22-20°C, and is reduced significantly when the finger temperature drops below 15°C (12-14, 17). CoWEDA is designed in such a way that the physiological criteria can be revised to create a variation that will meet the requirements of different users. Different physiological criteria will result in different CoWEDA outcomes. Table 8 shows the endurance time when the hand skin temperature drops to 15°C and hand manual performance degrades significantly. Table 9 shows the endurance time when the hand skin temperature drops to 5°C and cold injury is likely to occur. Exposure time durations that corresponded to estimated finger skin temperatures of 14°C were created as a function of Wind Chill Equivalent Temperature (WCT) (65). Endurance times ranged from 37 to 5 min when WCT values were from -20 to -50°C. These endurance times seem to be consistent with the CoWEDA endurance times without gloves in Table 8.

Table 8 CoWEDA endurance time when hand temperate drops to 15°C and hand manual performance drops significantly

Wind (m/s)	No gloves Rest					Light gloves Rest					Light glove Moderate Activity (250 W)				
	0.5	2.5	5	7.5	10	0.5	2.5	5	7.5	10	0.5	2.5	5	7.5	10
T_a															
-20	16	10	8	7	6	34	27	24	23	23	71	36	31	29	28
-25	14	9	7	6	6	30	23	22	21	20	43	29	26	25	24
-30	13	8	7	6	6	27	21	19	19	18	35	25	22	21	21
-35	12	8	6	6	5	24	19	18	17	16	30	22	20	19	18
-40	11	7	6	5	5	22	17	16	15	15	26	20	18	17	17

Table 9 CoWEDA endurance time when hand temperate drops to 5°C and cold injury likely occurs

Wind (m/s)	No gloves Rest					Light gloves Rest					Light glove Moderate Activity (250 W)				
	0.5	2.5	5	7.5	10	0.5	2.5	5	7.5	10	0.5	2.5	5	7.5	10
T_a															
-20	36	17	14	12	11		85	74	66	65					
-25	28	15	12	11	10	104	58	50	48	48					
-30	26	14	11	10	9	69	48	40	39	39			102	85	68
-35	23	12	10	9	8	59	40	38	36	36		70	52	51	43
-40	19	11	9	8	8	49	37	30	29	29	107	52	42	41	40

The thresholds outlined in Table 1 and Table 2 are tentatively selected from the literature or based on scientific expertise at USARIEM. More human physiology research will be conducted to refine these thresholds. Human research is costly both monetarily and in terms of human resources, and it is ethically challenging to investigate the human limits of pain, frostbite, and hypothermia. In addition, both the conditions of exposure and human variability contribute to the uncertainty, and ultimately the feasibility, of establishing absolute values for thermal thresholds. One extreme example might be the selection of a lethal core temperature for the PSDA developed by USARIEM and used by the USCG SAR-OPS. The literature and popular media identify isolated cases where victims recovered from very low body core temperatures. However, many other victims,

recovered with higher body temperatures, subsequently died from hypothermia. Pain and discomfort is partially subjective, and the perception of pain may be altered by anticipation and tolerance. Consequently, precise limits or critical thresholds for injury are not well defined, and due to the potential risk of injury, thresholds should err on the side of safety, and identify when the potential risk of injury is approaching a high degree of probability.

One of the challenges for cold weather ensemble selection is that the ensemble should keep the body warm, but at the same time avoid overheating, especially during exercise. It is possible to experience heat strain during high intensity exercise during exposure to cold (53). ISO 11079 suggests that skin temperatures should be maintained between the minimal and maximal skin temperatures, and the range is about 3-4°C, dependent on the metabolic rates (17). To a certain degree, this might be a method to keep warm and avoid overheating. However, sweat, especially heavy sweat, poses a serious problem. Excessive skin wettedness is associated with thermal and tactile discomfort while wet clothing reduces the total insulation and increases the probability of post-exercise chill (55, 66). It has been observed in a manikin study that moisture absorbed into underwear reduces total thermal insulation by as much as 25% (54). Therefore, in CoWEDA, torso skin wettedness is used as an indicator that underwear is getting wet. Currently, the threshold for skin wettedness is set at 0.5 (50%). Even though sweat is a serious problem during exercise in the cold, there are a lack of studies that investigate these problems. Further research is needed to understand the effects of moisture accumulation/sweat condensation on the skin and in clothing during cold exposure and to develop evidence based criteria to avoid overheating and excessive moisture accumulation. The CoWEDA sweat time identifies when the skin wettedness is high and thus will help users to take appropriate action if necessary.

The CoWEDA clothing database can be expanded to include more clothing items or to create a version for a specific military branch or user community. The program architecture is designed to make it easy to update the clothing properties and/or include more clothing items in the database. When there is a need to include new items, the items will be tested using our new test paradigm, pictures taken, and those data and

images will be processed and saved in the required format. After the new information is incorporated into the database, the new items will appear as CoWEDA clothing selection options.

CONCLUSIONS

CoWEDA is a software platform to deliver current knowledge of cold physiology and clothing properties for cold weather protection. The novel feature of CoWEDA is the integration of the six-cylinder thermoregulatory model, physiological criteria, a database of clothing biophysical properties, and new algorithms for calculating ensemble thermal and evaporative resistances into a single user-friendly software application. CoWEDA guides users, such as Commanders and Soldiers, to select the most appropriate cold weather ensemble(s) relative to the anticipated activities and environmental conditions.

CoWEDA is an innovative knowledge-based decision aid. It is the first tool that uses a human-centric approach, focused on human performance and safety, and that evaluates thermal performance of cold ensemble using physiological criteria as safety limits. It is the first tool that allows users to build their own ensembles from the available clothing items by body regions: clothing layers, gloves, boots and headgear, and to interpret the selection using physiological terms or to describe the consequences.

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