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Comparison of Cold Weather Clothing Biophysical Properties

US Army, Canadian Department of National Defence, and Norwegian Military

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COMPARISON OF COLD WEATHER CLOTHING BIOPHYSICAL PROPERTIES: US ARMY, CANADIAN DEPARTMENT OF NATIONAL DEFENCE, AND NORWEGIAN MILITARY

United States Army
Medical Research & Materiel Command

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14. ABSTRACT

This report provides quantitative biophysical assessments of current cold weather clothing ensembles used by the US Army, the Canadian Department of National Defence, and the Norwegian military. Standard tests for the thermal and evaporative resistances (Rt and Ret) were conducted for 22 military cold weather ensembles (9 United States (US), 8 Canadian (CA), and 5 Norwegian (N)) within climate controlled environmental chambers. Total thermal resistance (insulation) in clo units, the vapor permeability index (im), and the evaporative potential (im/clo) were calculated from Rt and Ret measurements. Simple comparisons of the measured values for each of the ensembles was made as well as predicted performances based on modeling of insulation required to maintain safe exposure times.

15. SUBJECT TERMS

thermal manikins; biophysics; protective clothing; cold injury; predictive modeling; thermoregulation

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EXECUTIVE SUMMARY

This report provides quantitative biophysical assessments of current cold weather clothing ensembles used by the US Army, the Canadian Department of National Defence, and the Norwegian military. Standard tests for the thermal and evaporative resistances (R_t and R_{et}) were conducted for 22 military cold weather ensembles (9 United States (US), 8 Canadian (CA), and 5 Norwegian (N)) within climate controlled environmental chambers. Total thermal resistance (insulation) in clo units, the vapor permeability index (i_m), and the evaporative potential (i_m/clo) were calculated from R_t and R_{et} measurements. Simple comparisons of the measured values for each of the ensembles was made as well as predicted performances based on modeling of insulation required to maintain safe exposure times.

Simple descriptive statistics were computed for all ensembles, and for each country independently. Total measured biophysical values (mean±SD; min-max) for the 22 ensembles were: R_t: 0.312 ± 0.083; 0.201-0.482, clo: 2.011 ± 0.533; 1.296-3.109, R_{et}: 46.831 ± 11.431; 23.5-67.77, i_m: 0.407 ± 0.062; 0.313-0.549, i_m/clo: 0.215 ± 0.064; 0.139-0.4. Ranking by level of clo showed Canadian and US ensembles (CA 6 and US 4) provide the highest level of thermal insulation; indicating higher protection from extreme cold weather extremes based on low activity or resting conditions. In contrast to levels of thermal insulation, the US Army ensembles, US 1 and US 2 provide the highest evaporative potential (i_m/clo) values, indicating reduced likelihood of imposed heat strain.

The use of simplified standard methods of modeling for three environmental conditions (-10, -20, and -30°C) was used to provide guidance levels of insulation required. The insulation required minimum and neutral (IREQmin and IREQneutral) were used to calculate the minimal and ideal amounts of insulation needed to maintain thermal balance (minimum) and to maintain an equilibrium balance (neutral). From these methods, none of the current ensembles meets the minimum required insulation for resting; or for moderate (2 MET) work in -30°C conditions. Only one ensemble (CA 6) meets the neutral (IREQneutral) criteria for -20°C conditions; while at moderate (2 MET) work rate several ensembles meet the minimal or neutral (IREQmin; IREQneutral) values for -10°C conditions

Heat stress modeling was conducted for each ensemble to provide a contrast of thermal burden and as an indication of the potential for increased sweating. Modeled heat stress in cold environmental conditions and moderate work rate showed the noticeable differences over a two hour period across uniforms. At the two hour mark, an absolute difference of 0.85 °C could be observed between the least (US 1) and most (US 4) thermally burdensome uniforms, with a standard deviation of 0.24 across all ensembles.

INTRODUCTION

US Armed Service members operate in a wide array of areas, under many different environmental conditions, and conduct varied and dynamic activities. Given these complex settings, the individuals within the Armed Forces constantly face the threat of succumbing to heat or cold related injuries [1-3].

In a recent report from Berko et al., [4], 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 (10,649 total for the period). Interestingly, cold related deaths (e.g., hypothermia) were twice as prevalent (63%; n = 6,660) than that of heat related deaths (e.g., heat stroke) (31%; n = 3,332); while other weather events (floods, storms, lightning) accounted for the last six percent (n = 662).

Exposure to natural weather events, such as extreme heat or cold, is a national and international concern. However, this is even more of an acute issue for the U.S. military, as they routinely travel and conduct a range of physical activities around the world within the full spectrum of extreme environmental conditions. Furthermore, the complexity of military operations and activities within this range of environments is more dynamic than that of civilian exposure events.

Figure 1 outlines the cold injury incidences for active duty members of the U.S. Army using a collection of published reports from the Medical Surveillance Monthly Report (MSMR) over a 20 year period [5-22]. From 1997 to 2017, the total reported incidences of clinically reported cold injuries for the active duty U.S. military is broken out into four main areas: frostbite, immersion foot and hand, hypothermia, and unspecified. The instances are shown as number of cases (n) and rate (per 100,000 person-years (p-yrs)); where frostbite (n=3,323; 33.3 p-yrs), immersion foot (n=839; 8.4 p-yrs), hypothermia (n=648; 6.4 p-yrs), and unspecified (n=1,873; 18.9 p-yrs), totaling 6,683; 67.5 p-yrs (Figure 2).

Figure 1. Incidences of Cold Injuries, Active U.S. Army 1997-2017

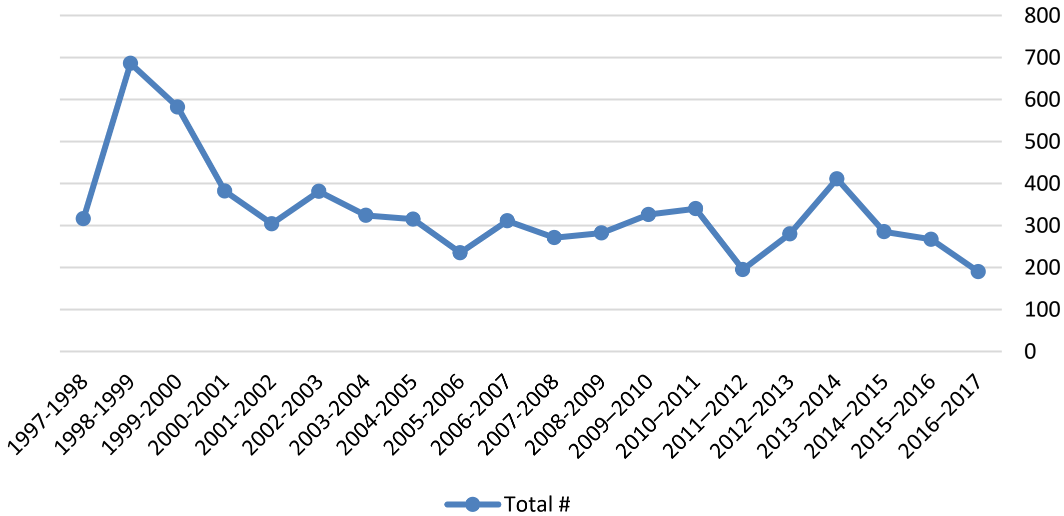
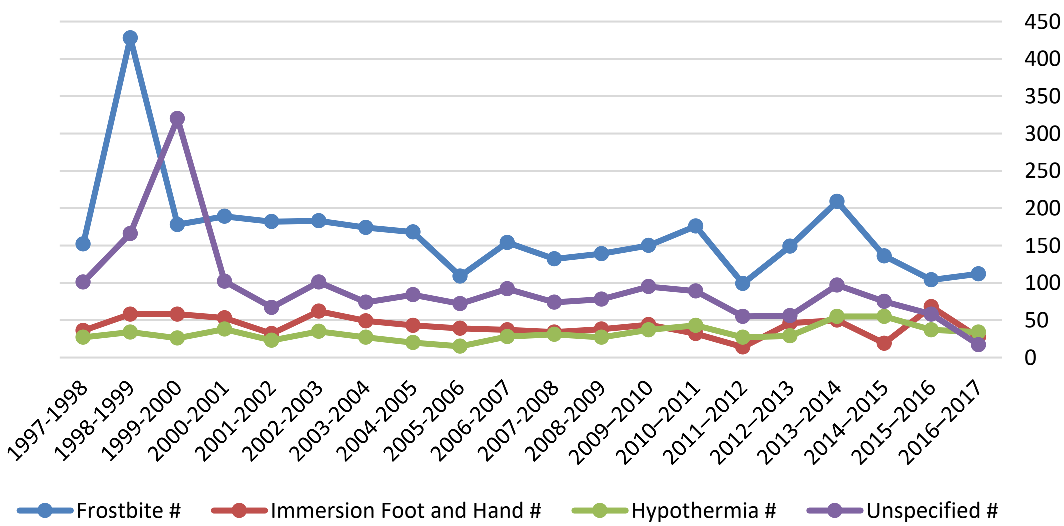


Figure 2. Incidences of Cold Injuries, by type, Active U.S. Army 1997-2017



Characterizing Cold Injuries

Characterizing cold related injuries is fairly complex, as the responses to cold have higher individual variability when compared to that of heat related injuries. From a clinical perspective, cold related injuries can be broadly binned into three categories: frostbite, nonfreezing cold injuries, and hypothermia. In addition, each of these has varying levels of severity and subcategories associated to them.

Frostbite is below the point at which skin tissue begins to freeze. While 0°C (32°F) is traditionally considered the freezing point of water, the freezing point of skin is understood to be marginally less due to of electrolytes [23]. Observed freezing points range from as low as -4.8°C to as high as -0.6°C [23-24].

Nonfreezing cold injuries include an array of injury events where tissue freezing has not occurred but damage occurs. The level of severity of nonfreezing injuries is determined by the temperature, duration, and wetness of the exposure to the tissue. Four of the more common specific types of nonfreezing injuries include immersion (trench) foot, chilblain, cold urticaria, and cold-induced bronchoconstriction [25]. Immersion foot is a nonfreezing injury where the foot becomes swollen, the skin is red initially but as severity increases the skin becomes lower in oxygen saturation and becomes cyanotic (purple, bluish discoloration) [23, 25]. Immersion foot is most often reported after tissue have been exposed for extended periods of time to non-freezing temperatures, between 0-15°C (32-60°F) [25]. The 'immersion' term itself refers to when the foot is actually immersed but more typically when the foot becomes immersed and remains wet within boots [23, 25]. Chilblains is considered a fairly common nonfreezing injury that appears as more superficial than immersion foot and occurs due to shorter term exposure (i.e., 1-5 hours) of temperatures below 16°C (60°F) [23]. Cold urticaria is expressed as a quick onset of redness, swelling and itchiness of the skin in response to short-term exposure (i.e., minutes) to cold environments [25]. Cold-induced bronchoconstriction is a physiological response where an individual's airways are narrowed during exercise in cold environments [23, 25-27].

Hypothermia as a broad category of cold injury is clinically described to be the point at which core body temperature has dropped below 35°C (95°F) [28]. However, hypothermia is more specifically defined with four levels of severity; where normothermia (normal temperature level) is approximately 37°C (98.6°F), mild hypothermia is between 91.4 – 95°C (33-35°F), moderate hypothermia being 85.2 – 89.6°C (29 – 32 °F), and severe hypothermia being 56.7 – 82.4°C (13.7 – 28°F) [23,28]. Table 2 outlines specific core temperature reference points associated with physiological changes / responses using work by Castellani et al., [23] and Pozos and Danzl [28].

Purpose and Approach

Clothing protects the wearer from environmental threats, e.g., hot or cold exposure. In order to understand the protection provided by specific clothing ensembles thermal sweating manikins have been historically used to provide quantitative assessments of the heat transfer (biophysical) properties of clothing ensembles, namely thermal and evaporative resistance (R_t and R_{et}).

This report provides quantitative biophysical assessments of the current cold weather clothing ensembles used by the US Army, the Canadian Department of National Defence, and the Norwegian military.

METHODS

Biophysical Assessments

Standard tests for the thermal and evaporative resistances (R_t and R_{et}) were conducted (ASTM F1291-16 & ASTM F2370-16) [29-30] for 22 military cold weather ensembles (9 United States (US), 8 Canadian (CA), and 5 Norwegian (N)) within climate controlled environmental chambers (Table 1; Appendix A). Each of the 22 ensembles varied in the types of material and number of layers.

Measures obtained for analysis included:

- thermal resistance (R_t) (Eq. 1)
- R_t is converted into units of clo (Eq. 2)
- evaporative resistance (R_{et}) (Eq. 3)
- R_t and R_{et} is converted into a vapor permeability index (i_m) (Eq. 4)
- together i_m and clo (i_m/clo) is used to represent evaporative potential [31-32]

Thermal resistance (R_t) is the dry heat transfer from the surface of the manikin through the clothing and into the environment, mainly from convection; where T_s is surface temperature, T_a is the air temperature in °C or K; Q is power input (W) to maintain the surface (skin) temperature (T_s) of the manikin at a given set point; A is the surface area of the measurement in m^2. Measures of R_t can then be converted to units of clo, where I_T is the total insulation including boundary air layers. Evaporative resistance (R_{et}) is heat loss from the body in isothermal conditions ($T_s \approx T_a$); where P_{sat} is vapor pressure in Pascal at the surface of the manikin (assumed to be fully saturated), and P_a is vapor pressure, in Pascal, of the chamber environment. Measures of R_t and R_{et} can then be used to calculate the vapor permeability index (i_m), a non-dimensional measure of water vapor resistance of materials.

$$R_t = \frac{(T_s - T_a)}{Q/A}\,[\mathrm{m^2K/W}] \qquad \text{Eq 1.}$$

$$clo = 6.45(R_t) \qquad \text{Eq 2.}$$

$$R_{et} = \frac{(P_{sat} - P_a)}{Q/A}\,[\mathrm{m^2Pa/W}] \qquad \text{Eq 3.}$$

$$i_m = \frac{60.6515 \cdot R_t}{R_{et}} \qquad \text{Eq 4.}$$

Ensembles

Twenty-two different ensemble configurations were tested as they would be worn. Full descriptions of each of the test configurations is outlined in Table 1; while associated photographs of ensemble components are provided in Appendix A.

Table 1. Ensemble descriptions

Ensemble		Description
US 1	US Army	US Army - Silk-weight undershirt and drawers; Mid-weight shirt and drawers
US 2	US Army	US Army - Silk-weight undershirt and drawers; Mid-weight shirt and drawers; Fleece Jacket
US 3	US Army	US Army - Silk-weight undershirt and drawers; Mid-weight shirt and drawers; Fleece Jacket; Soft Shell jacket and trousers
US 4	US Army	US Army - Silk-weight undershirt and drawers; Mid-weight shirt and drawers; Fleece Jacket; Soft Shell jacket and trousers; Extreme Cold Weather (ECW) Parka and trousers
US 5	US Army	US Army - Mid-weight shirt and drawers; Soft Shell jacket and trousers
US 6	US Army	US Army - Mid-weight shirt and drawers; Soft Shell jacket and trousers; Extreme Cold Weather (ECW) Parka and trousers
US 7	US Army	US Army - Silk-weight undershirt and drawers; Wind jacket; Soft Shell trousers
US 8	US Army	US Army - Silk-weight undershirt and drawers; Soft Shell jacket and trousers
US 9	US Army	US Army - Silk-weight undershirt and drawers; Extreme Cold Weather (ECW) jacket and trousers
CA 1	Canadian Department of National Defence	Canadian - Thermal undershirt and Long Johns; CADPAT ICE jacket and trousers
CA 2	Canadian Department of National Defence	Canadian - Thermal undershirt and Long Johns; CADPAT IECS Parka – HOOD DOWN; CADPAT IECS Bib pants
CA 3	Canadian Department of National Defence	Canadian - Thermal undershirt and Long Johns; CADPAT IECS Parka – HOOD UP; CADPAT IECS Bib pants
CA 4	Canadian Department of National Defence	Canadian - Thermal undershirt and Long Johns; CADPAT Fleece jacket and trousers; CADPAT IECS Parka - HOOD DOWN; CADPAT IECS Bib pants
CA 5	Canadian Department of National Defence	Canadian - Thermal undershirt and Long Johns; CADPAT Fleece jacket and trousers; CADPAT IECS Parka - HOOD UP; CADPAT IECS Bib pants
CA 6	Canadian Department of National Defence	Canadian - Thermal undershirt and Long Johns; CADPAT Fleece jacket and trousers; CADPAT IECS Bib pants; Canada Goose Snow Mantra Winter parka
CA 7	Canadian Department of National Defence	Canadian - Thermal undershirt and Long Johns; CADPAT Fleece jacket and trousers; CADPAT ICE jacket and trousers
CA 8	Canadian Department of National Defence	Canadian - Thermal undershirt and Long Johns; CADPAT Fleece jacket and trousers; CADPAT IECS Bib pants; Canada Goose Snow Mantra Winter parka
N 1	Norwegian military	Norwegian - Mesh underwear; wool terry cloth underwear; GORE-Tex® jacket and pants; white camouflage jacket and pants; hood down
N 2	Norwegian military	Norwegian - Mesh underwear; wool terry cloth underwear; Cotton Field Shirt; GORE-Tex® jacket and pants; hood down
N 3	Norwegian military	Norwegian - Mesh underwear; wool terry cloth underwear; Cotton Field Shirt; White Camouflage jacket and pants; hood down
N 4	Norwegian military	Norwegian - Mesh underwear; wool terry cloth underwear; Cotton Field Shirt; Cold Weather jacket and pants
N 5	Norwegian military	Norwegian - Mesh underwear; wool terry cloth underwear; Cotton Field Shirt; White Camouflage Uniform; Cold Weather jacket and pants

Insulation Required

A simple calculation based on the International Organization Standardization (ISO) technical report (ISO 11079) [33], was used as an evaluation metric of the insulation required (IREQ) for given environments and activities to compare ensemble performance. The IREQ method functionally describes the concept for balancing the heat exchange between the human and the environment, simplified as:

$$M - W = E_{res} + C_{res} + E + K + R + C + S \qquad \text{Eq 5.}$$

where M is metabolic heat produced, W is effective mechanical work and collectively M-W represents the heat produced within the human; while the opposite side of this balance, E_{res} and C_{res} represent the respiratory heat exchange (evaporative and convective), and E, K, R, and C represent the conventional heat exchange methods (evaporative, conductive, radiative, and convective) and S is heat storage.

The IREQ equation (Eqs. 6 and 7), outlines the rational balance of these methods to include a thermal insulation via clothing elements needed to maintain this balance, seen simply as:

$$IREQ = \frac{\bar{t}_{sk} - t_{cl}}{R+C} \qquad \text{Eq 6.}$$

more formally as:

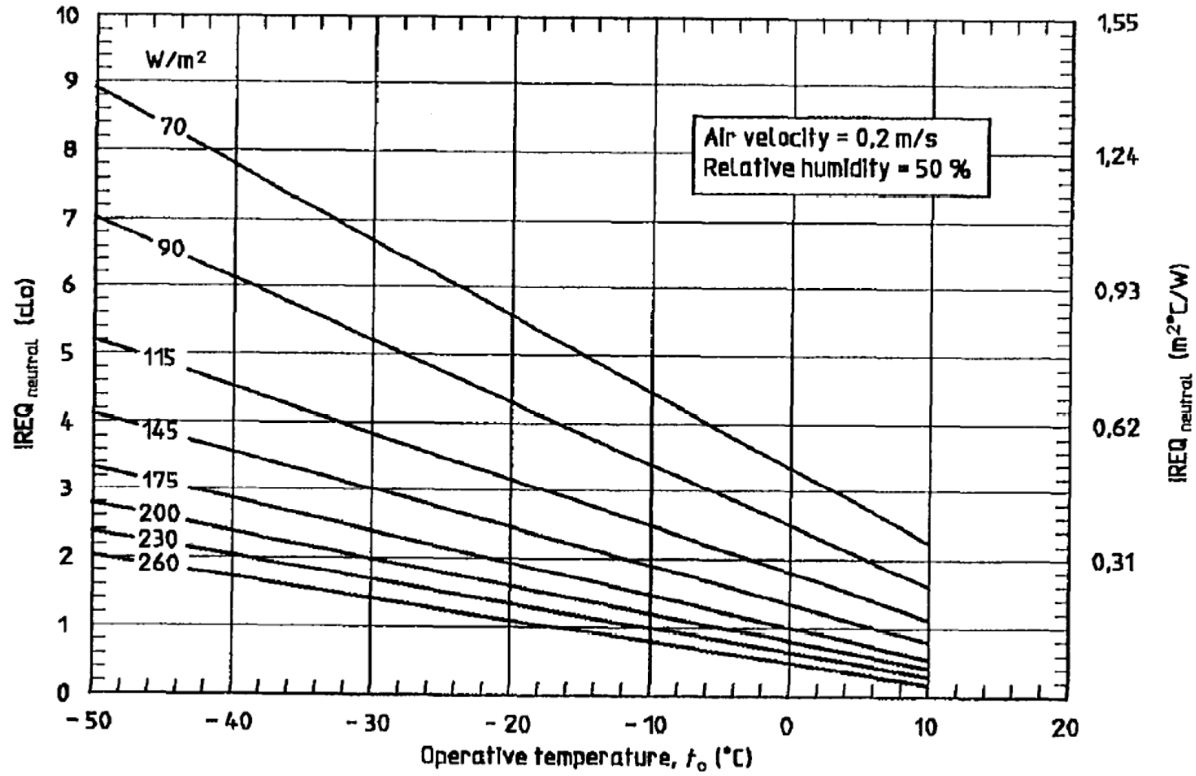
$$IREQ = \frac{\bar{t}_{sk} - t_{cl}}{M - W - E_{res} - C_{res} - E} \qquad \text{Eq 7.}$$

where t_{sk} is mean skin temperature, t_{cl} clothing surface temperature, and $M - W - E_{res} - C_{res} - E = R + C$

The insulation required minimum and neutral (IREQmin and IREQneutral) were used to calculate the minimal and ideal amounts of insulation needed to maintain thermal balance (minimum) and to maintain an equilibrium balance (neutral).

The ISO 11079 helpfully outlines a general scenario for the minimum required insulation ($IREQ_{min}$) for multiple work intensities and environments (Figure 3). From Figure 3, we can see that in in low air velocity conditions (still air; 0.2m/s) and relative humidity (RH) of 50% that the range of required clothing insulation for an individual slightly above resting (70 W/m^2) in 10 to -50 °C is 1.8 to 8.5 clo. Intuitively, as work rate intensifies to higher levels, this range shifts downward relative to environment.

Figure 3. Outline of minimum insulation required ($IREQ_{min}$) for various environmental conditions and work intensities [33]



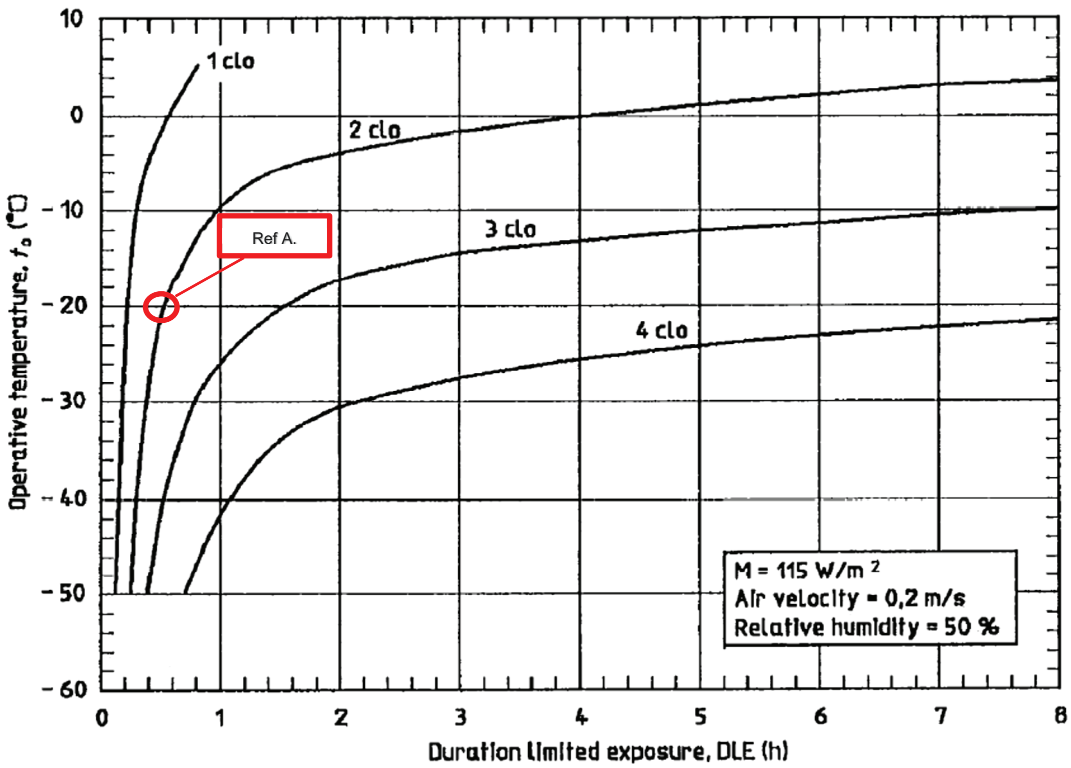
Duration Limited Exposure (DLE)

Along with the IREQ method, ISO 11079 [33] also outlines the calculation for a duration limited exposure (DLE) for estimating a maximal safe exposure time to a given environment and associated work intensity, in the event the insulation provided is insufficient (i.e., below the estimated IREQ). The DLE is the balance of the limits of body heat content (Q_{lim}) divided by the body heat storage (S), seen as:

$$DLE = \frac{Q_{lim}}{S}$$

The ISO 11079 has also outlined a general scenario for the DLE, in hours, at a working activity rate of 115 W/m^2 (~2 METS) for different clothing insulation values (1, 2, 3, and 4 clo) within various environments (Figure 4). For example, Figure 4 shows that in a clothing ensemble with insulation of 2 clo, working at 2 METS, in -20 °C conditions, that an individual should limit their exposure to no more than ~30 minutes (Figure 4; ref point A).

Figure 4. Outline of duration limited exposure (DLE) across cold environments for 4 levels of total clothing insulation (clo) at one work intensity [33]



Heat stress

Dynamic activities of military service members and increasing levels of insulation, can reduce the risk of cold exposure injuries but as a consequence can impose a level of heat stress on an individual. To outline the contrast of this and provide an indication of higher risks of sweating, complimentary heat stress modeling of each of these ensembles was conducted using a single, temperate environmental condition, and a single high work intensity rate to show implications of the potential for thermal strain. This modeling was conducted using the heat strain decision aid (HSDA) [34]. This biophysics-based model takes into account inputs of individual, clothing, activity, and environment and translates them to core temperature rise over time. Estimated values for the effects of wind velocity on these properties was used to provide inputs to this model [35].

RESULTS

Biophysical Results

Simple descriptive statistics were done for the total, and for each country independently. Total measured biophysical values (mean±SD; min-max) for the 22 ensembles were: R_t: 0.312 ± 0.083; 0.201-0.482, clo: 2.011 ± 0.533; 1.296-3.109, R_{et}:

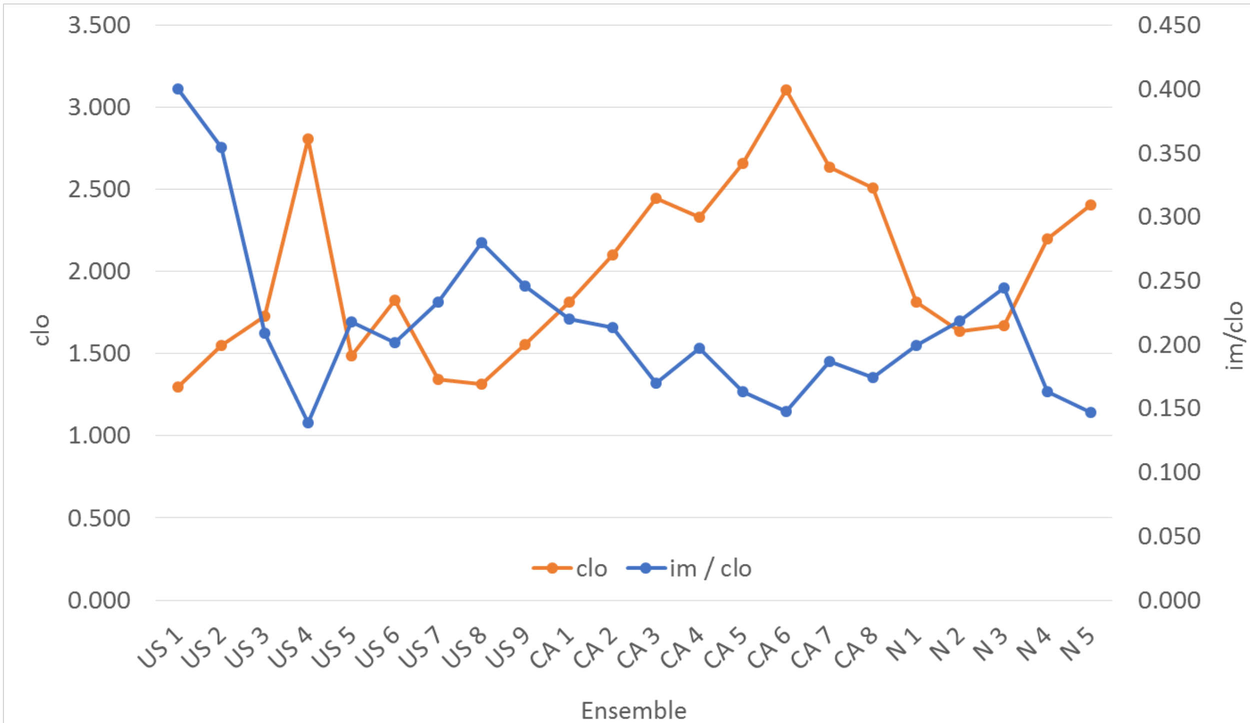
46.831 ± 11.431; 23.5-67.77, i_m: 0.407 ± 0.062; 0.313-0.549, i_m/clo: 0.215 ± 0.064; 0.139-0.4. US Army ensembles: R_t: 0.257 ± 0.072; 0.201-0.435, clo: 1.656 ± 0.468; 1.296-2.806, R_{et}: 40.552 ± 12.969; 23.5-67.77, i_m: 0.397 ± 0.082; 0.313-0.549, i_m/clo: 0.253 ± 0.081; 0.139-0.4. Canadian ensembles: R_t: 0.380 ± 0.06; 0.281-0.482, clo: 2.45 ± 0.389; 1.812-3.109, R_{et}: 51.888 ± 7.067; 42.72-63.55, i_m: 0.443 ± 0.029; 0.399-0.494, i_m/clo: 0.184 ± 0.025; 0.148-0.22. Norwegian ensembles: R_t: 0.302 ± 0.053; 0.254-0.373, clo: 1.945 ± 0.341; 1.638-2.406, R_{et}: 50.044 ± 10.460; 38.53-63.91, i_m: 0.368 ± 0.022; 0.354-0.408, i_m/clo: 0.194 ± 0.040; 0.147-0.244.

A graphical representation of the clo and i_m/clo for the 22 ensembles is shown in Figure 5; while the corresponding data is shown in Table 2. From Figure 5 a general trend of higher insulation relating to lower permeability (e.g., i_m/clo) can be observed. This indicates the need for well-defined tradeoff assessment for clothing usage based on anticipated activities and environments, i.e., high insulation protects from the cold; while related low permeability increases risk for thermal strain. This balance is specifically important when considering the added risk resulting from sweating in the cold (i.e., sweat freezes and increases risk of cold injuries).

Table 2. Biophysical measures for each ensemble

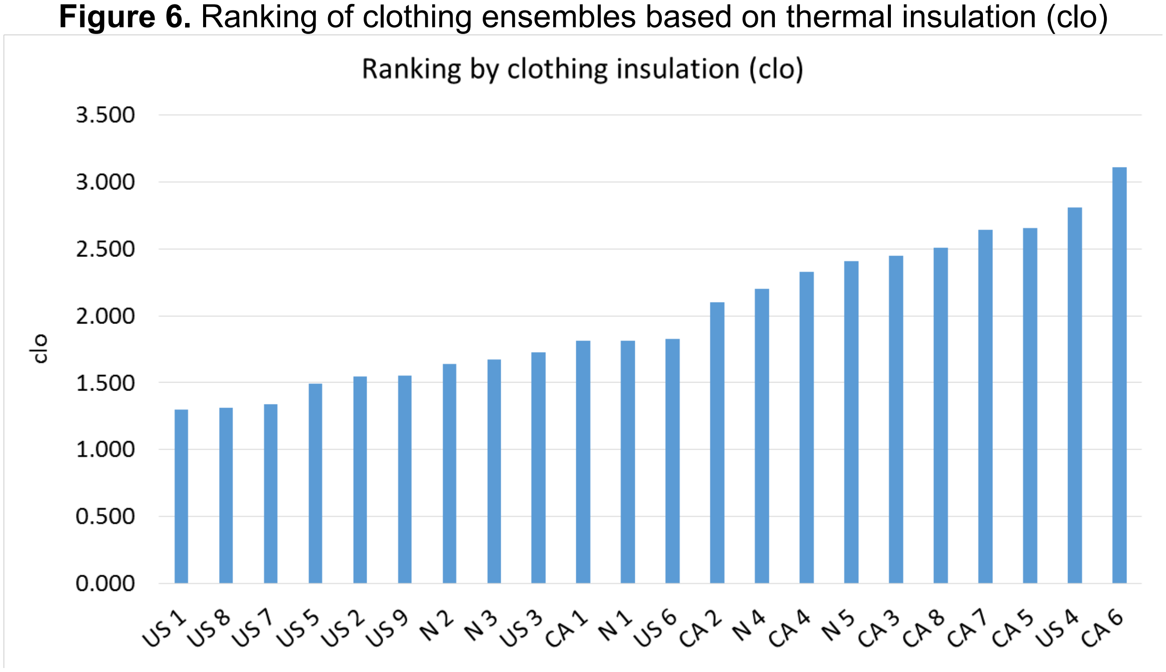
Ensemble	Thermal Resistance (R_t; m^2 K/W)	Thermal Insulation (clo)	Evaporative Resistance (R_{et}; m^2 Pa/W)	Permeability Index (i_m)	Evaporative Potential (i_m/clo)
US 1	0.201	1.296	23.50	0.519	0.400
US 2	0.240	1.548	26.53	0.549	0.354
US 3	0.268	1.729	44.98	0.361	0.209
US 4	0.435	2.806	67.77	0.389	0.139
US 5	0.231	1.490	43.19	0.324	0.218
US 6	0.283	1.825	46.71	0.367	0.201
US 7	0.208	1.342	40.36	0.313	0.233
US 8	0.204	1.316	33.64	0.368	0.280
US 9	0.241	1.554	38.29	0.382	0.246
CA 1	0.281	1.812	42.72	0.399	0.220
CA 2	0.326	2.103	44.01	0.449	0.214
CA 3	0.379	2.445	55.36	0.415	0.170
CA 4	0.361	2.328	47.79	0.458	0.197
CA 5	0.412	2.657	57.55	0.434	0.163
CA 6	0.482	3.109	63.55	0.460	0.148
CA 7	0.409	2.638	50.26	0.494	0.187
CA 8	0.389	2.509	53.86	0.438	0.175
N 1	0.281	1.812	47.210	0.361	0.199
N 2	0.254	1.638	43.050	0.358	0.218
N 3	0.259	1.671	38.530	0.408	0.244
N 4	0.341	2.199	57.520	0.360	0.163
N 5	0.373	2.406	63.910	0.354	0.147

Figure 5. Thermal insulation (clo) and evaporative potential (i_m/clo) for each ensemble



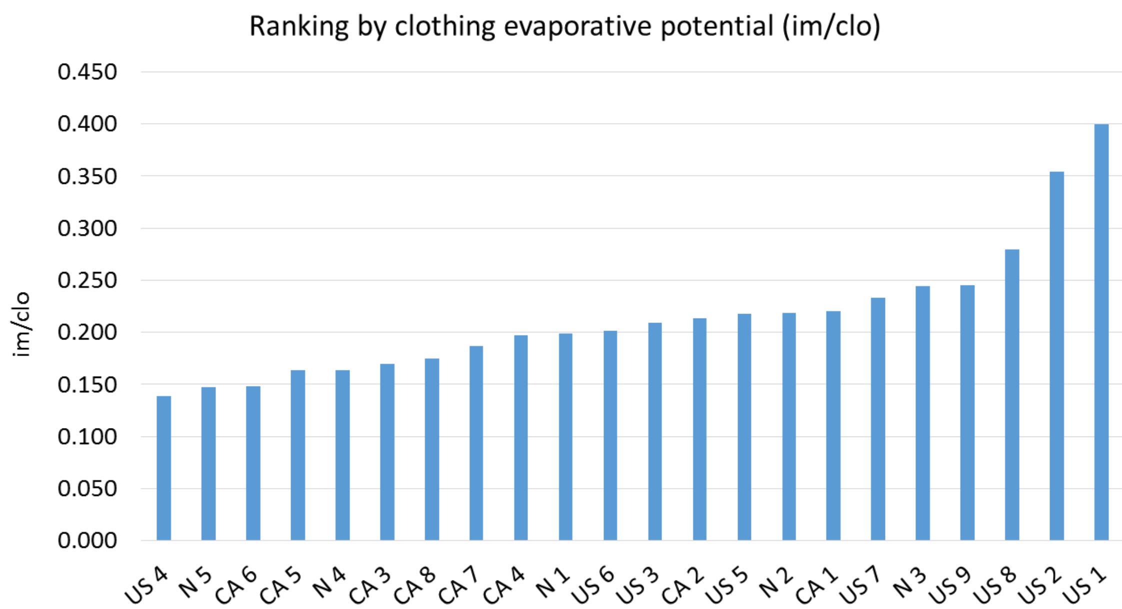
Ranking by level of thermal insulation (clo) is shown graphically in Figure 6. As can be seen the Canadian CA6 and US Army ensemble US 4 provide the highest level of thermal insulation. This higher value indicates higher protection from extreme cold weather extremes based on low activity or resting conditions.

Figure 6. Ranking of clothing ensembles based on thermal insulation (clo)



In contrast to levels of thermal insulation (clo), Figure 7 shows a ranking of clothing ensembles based on evaporative potential (i_m/clo). As can be seen the US Army ensembles, US 1 and US 2 provide the highest evaporative potential (i_m/clo) values, indicating reduced likelihood of imposed heat strain.

Figure 7. Ranking of clothing ensembles based on evaporative potential (i_m/clo)



Insulation Required

Comparisons of calculated insulation required minimal (in three environmental conditions at both resting (58.2 W/m^2) and 2 METs activity (116 W/m^2) is shown in Table 3.

Table 3. Calculated Insulation Required by Environment: resting and moderate activity

Environment	Activity Rate	Insulation Minimum Required (IREQmin) - clo	Insulation Required for Neutral Response (IREQneutral) – clo
-10°C, 50%RH, still air	Resting (58.2 W/m^2) 1 MET	5.1	5.5
-10°C, 50%RH, still air + 0.3 m/s	Resting (116 W/m^2) 2 MET	2.2	2.5
-20°C, 50%RH, still air	Resting (58.2 W/m^2) 1 MET	6.4	6.8
-20°C, 50%RH, still air + 0.3 m/s	Resting (116 W/m^2) 2 MET	2.9	3.2
-30°C, 50%RH, still air	Resting (58.2 W/m^2) 1 MET	7.8	8.1
-30°C, 50%RH, still air + 0.3 m/s	Resting (116 W/m^2) 2 MET	3.5	3.9

Comparisons of clothing insulation values in Table 2 and estimations of the required insulation in Table 3 show deficiencies and where clothing ensembles meet the guidance values. Table 4 shows where each ensemble meets or doesn't meet the standards outlined for resting and moderate activity in three environments. Table 4 and Figure 8 clearly show that within these three environments (-10, -20, and -30°C) that none of the ensembles meets the minimum required insulation for resting. Table 4 and Figure 9 show that none of the ensembles meet the required insulation for moderate (2 MET) work in -30°C conditions; while only one ensemble (CA 6) meets the neutral (IREQneutral) criteria for -20°C conditions. However, from Table 4 and Figure 9 we see that at a moderate (2 MET) work rate several ensembles meet the minimal or neutral (IREQmin; IREQneutral) values for -10°C conditions

Table 4. Ensemble comparison to guidance requirements for resting and moderate activity in three environmental conditions

	1 MET and -10°C	2 MET and -10°C	1 MET and -20°C	2 MET and -20°C	1 MET and -30°C	2 MET and -30°C
IREQmin	5.1	2.2	6.4	2.9	7.8	3.5
IREQneutral	5.5	2.5	6.8	3.2	8.1	3.9
US 1	1.3	1.3	1.3	1.3	1.3	1.3
US 2	1.5	1.5	1.5	1.5	1.5	1.5
US 3	1.7	1.7	1.7	1.7	1.7	1.7
US 4	2.8	2.8	2.8	2.8	2.8	2.8
US 5	1.5	1.5	1.5	1.5	1.5	1.5
US 6	1.8	1.8	1.8	1.8	1.8	1.8
US 7	1.3	1.3	1.3	1.3	1.3	1.3
US 8	1.3	1.3	1.3	1.3	1.3	1.3
US 9	1.6	1.6	1.6	1.6	1.6	1.6
CA 1	1.8	1.8	1.8	1.8	1.8	1.8
CA 2	2.1	2.1	2.1	2.1	2.1	2.1
CA 3	2.4	2.4	2.4	2.4	2.4	2.4
CA 4	2.3	2.3	2.3	2.3	2.3	2.3
CA 5	2.7	2.7	2.7	2.7	2.7	2.7
CA 6	3.1	3.1	3.1	3.1	3.1	3.1
CA 7	2.6	2.6	2.6	2.6	2.6	2.6
CA 8	2.5	2.5	2.5	2.5	2.5	2.5
N 1	1.8	1.8	1.8	1.8	1.8	1.8
N 2	1.6	1.6	1.6	1.6	1.6	1.6
N 3	1.7	1.7	1.7	1.7	1.7	1.7
N 4	2.2	2.2	2.2	2.2	2.2	2.2
N 5	2.4	2.4	2.4	2.4	2.4	2.4

Figure 8. Compared insulation (clo) values to guidance required (IREQmin and IREQnuetral) for three environments during rest.

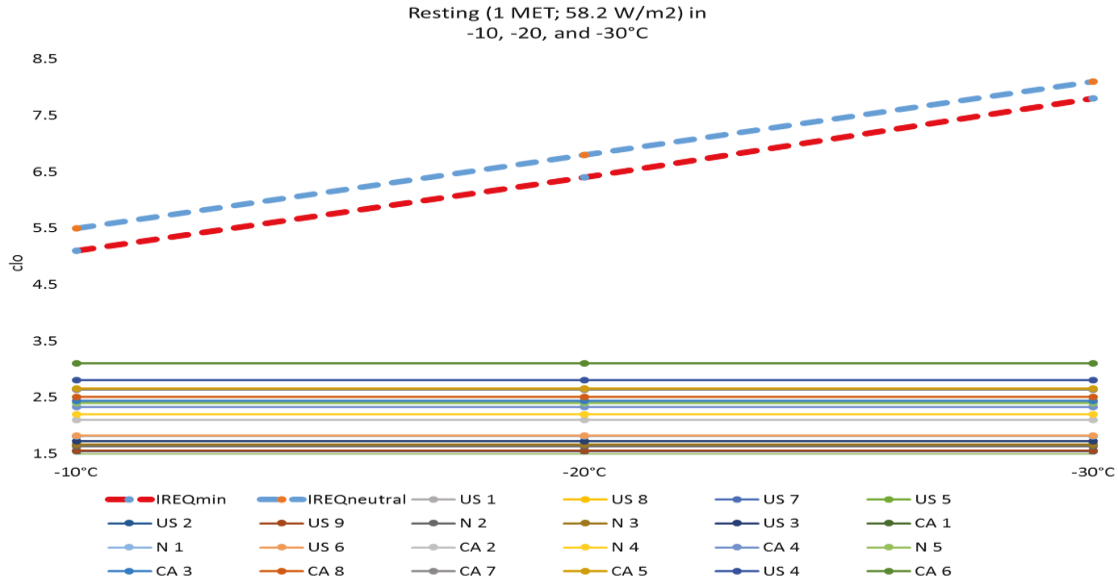
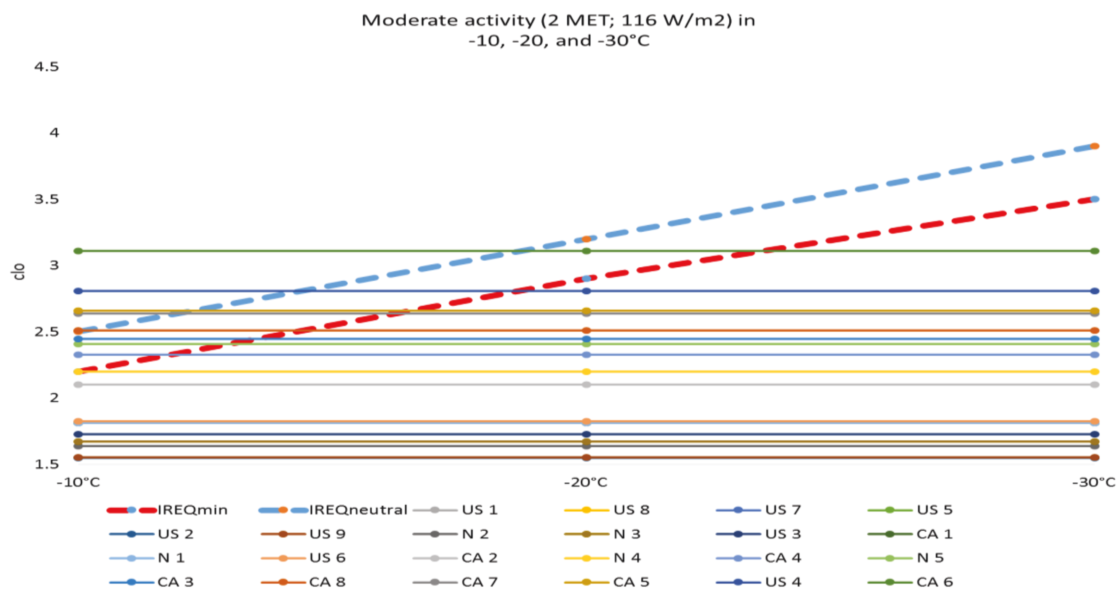


Figure 9. Compared insulation (clo) values to guidance required (IREQmin and IREQnuetral) for three environments during moderate activity (2 MET).



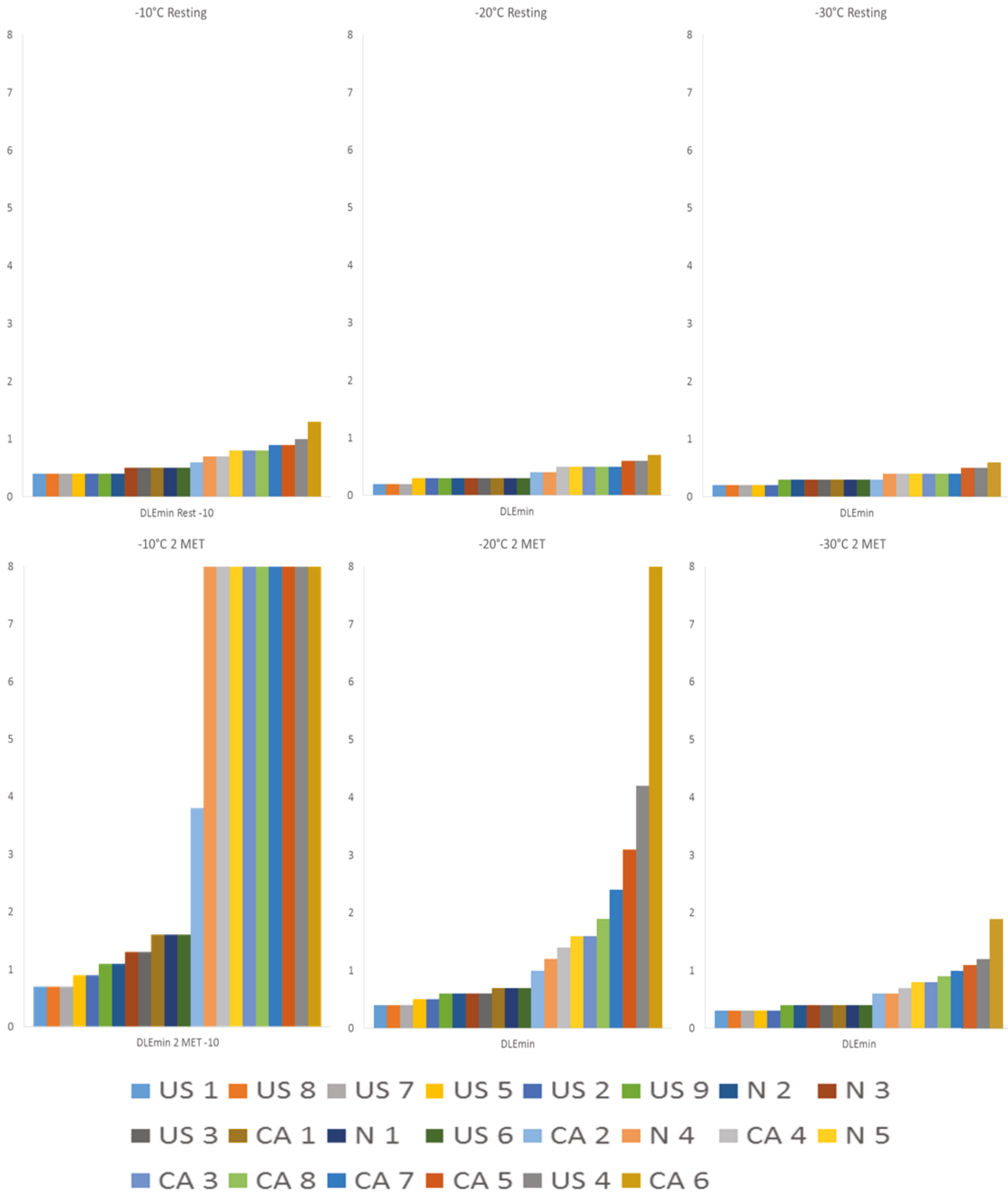
Duration Limited Exposure (DLE)

Comparisons of calculated duration limited exposure times (hours) in three environmental conditions at both resting (58.2 W/m^2) and 2 METs activity (116 W/m^2) is shown in both Table 5 and in Figure 10.

Table 5. Duration limited exposure (DLE) by ensemble for three environments (-10, -20, and -30°C during rest and moderate activity (2 MET)

	-10°C Rest		-10°C 2 MET		-20°C Rest		-20°C 2 MET		-30°C Rest		-30°C 2 MET	
Ensemble	DLEmin	DLEneu	DLEmin	DLEneu	DLEmin	DLEneu	DLEmin	DLEneu	DLEmin	DLEneu	DLEmin	DLEneu
US 1	0.4	0.3	0.7	0.5	0.2	0.2	0.4	0.3	0.2	0.2	0.3	0.2
US 8	0.4	0.3	0.7	0.5	0.2	0.2	0.4	0.3	0.2	0.2	0.3	0.2
US 7	0.4	0.3	0.7	0.5	0.2	0.2	0.4	0.3	0.2	0.2	0.3	0.2
US 5	0.4	0.4	0.9	0.6	0.3	0.3	0.5	0.4	0.2	0.2	0.3	0.3
US 2	0.4	0.4	0.9	0.6	0.3	0.3	0.5	0.4	0.2	0.2	0.3	0.3
US 9	0.4	0.4	1.1	0.7	0.3	0.3	0.6	0.4	0.3	0.2	0.4	0.3
N 2	0.4	0.4	1.1	0.7	0.3	0.3	0.6	0.4	0.3	0.2	0.4	0.3
N 3	0.5	0.4	1.3	0.8	0.3	0.3	0.6	0.5	0.3	0.3	0.4	0.3
US 3	0.5	0.4	1.3	0.8	0.3	0.3	0.6	0.5	0.3	0.3	0.4	0.3
CA 1	0.5	0.5	1.6	1	0.3	0.3	0.7	0.5	0.3	0.3	0.4	0.4
N 1	0.5	0.5	1.6	1	0.3	0.3	0.7	0.5	0.3	0.3	0.4	0.4
US 6	0.5	0.5	1.6	1	0.3	0.3	0.7	0.5	0.3	0.3	0.4	0.4
CA 2	0.6	0.6	3.8	1.6	0.4	0.4	1	0.7	0.3	0.3	0.6	0.5
N 4	0.7	0.6	8	2	0.4	0.4	1.2	0.8	0.4	0.3	0.6	0.5
CA 4	0.7	0.6	8	2.5	0.5	0.4	1.4	0.9	0.4	0.4	0.7	0.6
N 5	0.8	0.7	8	3.4	0.5	0.4	1.6	1.1	0.4	0.4	0.8	0.6
CA 3	0.8	0.7	8	3.4	0.5	0.4	1.6	1.1	0.4	0.4	0.8	0.6
CA 8	0.8	0.7	8	8	0.5	0.5	1.9	1.2	0.4	0.4	0.9	0.7
CA 7	0.9	0.8	8	8	0.5	0.5	2.4	1.4	0.4	0.4	1	0.8
CA 5	0.9	0.8	8	8	0.6	0.5	3.1	1.6	0.5	0.4	1.1	0.8
US 4	1	0.9	8	8	0.6	0.5	4.2	1.9	0.5	0.5	1.2	0.9
CA 6	1.3	1.1	8	8	0.7	0.6	8	3.8	0.6	0.5	1.9	1.3

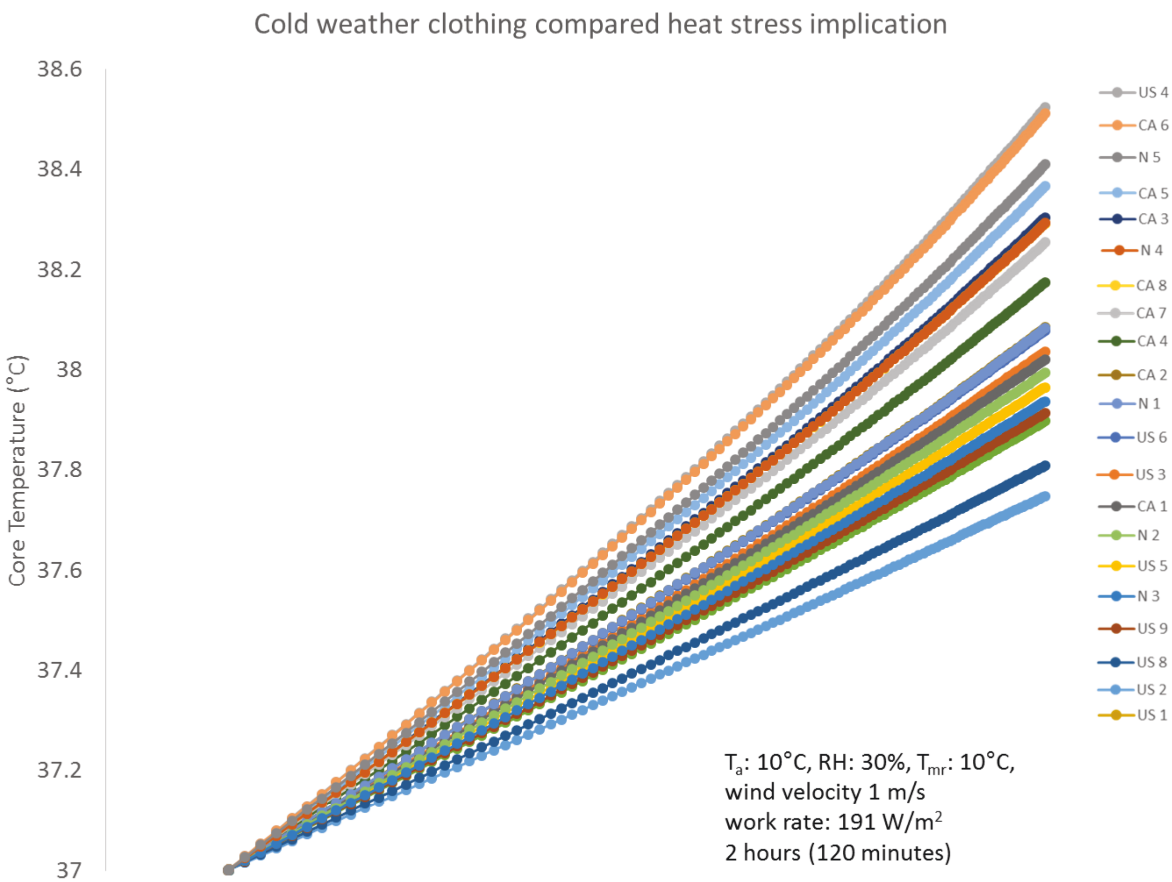
Figure 10. Duration limited exposure (DLE) (hours) by ensemble for three environments (-10, -20, and -30°C during rest and moderate activity (2 MET)



Heat stress

Comparisons of modeled heat stress in one cold environmental condition and moderate work rate (191 W/m^2) showed the noticeable differences over a two hour period across uniforms. At the two hour mark, an absolute difference of 0.85 °C could be observed between the least (US 1) and most (US 4) thermally burdensome uniforms, with a standard deviation of 0.24 across all ensembles (Figure 8).

Figure 11. Compared heat stress over a 120 minutes in a cold environment (10°C) at a moderate work rate (191 W/m^2)



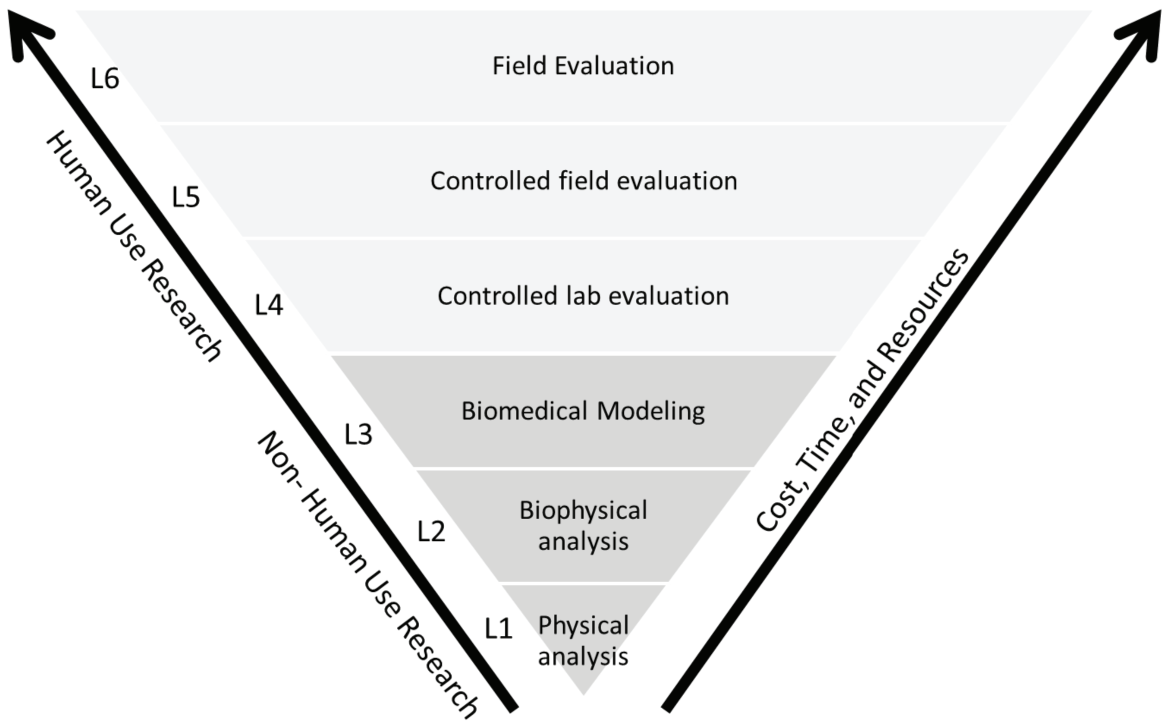
DISCUSSION

This study compared the biophysical characteristics of 22 cold weather ensembles using standard test methods and compared their performance using multiple modeling methods. This combination of testing and simple analytical assessment can prove as a meaningful step in the evaluation of clothing systems. However, it is important to note that more sophisticated modeling methods and human testing should be used for more comprehensive analyses. More complex physiological models such as the six cylinder thermoregulatory model (SCTM) from Xu and Werner [36], provide the added benefit of being rationally based and accounting for physiological responses in more detail (metabolism, vasomotor control, sweat production, and blood pooling) versus the simple heat balance methods of the IREQ [33].

The methods outlined in this report use the current minimal amount of testing that allows for modeling of human-level scenarios. From a time and cost perspective it is important to use all of the available methods to ensure both quantitative steps toward improvements as well as efficient and effective use of resources. Umbach [37] outlined a five level approach for clothing development and assessing the heat transfer properties of textiles; a simplified version of this is recreated in Figure 12 with a third level of biomedical modeling added, rather than a side process. Cost, time, and resources required increases with each level of assessment. At the lowest level of *physical analysis* (level 1), for example, clothing can be weighed and inspected for physical attributes. *Biophysical analysis* (level 2), which typically involves measurement of heat transfer properties, can be done using sweating guarded hotplate (SGHP) measurements followed by subsystem and full ensemble level assessments, each requiring specialized test equipment, facilities, and technicians. *Biomedical modeling* (level 3) can used to predict thermo-physiological impacts from the heat transfer properties of clothing, requiring expertise and time to perform specialized analyses. These first three levels require equipment and skills; however, they do not require the time, expense, and complexity of human subject research.

The traditional lowest level of human use research, *controlled lab evaluations* (level 4) requires specialized equipment and test facilities which not only increase costs but increase the supporting staff needed, broad expertise including physiology, and the added resources demand of studying human research volunteers (~8-20). *Controlled field evaluation* (level 5) may be more complex than level 4, with increases in cost, logistical complexity, and resources associated with the additional oversight required in a less contained environment, and typically an increase in the number of human research volunteers (20+), as well as a broader level of expertise (e.g., specialized understanding of activities being conducted). Once these controlled studies have been conducted, moving towards *field evaluations* (level 6) would include a much larger, more inclusive set of human research volunteers, seen more as customers or end users at this point, reflecting the targeted end user population.

Figure 12. Levels of clothing system testing



Assessing 2-dimensional swatches, textiles of single or multiple layered materials, can be done using a SGHP in accordance with ISO 11092 [38-39]. This method simulates the heat transfer of the human skin through the material tested into a controlled environment. While this method is a quick and cost effective means of evaluating textile materials, the resulting data often does not correspond to that of full ensembles. The main reason for this lack of correspondence is the fact that SGHP lacks the air gaps between the skin and the base layer, and between clothing layers that are present when 3-dimensional garments of varied form and fit are tested on the manikins. Xu et al., [40] outlines the critical importance of understanding the air boundary layers (‘air gap’) between clothing layers. Testing with thermal manikins allows for an inclusive system-level testing of the total resistances (thermal and evaporative) of an ensemble; while the total resistance of any ensemble consists of three main elements: air gap (R_{gap}), clothing textile (R_{cl}), and boundary layer (R_{bl}); where the total is seen as: $Resistance = R_{gap} + R_{cl} + R_{bl}$. While work has been done to estimate the air gap layers [41-43], more work is needed for an open-access standard (e.g., ISO, ASTM).

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APPENDIX A.

US Army Extended Cold Weather Clothing Elements

Element	Materials	Figure
Silk-weight Underwear	Desert Sand 503 colored, 100% polyester, circular knit plaited jersey (Polartec Power Dry silk-weight style 9042). Plaited circular knit construction	A1
Mid-weight Underwear	Desert Sand 503 colored, 93% polyester and 7% spandex circular knit plaited jersey, heavyweight jersey with stretch (Polartec Power Dry Heavyweight Jersey/Shearling Grid, Style 9110). Plaited circular knit construction.	A2
Fleece Jacket	Constructed with Foliage Green 504 or Tan 499 colored, 100% virgin filament polyester fabric (Polartec Thermal Pro style 4060). Construction is double needle bar raschel warp knit, high pile, double velour.	A3
Soft Shell Jacket and Trousers	Cloth for Type I is a plain weave, stretch, nylon and spandex cloth with water repellency (Nextec Application Inc., Style GLACIER). Cloth for Type II is a twill weave, aramid, cellulosic, synthetic cloth with water repellency.	A4
Lightweight GORE-Tex® Jacket and Trousers	Jacket and trousers are constructed with two-layer GORE-Tex®fabric developed based on the technology of GORE-Tex® Paclite Shells.	A5
Extreme Cold Weather Jacket and Trousers	Parka and trousers are constructed with an outer shell fabric that has a water resistant finish (Praetorian, Nextec Style No. 1161) and with PrimaLoft Sport Thermal bonded high-loft insulation.	A6

A1. Silk-weight underwear (US Ensembles)

A2. Mid-weight underwear (US Ensembles)

A3. Fleece Jacket (US Ensembles)

A4. Soft Shell Jacket and Trousers (US Ensembles)

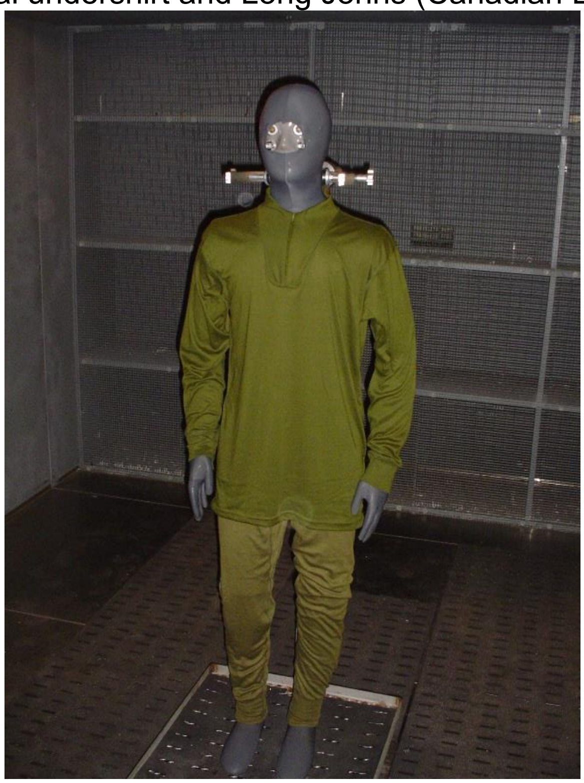
A5. Lightweight GORE-Tex® Jacket and Trousers (US Ensembles)

A6. Extreme Cold Weather Jacket and Trousers (US Ensembles)

Canadian Cold Weather Clothing Elements

Element	Materials	Figure
Thermal undershirt and Long Johns	NSN: 8415-21-914-5155	B1
CADPAT Fleece jacket and trousers	NSN: 8415-21-920-8590	B2
CADPAT ICE jacket and trousers	Nylon and cotton	B3
CADPAT IECS Parka	Nylon and cotton NSN: 8415-21-921-6910 / 8415-21-920-9997	B4
CADPAT IECS Bib Pants	NSN: 8415-21-913-6651	B5
Canada Goose Snow Mantra Winter parka	Outershell: 85% polyester, 15% cotton; lining: 100% nylon; neck liner: natural coyote fur; insulation: goose down	B6

B1. Thermal undershirt and Long Johns (Canadian Ensembles)



B2. CADPAT Fleece jacket and trousers (Canadian Ensembles)

B3. CADPAT ICE jacket and trousers (Canadian Ensembles)

B4. CADPAT IECS Parka (Canadian Ensembles)

B5. CADPAT IECS Bib Pants (Canadian Ensembles)

B6. Canada Goose Snow Mantra Winter parka (Canadian Ensembles)

Norwegian Cold Weather Clothing Elements

Element	Materials	Figure
Net underwear	85% Rhovyl; 15% Modal	C1
Wool Terry Cloth Underwear	70% wool; 30% polyester	C2
Cotton Field Shirt	100% cotton; knitted terry cloth	C3
M/02 Membrane Field Uniform (GORE-Tex®)	3 layer membrane laminate	C4
M/97 Camouflage Uniform (White)	Polyester and microfibre mixture	C5
Cold Weather Jacket and Trousers	Layering of polyester and patented filling material	C6

C1. Net Underwear (Norwegian Ensembles)

C2. Wool Terry Cloth Underwear (Norwegian Ensembles)

C3. Cotton Field Shirt (Norwegian Ensembles)

C4. M/02 Membrane Field Uniform (GORE-Tex®) (Norwegian Ensembles)

C5. M/97 Camouflage Uniform (White) (Norwegian Ensembles)

C6. Cold Weather Jacket and Trousers (Norwegian Ensembles)

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