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Choice of cold weather combat clothing affects manual performance, body temperatures and comfort in a sub-Arctic climate

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ABSTRACT
Appropriate clothing is important for maintaining operative capability during cold weather operations. This study examined the impact of different cold weather combat uniforms on body temperature, manual performance, comfort and perspiration among nine male soldiers (aged 24 ± 4 years) in field conditions (−2 to 5 °C). They completed three trials, consisting of a 1-h walk at 5 km/h and 1 h passive standing, wearing uniforms with varying insulation levels (1.9, 2.2 and 2.5 Clo). The results show that uniform type and insulation significantly affect skin temperature, moisture accumulation and manual dexterity in mild sub-Arctic winter conditions. Results also indicate that the insulation and design of hand protection significantly influence hand and finger skin temperatures, which in turn affects manual performance, independent of overall clothing insulation. Finally, while models like required clothing insulation (IREQ) are useful for initial recommendations, individual adjustments are needed to maintain comfort and prevent cold weather injuries.

KEYWORDS
manual dexterity; cold weather clothing; military; IREQ; cold weather operations

1. Introduction

Soldiers operating in cold environments face challenges maintaining comfort, performance and health. Despite the protective measures provided by cold weather combat clothing, the risk of body cooling remains significant during cold weather operations (CWOs), with extremities such as the hands and feet being particularly vulnerable. Manual finger dexterity is reduced when finger skin temperatures fall below 12–20 °C [1] or hand temperature drops below 15 °C [2]. This loss of motor skills can have severe consequences for soldiers, impacting essential tasks like fastening gear, zipping, lacing field boots, setting up tents, handling weaponry, opening field rations, managing protective equipment, and handling displays and controls.

Furthermore, extremity cooling can cause cold weather injuries (CWIs), e.g., non-freezing cold injuries (NFCIs) and freezing cold injuries (FCIs) [3,4]. These can cause lasting harm. A history of NFCIs and FCIs can further reduce manual dexterity and the ability to carry out manual work or tasks that require fine motor skills in cold conditions. These CWIs may disturb blood circulation, cause nerve damage, induce cold intolerance and persistent pain, and elevate the risk of re-injury in the same area [5–7]. Thus, the consequences of NFCIs and FCIs extend beyond the battlefield, potentially making soldiers unfit for continued service and impairing their civilian employability, while also potentially reducing their overall quality of life.

Maintaining thermal balance during CWOs depends on a complex interplay of factors, including air temperature, air velocity, humidity, radiation and metabolic heat production, as well as individual physiological variables and the thermal properties of worn clothing. While thermoregulatory effector mechanisms, such as regulating blood flow, sweating and shivering, offer short-term solutions for the whole body, they do not adequately address extremity discomfort. For instance, reducing skin blood flow will reduce the overall rate of cooling but can cause the extremities to cool down faster than the rest of the body.

The most effective form of human thermoregulation is thus behavioural adaptation, especially in cold environments, where the effectiveness of physiological adaptation is limited [8]. Examples of behavioural adaptations are adjusting posture, seeking shelter or warmth, regulating physical activity and wearing suitable clothing for both the environmental conditions and the activity. During military missions, however, changing clothing or seeking shelter is not always possible. Additionally, adapting clothing in cold environments based on weather and activity requires expertise and experience [9,10]. This means that individuals less accustomed to cold conditions may rely more heavily on their clothing and equipment compared to those with experience in such environments.

While thermal insulation is needed to maintain body temperature during CWOs, other properties, e.g., moisture handling and transfer, clothing layers and weight, are also important. Moisture management is especially important during extended CWOs, as wet clothing can lead to discomfort and an increased risk of CWIs due to accelerated heat loss [11,12]. The source of moisture may be the environment or the body or both. Therefore, the clothing should keep rain and snow out, while allowing heat to dissipate and sweat to evaporate. Shifting conditions, in particular (e.g., transitioning from skiing

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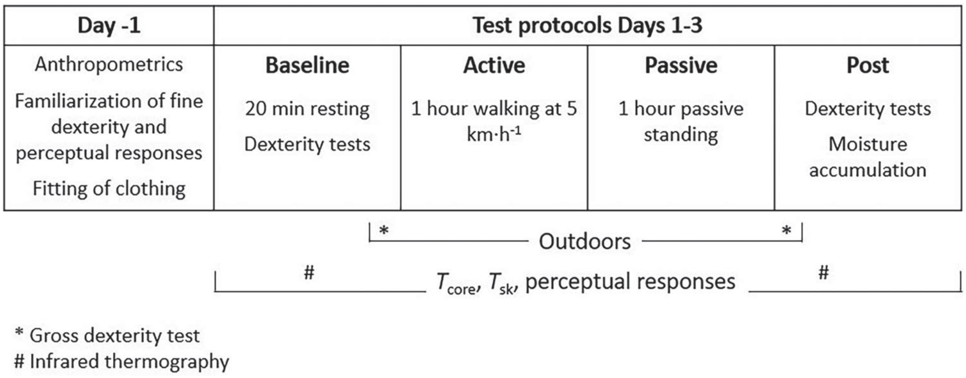

Figure 1. Test set-up with primary variables.

Note: T_{core} = core temperature; T_{sk} = mean skin temperature.

with heavy load to immobile guard duty), can be a challenge. Furthermore, the weight, bulk and number of layers in the clothing increase the metabolic cost of activities, thereby raising body heat production [13,14]. This can cause additional perspiration, further increasing moisture in the clothing [15]. It may also affect physical performance by reducing the work economy [13].

Different countries have varying prerequisites for coping with cold environments, each offering distinct cold weather combat clothing solutions. To ensure effective interoperability during military operations, every soldier should be equipped to handle the specific environmental challenges they may encounter. Published research on the effects of combat clothing on thermal responses and manual performance in the cold has been relatively limited, especially in real-world military scenarios. However, some studies have demonstrated that proper clothing design and clothing selection are essential for maintaining thermal balance, preventing CWIs and keeping manual performance in military [16] and occupational [17] settings.

Thermoregulatory models and calculations have been developed as tools for predicting cold stress, the risk of CWIs and survival rates. These models are based on simulated human thermoregulatory responses as a function of the environment, clothing, activity level and body characteristics, and they often use data for insulative properties of clothing from manikin testing. These models can recommend the level of thermal insulation to be worn, or the endurance time when wearing specific clothing ensembles, in different climates and activities [18,19]. In real military operations, however, factors such as physical activity, environmental changes and operational constraints create complexities that are difficult to model. To ensure that the models can provide reliable clothing recommendations for military applications, it is important to assess whether their predictions align with physiological outcomes observed in field settings.

The primary objective of this study was to investigate how three distinct cold weather combat uniforms from different countries in a specific scenario impact body temperatures, manual performance, comfort and perspiration in a field environment. Additionally, the study aimed to examine whether the extent to which soldiers are overdressed or underdressed according to the required clothing insulation (IREQ) model corresponds with their physiological responses.

2. Methods

2.1. Participants

Nine healthy Swedish male soldiers stationed in a sub-Arctic climate volunteered to participate in this study. Participant characteristics (mean ± *SD*) were: age, 24 ± 4 years; height, 184 ± 7 cm; body mass, 92.2 ± 11.1 kg; body fat percentage, 16.2 ± 4.2%; and experience as a soldier, 5 ± 2 years. In line with the principles of the Declaration of Helsinki, the participants were informed about the test protocol and their right to withdraw from the experiment at any time before they provided their written informed consent. Ethics approval for this study was granted by the Swedish Ethical Review Authority (Approval No.: 2023-02263-02). Prior to the experimental sessions, participants were asked to refrain from strenuous physical exercise 24 h before the tests, and coffee and alcohol 12 h before the tests. They were also asked to eat breakfast and stay hydrated before attending the tests.

2.2. Experimental design and clothing

The study employed a prospective, randomized, crossover design. Participants served as their own controls and completed three experimental field trials along with familiarization and preliminary measurements, as indicated in Figure 1. The trials were conducted on three consecutive days, and all trials started at the same time of day (arrival at 08:00; cold air exposure outdoors from about 10:00 to 12:00). The environmental conditions in terms of ambient temperature and wind during the cold exposure were the following: 4.1–5.0 °C and 3.1–7.0 m s^{-1} for day 1; −1.4 to −2.2 °C and 4.0–5.0 m s^{-1} for day 2; and 0.5–1.0 °C and 4.0–5.0 m s^{-1} for day 3. These measurements were recorded by the Swedish Meteorological and Hydrological Institute at Arvidsjaur Airport, Sweden.

The three clothing ensembles tested (Table 1) were from three different European countries. Each nation's configuration was chosen from their selection of cold weather uniforms based on a specific scenario. The scenario was that the soldiers would walk at a moderate pace for about 1 h, followed by a period of passive phase for an unknown reason, during which they could not change clothing or seek shelter. While one country had only one choice of active cold weather uniform, the other two had several alternative cold weather uniform items. Representatives from their armed forces, with extensive cold weather experience, made the decision on which uniform

Table 1. Description and specifics of the clothing ensembles used.

	Clothing ensemble		
Category / parameter	HIGH	MED	LOW
Underwear	Wool briefs	Participants' own briefs	Polyester briefs
Base layer	Wool mesh shirt Wool mesh pants	Cotton T-shirt Wool pants	Polyester shirt Polyester pants
Middle layer	Wool shirt Wool trousers	Wool jacket	Wool shirt
Outer layer	Combat jacket Combat pants Camouflage jacket Camouflage pants Cotton/polyester cap	Softshell combat vest Combat jacket Combat pants Gaiters Wool beanie Goggles	Jacket Combat pants Gaiters Polyester beanie
Handwear	Wool mittens Polyester and leather overmitts	Polyester gloves	Polyester and leather gloves
Footwear	Thin wool socks Thick wool socks Leather winter boots	Thin wool socks Thick wool socks Leather winter boots	Thick wool socks Leather winter boots
Ensemble weight (kg)	7.0 ± 0.3	6.4 ± 0.3	5.3 ± 0.3
Total insulation (Clo)	2.5	2.2	1.9
Estimated intrinsic clothing insulation (Clo)	2.2	1.9	1.5
Estimated clothing area factor	1.7	1.6	1.5
Hand insulation (Clo)	0.092	0.097	0.072

Note: The same military boots (2.0 ± 0.1 kg) were worn under all ensemble configurations.

The stated material is the one that the garment has in the largest proportion. Insulation values (Clo) for the total insulation (I_T) and hand insulation were attained by measurements on a static thermal manikin placed in a climatic chamber with environmental conditions of 10 °C, 50% relative humidity and a wind speed of < 0.2 m/s according to Standard No. ISO 9920:2009 [21]. Local hand insulation was derived from hand-segment power data and the hand-to-body surface area ratio.

configuration to choose. This resulted in the differences seen in materials, layers and, consequently, insulation that is further referred to as high (HIGH), medium (MED) and low (LOW). To prevent the risk of foot injury (e.g., blisters), the soldiers exclusively used Swedish military winter boots and Swedish woollen socks for all configurations.

All participants were equipped and dressed in underwear and base-layer clothing on all days, and baseline measurements were collected with the participants in a seated position wearing base-layer clothing at room temperature (20.6 ± 0.3 °C, 32 ± 4% relative humidity) for a minimum of 20 min. The trials consisted of a 1-h walk at 5 km/h (active phase) on a snowy road followed by 1 h of simulated guard duty (passive phase), for which they were to remain in a standing position. The trials were conducted outdoors (in Arvidsjaur, Sweden), with the soldiers wearing one of three different winter uniform ensembles with different compositions and varying total clothing insulation: HIGH (2.5 Clo), MED (2.2 Clo) and LOW (1.9 Clo) [20,21]. The ensembles were worn in a balanced order, i.e., three participants wore HIGH insulation, three MED insulation and three LOW insulation each day, rotating so that all nine participants had worn all three ensembles once during the 3 days of testing.

To test the differences due to the actual clothing, and not the soldiers' ability to regulate the clothing according to activity and ambient conditions, the participants were not allowed to don, doff or otherwise regulate clothing during the trials. They were also asked to walk normally and not change their behaviour during the passive phase (e.g., pulling their fingers into the centre of the gloves, warm their hands on other body parts or moving to increase blood flow to the feet or hands). All clothing items were weighed separately before and immediately after the experiment (±0.1 g, maximum 16.2 kg) (MS16001L and SB16001; Mettler Toledo, Switzerland,) to measure weight gain, as an indicator of moisture accumulation in the clothing.

2.3. Preliminary measurements and familiarization

Most preliminary measurements and familiarizations were performed on the day before the first test day. Each participant's height (Seca 217 Stadiometer, Hamburg, Germany), body mass (±0.05 kg) (Astra B; Tanita, Japan) and body composition (Inbody 770; InBody Co. Ltd, Republic of Korea) (measured in a fasting state before breakfast) were measured and recorded. The correct sizes of clothing for use in the tests were selected from a wide range of available sizes. A size was considered correct when the participant found a size that was well-fitted and comfortable, and which was also approved by a member of the scientific team. Participants completed six familiarization trials for each fine manual dexterity subtest (dominant hand, non-dominant hand, both hands and assembly) without gloves, to minimize practice effects before the experimental testing. No familiarization of the gross manual dexterity test was performed because the participants were already familiar with the tasks.

2.4. Physiological measurements

The temperature of the skin was measured every minute at eight positions with wireless temperature sensors (DS 1922L Thermochron iButton; Maxim, USA) throughout the baseline measurements and cold exposure. The iButton sensors were attached directly to the skin with Fixomull over the scapula and on the chest, forehead, anterior thigh, calf, upper arm, forearm and dorsal side of the hand (T_{hand}). Mean skin temperature (T_{sk}) was calculated according to Standard No. ISO 9886:2004 [22]:

$$\begin{aligned}T_{\text{sk}} = {} & 0.07 \times T_{\text{forehead}} + 0.175 \times T_{scapula} \\ & + 0.175 \times T_{\text{upper chest}} + 0.07 \times T_{\text{upper arm}} \\ & + 0.07 \times T_{\text{forearm}} + 0.05 \times T_{\text{hand}} \\ & + 0.19 \times T_{\text{anterior thigh}} + 0.2 \times T_{\text{calf}}. \end{aligned} \tag{1}$$

Thermistors (EU-U-3V-0, Grant, UK) were also placed on the skin over the middle phalanx on the dorsal side of the middle finger of the non-dominant hand (T_{finger}) and on the dorsal side of the first toe. The temperature on the finger and toe was recorded every 10 min during the simulated guard duty (Eltek 1000 Squirrel; Grant, UK).

In addition, the skin temperature of the palmar side of the right hand and on the skin over the distal phalanxes of each finger on the palmar side was measured using a thermography camera at baseline, immediately after the 20-min stabilization period and directly before the Purdue pegboard (PP) test, and again immediately after the cold exposure, directly before the post-exposure PP test. Thermograms were recorded with a FLIR T460 imager (FLIR Systems, Sweden), with a resolution of 320 × 240 pixels (76,800 pixels), measuring range of −20 to +120 °C, accuracy of 2%, sensitivity ≤ 0.04 °C, infrared spectral band of 7.5–13 μm and autofocus, setting the emissivity at 0.98. The camera was turned on 30 min before the measurements to allow for sensor stabilization, and was positioned on a tripod 76 cm from the subject, perpendicular to the region of interest (ROI). An anti-reflective blue background was set behind the hand to minimize any reflection from infrared radiation [23].

Thermograms were analysed with FLIR ResearchIR Max, version 4.40.7.26, which allowed us to obtain the average temperature of each manually outlined ROI. Variations in surface area between participants were accounted for by manual readjustment of each ROI prior to extracting average and standard deviation values. The digits were isolated using a rectangular ROI extending from the base of each finger where it connects to the palm to the fingertip, with slight reductions of the ROI borders to avoid edge effects and isolate the finger from the background. The palm was isolated using a polygonal ROI encompassing the thenar and hypothenar eminences.

Temperature in the gastrointestinal tract as indicator of core temperature (T_{core}) was registered telemetrically by use of telemetric pills that the participants swallowed in the morning at 06:00 each test day (e-Celsius; BodyCAP, France).

Nude body mass was recorded pre and post test. To ensure that the participants had some liquid intake during the approximately 3-h period when they were otherwise not allowed to eat or drink, they were provided with 0.2 L tempered water after the baseline period (the amount was subtracted from the post-test body mass measurements). Body mass loss was calculated as change in body mass from pre-trial to post-trial measurements and used as an indicator of sweating.

The cold exposure was stopped, and dexterity tests were then performed if the termination criterion was reached: either one of the skin temperatures remained below 10 ℃ for longer than 20 min, or dropped below 8 °C. These criteria were chosen to reduce the risk of CWIs for the participants.

2.5. Manual dexterity measurements

Fine manual dexterity was assessed using the PP test (Lafayette Instruments, Inc., USA). In the first tests, the participants placed as many pegs as possible into a board with fitting holes in 30 s. The test was repeated three times: first with the dominant hand, then with the non-dominant hand and, finally, with both hands. Following this, the participants completed a PP assembly test, in which they assembled as many sets as possible consisting of a peg, two sleeves and a washer into the same kind of board, using both hands in 1 min. Gross manual dexterity was assessed by a magazine loading task [24]. The task consisted of loading as many dummy cartridges as possible in 130 s into an AK5 rifle magazine, each magazine having a capacity of 30 cartridges. The gross manual dexterity test was performed outside wearing thin wool gloves both at baseline (directly before starting the march) and after the simulated guard duty. To avoid the risk of FCIs when touching metal with bare hands in cold conditions, the fine manual dexterity tests (PP tests) were performed indoors both at baseline and following the passive phase without the use of gloves. The PP tests were performed by two participants at the same time. For the post test, participants waited outdoors until it was their turn to perform the tests. Upon entering the testing facility, they removed their gloves and thermograms were captured promptly using a prepared camera set up to minimize delay, followed by the PP tests. The order of the participants was set to be the same for each measurement, with approximately 20 min between the first and the last participant. However, if a participant reached the termination criteria, they were moved forward to avoid further cold exposure.

2.6. Perceptual responses

Perceptual responses were assessed at the start, middle and end of both the march and the simulated guard exercise. Perceived thermal sensation (PTS) and pain were assessed for the whole body, head, hands and feet. PTS was assessed using a 7-point scale (1 = *cold*, 7 = *hot*) [25], and pain was evaluated using the Borg 0–10 scale (0 = *none at all*, 10 = *maximally strong*) [26]. Rate of perceived exertion (RPE) was measured using the 6–20 Borg scale (6 = *very, very light*; 20 = *maximal exertion*) [26]. Sensation of shivering and sweating was rated on a 1–7 scale (1 = *vigorously shivering*, 7 = *heavy sweating*) [27], and thermal comfort on a 1–4 scale (1 = *comfortable*, 4 = *very uncomfortable*) [28].

2.7. Insulation required versus actually worn insulation calculations

One goal of this study was to assess whether variance between physiological outcomes could be explained by variations in required clothing insulation. To that end, the deviation between required clothing insulation and actually worn clothing insulation ($\Delta\text{Clo} = \text{Clo}_{\text{actual}} - \text{Clo}_{\text{required}}$) is used as explaining variable. Standard No. ISO 11079 IREQ [18] describes a mathematical procedure to calculate the required intrinsic clothing insulation (IREQ) for humans to remain in thermal balance based on metabolic rate, body surface area,

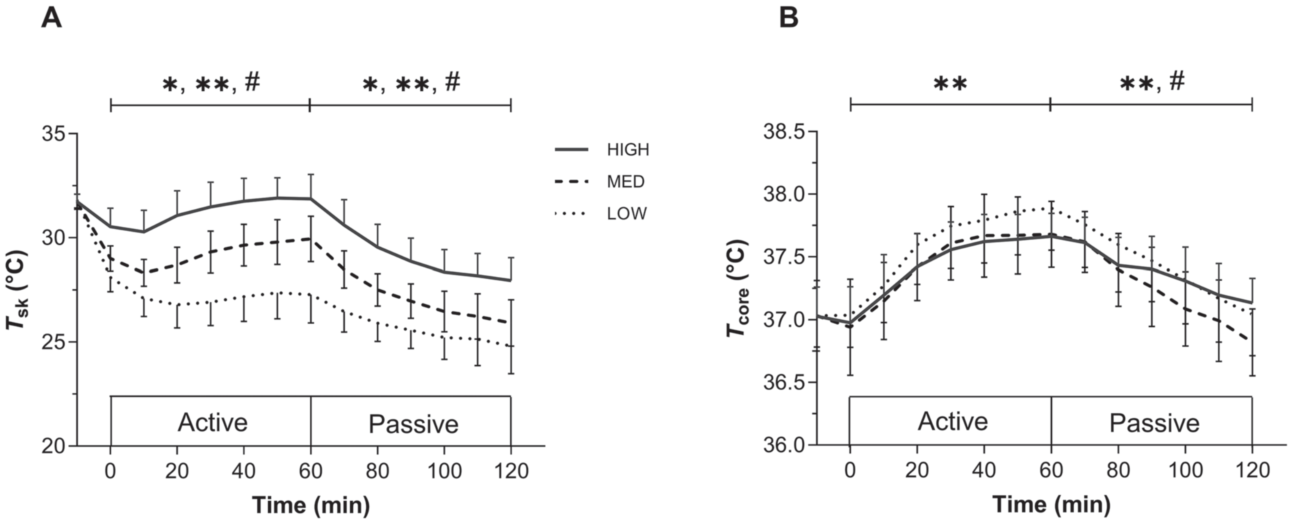

Figure 2. (A) Mean skin temperature (T_{sk}) and (B) core temperature (T_{core}) for the three clothing ensembles (HIGH, MED, LOW) from baseline through the active and passive phase.

Note: *Significant main effect of clothing ensemble. **Significant main effect of time. #Significant interaction between clothing ensemble and time. Values presented as mean ± standard deviation.

thermal environment (air temperature, mean radiant temperature, humidity and wind speed) and wind permeability of the clothing ensemble (< 8 L/m^2/s). IREQ includes the effects of body movement and wind that reduce the insulative value of the clothing ensemble relative to its static state. Therefore, in order to compare the calculated IREQ values with measured thermal manikin values, the IREQ values are converted to the intrinsic static clothing insulation ($I_{cl,required} = clo_{required}$), also as described in Standard No. ISO 11079. Furthermore, note that the thermal manikin measurements provide total static insulation (I_T), which is a combination of the intrinsic static clothing insulation (I_{cl}) and the insulation provided by the surrounding air layer (I_{air}), corrected for added surface area by the clothing (f_{cl}):

$$I_T = iI_{cl} + iI_{air}/f_{cl}.$$

The ensemble intrinsic clothing insulative values were estimated by assuming that the air insulation (I_a) was 0.085 m^{2}K/W (about 0.55 Clo) and consequently iterating the clothing area factor (f_{cl}) until ($I_{T,measured} - I_{T,estimated}$) < 0.001 Clo. The resulting values are presented in Table 1.

The ΔClo values were calculated separately for the active and passive experiment phases. For both phases, the thermal environment input was as described in Section 2.2. Wind speed was reported 10 m above ground level and converted from the 10 m value to the 2 m value as $w_{2m} = 0.667\, w_{10m}$ [29]. For the active phase, the metabolic rate (in watts per square metre) was calculated using the Pandolf equation for heat production (in watts) [30] and dividing by the average participant body surface area [31]. The inputs for the Pandolf equation were the average participant body weight, the weight of the clothing ensemble as carried load and walking at 5 km/h on a near-flat top road; which resulted in 171, 173 and 174 W/m^2 for the LOW, MED and HIGH clothing ensembles, respectively. For the passive condition, 1.5 Met or 90 W/m^2 was assumed for the standing activity of the passive phase.

2.8. Statistical analysis

Statistical analyses used SPSS version 27.0. Two-way repeated-measures analysis of variance (ANOVA) was used to analyse the main effects of time and clothing configuration, and the interaction between clothing configuration and time on T_{sk}, T_{core}, and palm and finger skin temperatures measured with thermography. For the skin temperatures measured with thermography, the significant main effect of clothing ensemble was followed up using Bonferroni's multiple comparisons test. One-way repeated-measures ANOVA was used to test for differences in fine manual dexterity, gross manual dexterity, T_{finger}, T_{hand}, rate of change in T_{core} and T_{sk}, total body mass loss and moisture accumulation between the three clothing ensembles. Where significant differences were found between ensembles, pairwise comparisons with Bonferroni corrections were used to identify the ensembles between which the difference originated. The Wilcoxon signed-ranks test was used for paired samples between the clothing configurations for the non-parametric data (RPE, PTS, pain, sensation of shivering and sweating, and thermal comfort). The R-package lme4 1.1-32 was used for multilevel model analysis to test the association between outputs and the deviation between required and actual clothing insulation. Additionally, the conditional percentage of explained variance (r^2) was calculated, considering both the fixed and random effects of individuals who repeated the test under three conditions. Non-parametric data are presented as the median and range, and all other data are presented as the mean ± standard deviation, and differences are considered significant if $p < 0.05$.

3. Results

3.1. Thermal responses

T_{sk} changed over time during both the active and passive phases (Figure 2(A)). The rate of change in T_{sk} from baseline through the active phase differed significantly between the ensembles ($p < 0.05$). The soldiers had the slowest rate of change when wearing the HIGH clothing ensemble ($0.1 \pm 1.1\,^{\circ}\mathrm{C} \times \mathrm{h}^{-1}$), followed by MED at an intermediate rate ($-1.8 \pm 1.0\,^{\circ}\mathrm{C} \times \mathrm{h}^{-1}$) and the fastest rate of change with the LOW ensemble ($-4.5 \pm 1.2\,^{\circ}\mathrm{C} \times \mathrm{h}^{-1}$). Rate of change in T_{sk} during the passive phase was significantly slower wearing LOW ($-2.4 \pm 1.1\,^{\circ}\mathrm{C} \times \mathrm{h}^{-1}$) compared to MED ($-3.9 \pm 0.6\,^{\circ}\mathrm{C} \times \mathrm{h}^{-1}$, $p = 0.047$) and HIGH ($-3.8 \pm 0.6\,^{\circ}\mathrm{C} \times \mathrm{h}^{-1}$, $p < 0.001$). T_{core} increased during the active phase and decreased during

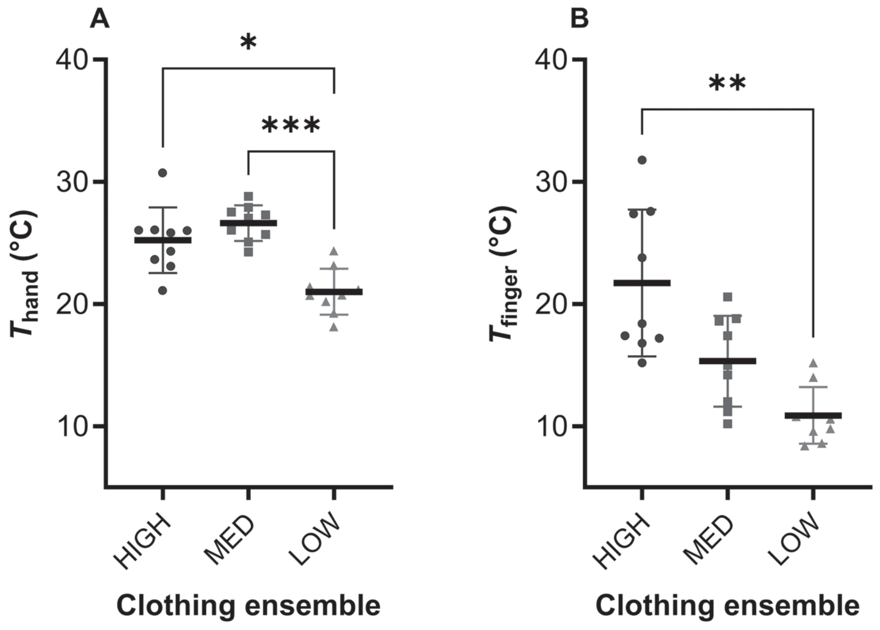

Figure 3. (A) Hand skin temperature (T_{hand}) measured with an iButton and (B) middle finger (finger III) skin temperature (T_{finger}) measured with a thermistor at the end of the passive phase when wearing three different clothing ensembles (HIGH, MED, LOW).

Note: *Significant difference ($p < 0.05$). **Significant difference ($p < 0.01$). ***Significant difference ($p < 0.001$). Individual data points plotted, with mean (horizontal lines) and standard deviation (error bars).

the passive phase (Figure 2(B)). There were no significant differences in T_{core} between the clothing ensembles during the active phase. For T_{core}, the rate of change during the passive phase was significantly slower wearing HIGH (−0.5 ± 0.1 ℃ × h^{-1}) compared to MED (−0.9 ± 0.3 ℃ × h^{-1}, $p = 0.015$) and LOW (−0.8 ± 0.2 ℃ × h^{-1}, $p = 0.011$).

At the end of the passive phase, T_{hand} was lowest wearing LOW. It was 4.2 ± 1.1 and 5.6 ± 0.7 ℃ higher when wearing HIGH and MED, respectively (Figure 3(A)). T_{finger} was also lowest wearing LOW, with a 10.8 ± 2.0 ℃ difference compared to HIGH (Figure 3(B)). Toe temperature at the end of the passive phase did not differ between clothing ensembles (HIGH, 27.8 ± 2.9 ℃; MED, 27.8 ± 2.4 ℃; LOW, 26.9 ± 2.7 ℃; $p = 0.742$).

On the second test day, two participants reached the termination criteria when waiting outside for their turn to perform the PP test post cold exposure. One participant wearing MED had to do the PP test 4 min before the set time, and one participant wearing LOW had to do the PP test 22 min before the set time.

Palm and skin temperatures of the distal phalanxes of the five fingers on the right hand as measured via thermography (Figure 4) all significantly decreased with time ($p < 0.001$). Clothing had a significant main effect ($p < 0.05$) on skin temperature for the palm (Figure 4(A)), and the middle finger (finger III) (Figure 4(D)), the ring finger (finger IV) (Figure 4(E)) and the little finger (finger V) (Figure 4(F)). There were no significant differences in baseline temperatures measured via thermography between the clothing ensembles. Palm temperature was 3.5 and 4.1 ℃ lower wearing LOW than MED and HIGH, respectively. HIGH temperatures were higher (3.6–5.5 ℃) than MED and LOW for fingers III, IV and V.

3.2. Perceptual responses

There were no significant differences ($p = 0.104$) in RPE between the median [range] HIGH (10 [8, 12]), MED (10 [7, 11]) or LOW (9 [8, 11]) ensembles during walking at 5 km/h. When wearing HIGH, participants reported that their body felt warm at the end of the active phase; while wearing LOW, they felt between neutral and slightly warm (Table 2). Participants reported moderate to some sweating during the active phase for all ensembles. Wearing LOW, the participants felt that their hands became cold during the passive phase, while wearing HIGH their hands felt slightly cool. Between moderate and slight shivering was reported at the end of the passive phase wearing LOW versus no shivering wearing HIGH. The participants felt uncomfortable wearing HIGH at the end of the active phase and when wearing LOW at the end of the passive phase. No pain was reported in the body, face or feet for any clothing ensemble. No pain in the hands was reported wearing HIGH, whereas all but one reported pain in the hands wearing LOW at the end of the passive phase. Durning the same phase, three participants reported very mild to quite strong pain in the hands when wearing MED.

3.3. Manual dexterity

Table 3 presents the change in fine manual dexterity (PP assembly) and gross manual dexterity (magazine loading) scores from baseline to post passive phase. The PP assembly test and the magazine loading test showed significant differences between ensembles. The PP assembly score decreased 17 ± 4 and 18 ± 6 percentage points more wearing MED and LOW than HIGH, respectively (Figure 5(A)). For the magazine loading task, the difference between HIGH and LOW was 22 ± 4 percentage points (Figure 5(B)).

3.4. Clothing moisture accumulation

Total body mass loss (used as an indicator of sweating) was significantly higher for HIGH (0.7 ± 0.3 kg) than LOW (0.4 ± 0.2 kg, $p = 0.010$), but there was no significant difference with MED (0.5 ± 0.2, $p = 0.349$). The highest level of moisture accumulation was found in the HIGH clothing ensemble (180 ± 69 g) with 78 ± 17 g less in MED, and a further 36 ± 11 g less in LOW

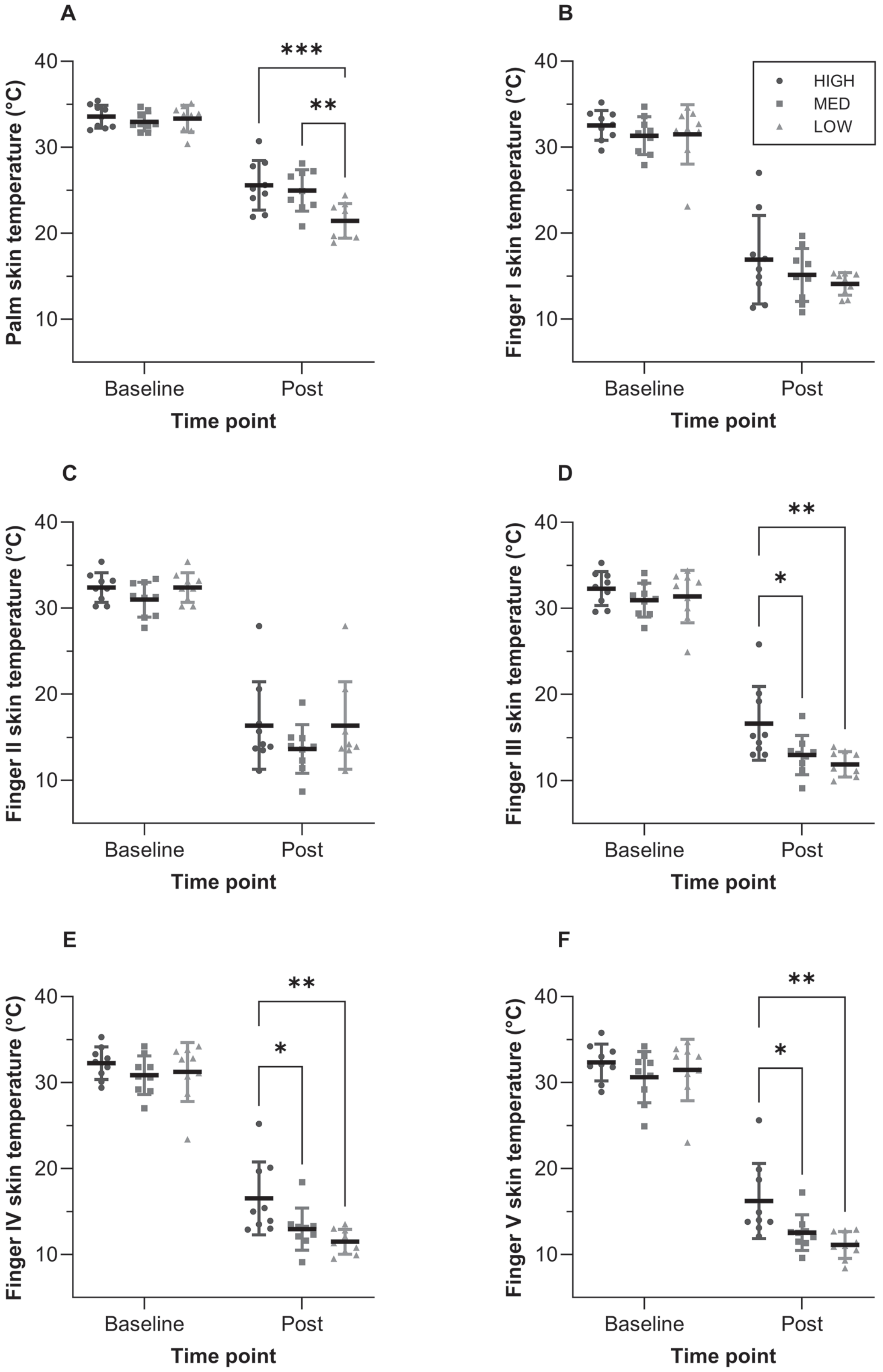

Figure 4. Individual skin temperatures of the palm and fingers obtained by infrared thermography on the ventral surface of the hand at baseline and after completion of the passive phase for the three clothing ensembles (HIGH, MED, LOW): (A) palm; (B) thumb (finger I); (C) index finger (finger II); (D) middle finger (finger III); (E) ring finger (finger IV); (F) little finger (finger V).

Note: *Significant difference ($p < 0.05$). **Significant difference ($p < 0.01$). ***Significant difference ($p < 0.001$). Individual data points are plotted, with mean (horizontal lines) and standard deviation (error bars).

(Figure 6(A)). For the base layer, HIGH had a higher level of moisture accumulation compared to both MED ($p = 0.003$) and LOW ($p < 0.001$) (Figure 6(B)). Furthermore, HIGH also displayed a higher level of accumulated moisture in both the middle and outer layers when compared with MED ($p = 0.022$) and LOW ($p = 0.003$). There were no differences in accumulated moisture in the footwear between the clothing ensembles. In the hand wear, HIGH had the most moisture accumulated, followed by MED and then LOW, with significant differences between all ($p < 0.01$).

Table 2. Perceptual responses at baseline and the end of the walking and the passive periods while wearing three different clothing ensembles.

Measure	Clothing ensemble	Baseline	Active	Passive
PTS body[a]	HIGH	4 [4, 4]	6 [5, 7]*	3 [3, 4]
	MED	4 [3, 4]	5 [4, 6]	3 [1, 3]
	LOW	4 [4, 5]	4.5 [2, 5]#	2 [1, 4]
PTS hands[a]	HIGH	4 [4, 4]	6 [5, 7]	3 [2, 4]*
	MED	4 [4, 4]	6 [5, 7]	2 [1, 3]
	LOW	4 [4, 5]	5 [5, 7]	1 [1, 2]#
PTS head[a]	HIGH	4 [4, 4]	5 [2, 7]	3 [2, 5]
	MED	4 [4, 4]	4 [3, 6]	3 [2, 4]
	LOW	4 [4, 5]	4 [2, 5]	3 [2, 4]
PTS feet[a]	HIGH	4 [3, 4]	6 [4, 7]	4 [3, 4]
	MED	4 [2, 4]	5 [4, 6]	4 [3, 4]
	LOW	4 [3, 5]	5 [4, 6]	4 [3, 4]
Pain hands[b]	HIGH	0 [0, 0]	0 [0, 0]	0 [0, 0]*
	MED	0 [0, 0]	0 [0, 0]	0 [0, 4]*
	LOW	0 [0, 0]	0 [0, 0]	3 [0, 5]
Thermal comfort[c]	HIGH	1 [1, 2]	3 [2, 3]*	2 [1, 2]*
	MED	1 [1, 2]	2 [1, 3]	2 [1, 3]
	LOW	1 [1, 2]	2 [1, 3]#	3 [2, 3]#
Shivering/sweating sensation[d]	HIGH	4 [4, 4]	6 [5, 6]	4 [3, 4]*
	MED	4 [4, 4]	6 [4, 7]	3 [3, 4]
	LOW	4 [4, 4]	5 [4, 6]	2.5 [2, 3]#

[a] 1 = *cold*; 2 = *cool*; 3 = *slightly cool*; 4 = *neutral*; 5 = *slightly warm*; 6 = *warm*; 7 = *hot*.

[b] 0 = *none at all*; 0.5 = *very mild (barely perceptible)*; 1 = *very weak*; 2 = *weak*; 3 = *moderate*; 4 = *somewhat strong*; 5 = *strong*; 6; 7 = *very strong*; 8; 9; 10 = *maximally strong*.

[c] 1 = *comfortable*; 2 = *slightly uncomfortable*; 3 = *uncomfortable*; 4 = *very uncomfortable*.

[d] 1 = *vigorously shivering*; 2 = *moderately shivering*; 3 = *slightly shivering*; 4 = *neither shivering nor sweating*; 5 = *some sweating*; 6 = *moderate sweating*; 7 = *heavy sweating*.

*Significantly different from paired sample wearing LOW.

#Significantly different from paired sample wearing HIGH.

Note: Data presented as the median [range]. PTS = perceived thermal sensation.

Table 3. Changes in Purdue pegboard (PP) and magazine loading test score from baseline to post-passive phase while wearing three different clothing ensembles (HIGH, MED, LOW).

Test	Clothing ensemble			
	HIGH	MED	LOW	*p*
PP assembly (number of pegs)	−1.1 ± 5.4	−9.0 ± 4.2*	−9.7 ± 5.1*	0.003
PP dominant hand (number of pegs)	−1.1 ± 2.3	−1.8 ± 1.3	−1.9 ± 1.8	0.563
PP non-dominant hand (number of pegs)	−1.3 ± 3.4	−1.3 ± 2.9	−2.9 ± 1.5	0.280
PP both hands (number of pegs)	−1.0 ± 2.1	−1.1 ± 0.9	−2.1 ± 2.0	0.314
Magazine loading (number of cartridges)	−1.9 ± 8.8	−10.2 ± 4.4	−14.2 ± 5.7*	0.004

Note: *Significantly different from HIGH.

Data presented as mean ± standard deviation. *p* values from one-way analysis of variance (ANOVA). The magazine loading task was performed with thin wool gloves.

3.5. Required clothing insulation and physiological responses

The multilevel regression analysis revealed a significant positive relationship between ΔClo values (static intrinsic Clo of the ensemble worn minus static intrinsic required insulation for thermal neutrality) and moisture accumulation, with an intercept of 81 g (95% confidence interval [CI] [49, 113]) and a slope of $144\ \mathrm{g} \times \Delta\mathrm{Clo}^{-1}$ (95% CI [104, 184], conditional $R^2 = 0.78$) (Figure 7(A)). Similarly, the relationship with finger skin temperature had an intercept of 40 °C (95% CI [35, 46]) and a slope of $16\,^{\circ}\mathrm{C}\cdot\Delta\mathrm{Clo}^{-1}$ (95% CI [13, 20], conditional $R^2 = 0.78$) (Figure 7(B)). For comfort ratings, increased ΔClo during the active phase was significantly associated with decreased thermal comfort (conditional $R^2 = 0.66$) (Figure 7(C)), and during the passive phase a lower ΔClo value was significantly associated with reduced thermal comfort (conditional $R^2 = 0.63$) (Figure 7(D)). The model explained that 40–70% of the variance in finger skin temperature, moisture accumulation and comfort were due to differences in ΔClo. The increase in R^2 (from marginal to conditional) upon including participants as a random-effects variable shows the effect of individual variation on the dependent variables.

4. Discussion

This study highlights the impact of cold weather combat clothing choices on body temperatures, hand and finger skin temperature, manual performance, perspiration, moisture accumulation, comfort and the associated CWI risk in mild sub-Arctic winter conditions. Generally, lower insulation results in decreased T_{sk}, less sweating and reduced moisture accumulation within the clothing during walking. Higher insulation levels, however, maintain higher hand and finger skin temperatures, enhance comfort and improve manual dexterity during periods of passivity. Nonetheless, there are interindividual differences in physiological and performance outcomes that cannot be attributed solely to ambient temperature or clothing insulation.

4.1. Skin temperature and manual dexterity

Fine finger dexterity decreased after cold exposure when wearing the MED and LOW ensembles. The mean change in the PP assembly test was a 3% decline when wearing HIGH, compared to a 20% decline when wearing MED and LOW. Daanen [32] found reduced finger dexterity when the finger skin temperature was below 14 °C. Wiggen et al. [17] suggested a drop in both fine and gross finger dexterity at a finger skin temperature lower than 20 °C, while Schiefer et al. [33] reported reduced manual performance at a finger skin temperature of 20–22 °C, as well as a more pronounced performance drop at 15–16 °C. In our study, all but one participant had a finger skin temperature of 14 °C or lower when wearing the LOW ensemble, and five participants had a finger skin temperature of 14 °C or lower when wearing the MED ensemble. All participants had finger skin temperatures above 14 °C when wearing the HIGH ensemble. Hand skin temperature did not significantly differ between HIGH and MED, indicating that finger skin temperature was the key factor affecting fine manual dexterity, emphasizing the importance of measuring finger skin temperature, in addition to hand skin temperature.

Based on our results, it appears that utilizing thermography to measure finger and hand skin temperatures following cold exposure is a practical alternative when thermistors or iButtons prove to be cumbersome in field settings.

T_{core} did not drop below baseline levels, indicating that the significant impact on manual dexterity was due to local skin temperature. This aligns with previous research that emphasizes the importance of local skin temperature in cold-induced reductions in manual dexterity [2,34].

Gross finger dexterity was significantly more reduced when wearing LOW compared to HIGH, with a difference of 22 percentage points. There was no significant difference compared to MED, despite an average 18% decline in the score versus a 2% decline wearing HIGH. However, the observed

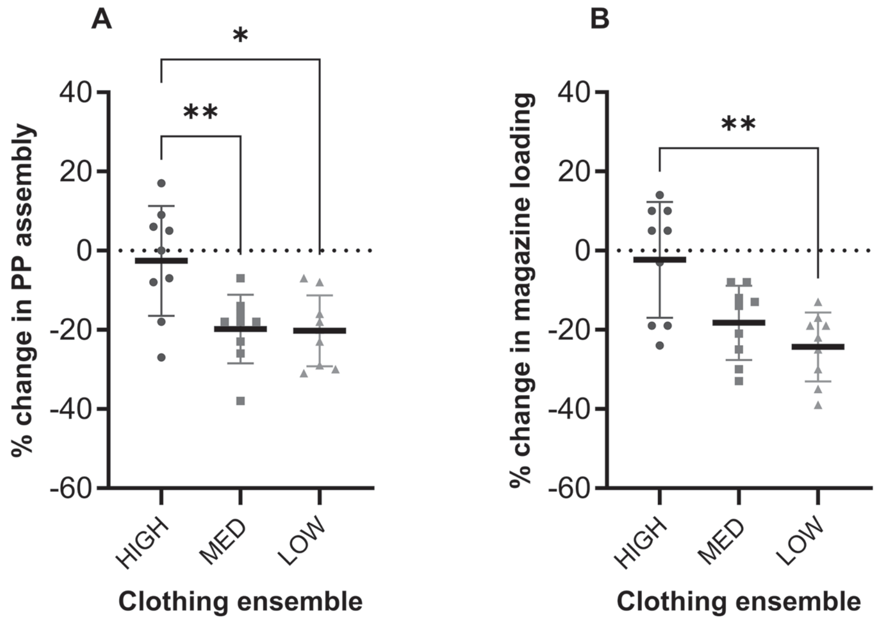

Figure 5. Changes in (A) Purdue pegboard (PP) assembly and (B) magazine loading between baseline and after the passive phase while wearing three different clothing ensembles (HIGH, MED, LOW).

Note: *Significant difference ($p < 0.05$). **Significant difference ($p < 0.01$). Individual data points plotted, with mean (horizontal lines) and standard deviation (error bars).

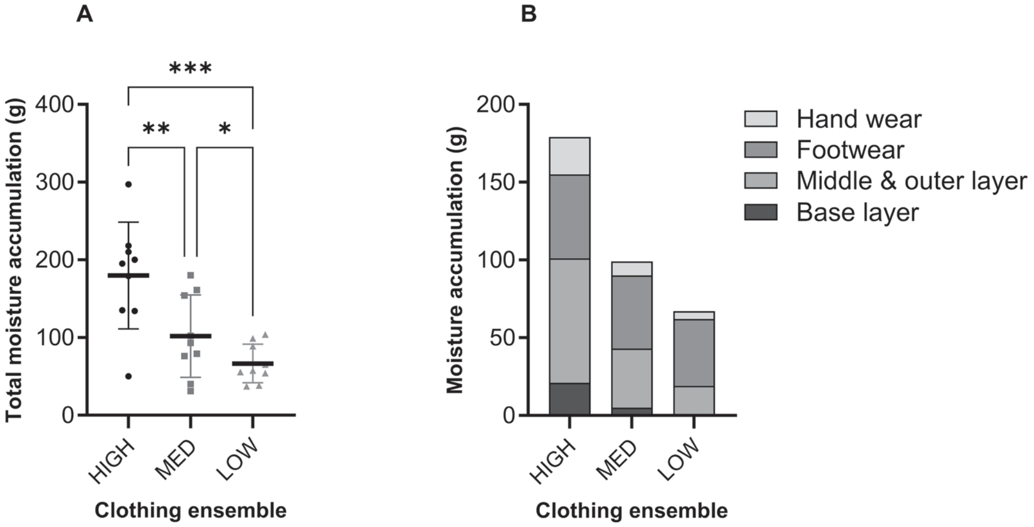

Figure 6. (A) Total moisture accumulation and (B) mean moisture accumulation in the clothing layers in the three different clothing ensembles (HIGH, MED, LOW).

Note: *Significant difference ($p < 0.05$); **Significant difference ($p < 0.01$); ***Significant difference ($p < 0.001$). In (A) individual data points plotted, with mean (horizontal lines) and standard deviation (error bars).

decrease in magazine loading speed in cold conditions aligns with prior research results, reporting reductions of approximately 21% [35] and less than 15% [24], on average. These results demonstrate that even brief exposure in a mild sub-Arctic climate can impair fine and gross manual dexterity if the thermal protection is inadequate.

It is worth noting that the participants wore the same footwear for all three ensembles, resulting in no significant difference in toe temperature, despite the difference in clothing insulation and the subsequent T_{sk}. Furthermore, they wore different handwear for each of the three ensembles, which resulted in varying finger skin temperatures. This shows the importance of extremity protection regardless of the overall clothing insulation.

Manual dexterity significantly declined when individuals wore either the MED or LOW insulation ensembles, both of which included gloves for hand insulation. Conversely, wearing the HIGH ensemble with mittens led to only minor reductions in manual dexterity. The LOW gloves provided least protection against the cold, consistent with their lower insulation value. Although manikin measurements showed that the MED gloves had better insulation than the HIGH mittens, in practice, the fingers in the HIGH mittens retained heat more effectively due to the design of the mittens. Hand temperature data indicated that the MED gloves offered better protection against the cold compared to the LOW gloves. However, much of this protection was lost for the fingers, highlighting that the design (gloves vs mittens) is as important as insulation value for keeping hands and fingers warm during cold exposure.

Before the dexterity assessments, participants removed their assigned gloves or mittens. For the gross manual dexterity task, however, all participants wore the same thin wool

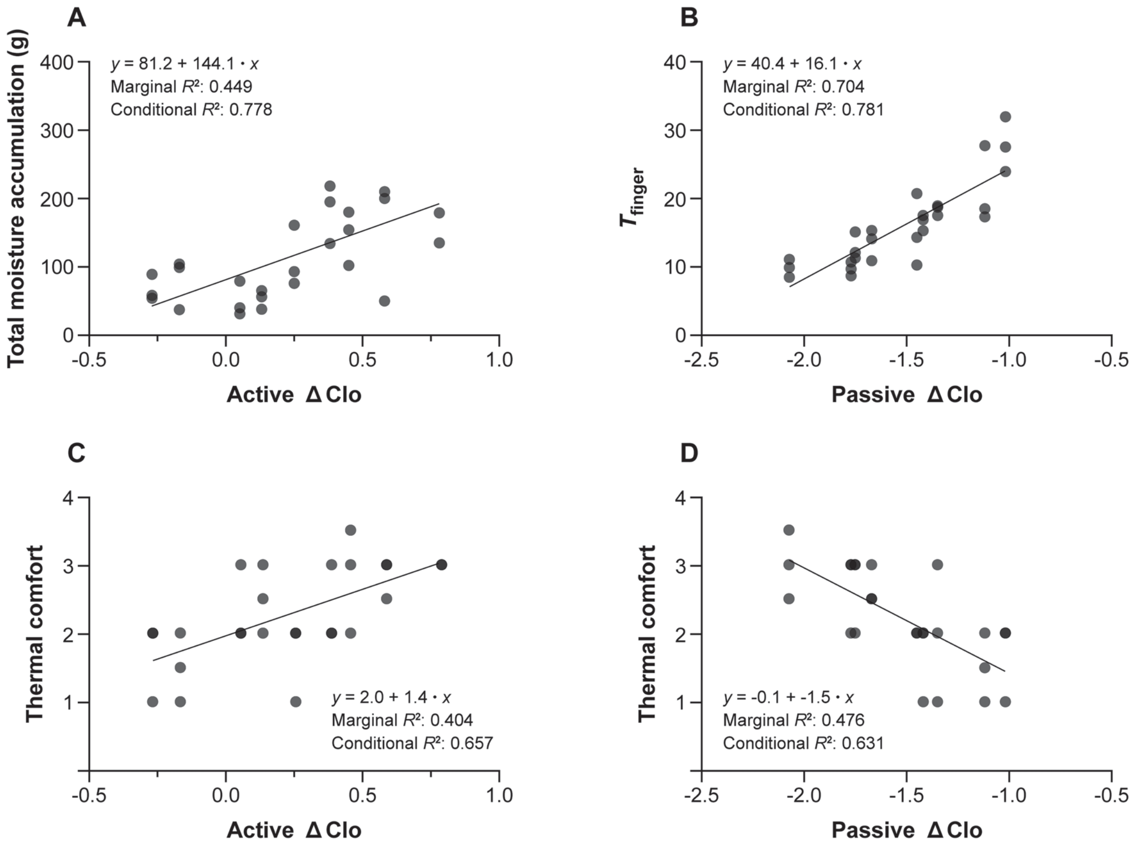

Figure 7. (A) Total moisture accumulation in the clothing, (B) finger skin temperature (T_{finger}) at the end of the passive phase, and (C) active and (D) passive thermal comfort for ΔClo values (static intrinsic Clo of the ensemble worn minus static intrinsic Clo required for neutrality).

Note: Thermal comfort variable scaled from 1 to 4, where higher values indicate increasing discomfort (1 = *comfortable*, 4 = *very uncomfortable*).

gloves to avoid direct contact with cold metal while ensuring that handwear did not differ between clothing ensembles. This approach removed the influence of ensemble-specific handwear on performance and allowed us to isolate the physiological effects of the clothing systems, given that gloves and mittens reduce manual dexterity [36]. If the assigned gloves or mittens were not removed before such tasks, gloves would most likely demonstrate better dexterity compared to mittens. Previous research has shown that object size, glove type and temperature all impact manual dexterity. Double gloving may be recommended for increased insulation, with the inner glove being used to perform precision tasks [37]. Nevertheless, while mittens may compromise dexterity, they offer better protection against heat loss, as evidenced by the lower finger skin temperatures in the MED and LOW ensemble compared to the HIGH ensemble. The need to remove participants from the cold because their skin temperatures reached the termination criteria while wearing the LOW ensemble underscores the risk of CWIs with inadequate clothing. Therefore, the choice between gloves and mittens should consider specific environmental conditions and activity requirements, with mittens being favoured for heat conservation and gloves for better dexterity.

In our study, we observed substantial variations in finger skin temperature (T_{finger} ranging from 15.2 to 31.8 °C) and both gross and fine manual dexterity (with changes ranging from −24 to +14% and from −27 to +17%, respectively) among participants when wearing the HIGH ensemble. These variations suggest that clothing insulation was suitable for some individuals but slightly excessive or inadequate for others. When participants wore the LOW ensemble, however, exposure to cold conditions consistently led to low finger skin temperatures (ranging from 8.4 to 15.2 °C) and a subsequent decline in manual dexterity (with declines of 7–31 and 13–39% in fine and gross manual dexterity, respectively). This indicates that the clothing was generally insufficient for passive standing among all participants.

When the insulation of the worn clothing was compared to the insulation required to maintain thermal balance without discomfort or risk of cold stress in the specific environments, all participants were underdressed during the passive phase. Generally, the greater discrepancy between the required and actual insulation worn, the lower the skin temperature on the fingers, and the less comfort they experienced. However, even when accounting for both insulation value and environmental factors, there were still significant individual differences in finger temperature and thermal comfort. These differences likely reflect well-known interindividual variability in vasoconstrictor responsiveness and peripheral circulation [8,38,39]. These findings highlight the importance of considering individual variation in thermal responses when making clothing choices. This approach ensures that all personnel can maintain thermal comfort, performance and health, particularly in demanding environmental conditions.

4.2. *Moisture accumulation and comfort*

During the active phase, the LOW ensemble was more comfortable and resulted in less sweating (measured as total body mass loss) and accumulated moisture compared to the HIGH ensemble. However, the HIGH ensemble provided improved comfort, maintained higher skin temperatures and resulted in smaller changes in manual dexterity during periods of physical inactivity, despite the higher moisture accumulation in the clothing during the active phase. This can be attributed to the higher insulation value of the ensemble and probably the unique properties of wool used in the HIGH ensemble's base and middle layers. Wool fibres can retain moisture, from sweat or light rain, within their central cortex while keeping their hydrophobic surface dry. As a result, wool fibres provide relatively high thermal resistance, and a comfortably dry, warm sensation, even when the fabric contains 30–40% moisture, provided that these distinctive qualities of wool fabrics are not compromised by excessive antifelting treatments [40,41].

The increased insulation and weight of the HIGH ensemble, while effective in terms of heat conservation during the passive phase, resulted in elevated skin temperatures, an uncomfortable warm sensation, the sensation of moderate sweating, increased body mass loss, and moisture accumulation within the clothing during the active phase. In addition to the insulation being too high for the activity, previous research has shown that wearing extra clothing imposes an additional muscular [13] and metabolic cost [14,42] on the wearer. This heightened cost leads to increased heat production during physical activity, thus necessitating a more pronounced need for heat dissipation mechanisms. Consequently, when wearing clothing that provides excessive insulation during physical activity, thermoregulatory mechanisms aimed at enhancing heat loss to the environment are activated, as observed in our study with elevated T_{sk} and sweating.

However, excessive clothing can create a hot and humid microclimate close to the skin, leading to sweat accumulation without effective heat loss through evaporation. This increased metabolic cost, demand for heat dissipation and accompanying body mass loss due to sweating carry negative implications. Not only do they result in moisture accumulation within the clothing, but also necessitate the replacement of lost body water, and increased energy need, which is difficult to maintain during CWOs [43].

Further, our results show that considering both the environment and the activity, participants were overdressed in 21 out of 27 occasions according to the IREQ neutral calculations. Even when accounting for insulation value and environmental factors, there were still considerable individual differences in moisture accumulation and thermal comfort during the active phase.

Tissue temperatures determine the physiological responses, but comfort and thermal sensation are key elements in determining temperature-regulating behaviour [28]. Keeping soldiers comfortable is important, as it can affect their well-being and morale, and likely their performance. Clothing plays a significant role in maintaining thermal comfort in cold environments by controlling heat loss. Evaluating both thermal comfort and thermal sensation is necessary for understanding combined sensations, such as those often experienced during winter [28].

In our study, thermal comfort and thermal sensation scores were congruent, with participants generally feeling warm and uncomfortable during physical activity, and cold and uncomfortable in the passive phase. This indicates that maintaining thermal comfort under changing conditions is challenging and depends on several factors. Thermal discomfort is correlated with both decreased T_{sk} and increased sweating, and in some cases, comfort or discomfort can be anticipatory rather than a reaction to body temperature [28]. Therefore, while protecting soldiers from heat loss is crucial, cold weather combat clothing can also lead to thermal dissatisfaction, particularly under shifting conditions. This shows the need for actively regulating clothing insulation and incorporating ventilation features like zippers to manage heat and moisture during varying work intensities in the cold.

It is essential to emphasize that successful moisture management requires discipline, both during and after physical activity, ensuring optimal comfort and performance.

4.3. Limitations

Some limitations of this study should be considered when interpreting these results. Firstly, the study was conducted in moderately cold conditions, which limits our ability to comprehensively evaluate the entire winter clothing concept for all nations. Therefore, the outcomes should primarily be interpreted within the context of mild sub-Arctic winter conditions and short-term exposures. Extrapolation to prolonged operations or extreme weather conditions should be made with caution. Secondly, the outcomes of this study are a direct result of selecting specific components from the available clothing and equipment of each country for this scenario. If different components had been chosen, the results could have been different.

Another notable limitation is the exclusive use of male participants, which narrows the generalizability of the findings. We also recognize that moisture transport is a crucial factor in military clothing, and having data on the permeability of the clothing would have been valuable for interpreting the results. Nevertheless, the results provide valuable insight into the significant impact that the choice of clothing can have on soldiers' comfort, performance and health.

We chose to conduct the study in the field due to the general lack of field studies in military human factors research, even though findings are often applied in real-world conditions. While the slightly varying climatic conditions between days may have introduced interactions between the day, participant and clothing, these factors were accounted for in the IREQ calculations, and this adjustment did not influence the results or alter the conclusions. Exact capture times for the thermograms were not logged. As a result, minor between-trial differences in the time from leaving the outdoor environment to thermogram capture cannot be ruled out and may have influenced post-exposure finger skin temperatures.

A further limitation is that although participants were highly familiar with magazine loading as a standard soldier task, they did not complete dedicated pre-training with the thin gloves used during the gross manual dexterity assessment. While the glove type was consistent across all clothing concepts, prior task-specific training might have reduced intra-individual variability. However, our findings show that magazine loading is a usable indicator of gross manual dexterity, and with similar results to the PP tests, offers a viable alternative when a PP test is unavailable in the field.

4.4. Practical implications

In military CWOs involving multiple countries, it is essential to consider not only how soldiers are behaviourally prepared, but also the variations in clothing among the participating countries. It is important to recognize that our study primarily reflects the impact solely of clothing. In real-world operational contexts, experienced soldiers employ various techniques to enhance their comfort, performance and health during both physical activity and passive phases. These strategies include adjusting insulation and ventilation by donning or doffing clothing items or opening zippers and buttons as necessary based on environmental and activity considerations. Additionally, the strategies may involve subtle muscle movements to facilitate blood circulation when at rest or similar activity. However, accurately timing these measures requires knowledge, discipline, experience and proper training. Therefore, our results are more applicable to soldiers lacking prior experience in such environments.

Nonetheless, it is worth noting that less experienced soldiers often wear suboptimal clothing and equipment for these conditions. Unsuitable combat clothing for CWOs among some countries can have significant practical consequences, affecting interoperability, operational efficiency, safety, coordination and resource management for multinational military forces operating in Arctic and sub-Arctic conditions. Standardizing and improving cold weather gear across coalition members and providing training and support to ensure readiness in diverse climates can help address these challenges.

5. Conclusion

This study finds that the type and insulation of cold weather combat clothing affect hand and finger skin temperature, moisture accumulation, comfort and manual performance in a mild sub-Arctic winter climate. Wearing inadequate or inappropriate clothing in the cold quickly leads to low skin temperatures and thus loss of dexterity, which correlate with increased risk of CWIs.

Our results demonstrate a significant association between thermal comfort, moisture accumulation and finger skin temperature on one side and the difference between the actual clothing insulation worn and the insulation required to maintain thermal balance (IREQ neutral) on the other.

Additionally, the study indicates that the insulation and design of extremity protection significantly influence the skin temperatures of these areas, independent of overall clothing insulation.

The results emphasize the importance of considering the insulation level, clothing type and behavioural adaptations to mitigate CWIs, ensuring effective and safe performance in sub-Arctic winter climates. Models provide a useful starting point for clothing recommendations, but individual variations require personal adjustments to prevent excessive moisture accumulation, maintain comfort and avoid CWIs.

Our findings provide valuable insights for the development and selection of appropriate cold weather clothing for specific military operations in mild sub-Arctic environments.

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Disclosure statement

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