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Cold weather operations: Preventive strategies in a military context

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ABSTRACT
Military cold weather operations (CWOs) introduce a range of challenges, including extreme temperatures, strong winds, difficult terrain, and exposure to snow, ice, and water. Personnel undertaking these missions face a heightened risk of cold weather injury (CWI), such as hypothermia, freezing cold injuries, and non-freezing cold injuries. The risk of these injuries is influenced by various factors, including age, sex, and body composition. To ensure optimal and safe performance in CWOs, it is crucial to implement effective preventive measures against CWI. This article emphasizes the most pertinent strategies for CWI prevention in CWOs. Initially, it is important to assess individual vulnerability to CWI. Education and training on CWI prevention should be provided before deployment in CWOs. During CWOs, attention should be given to crucial behaviors such as using a proper layered clothing system, recognizing the risks associated with prolonged stationary periods in cold conditions, consuming adequate calories, and staying hydrated. Additionally, environmental monitoring using tools like the windchill index and regular checks on physical status are essential. Although monitoring by itself does not prevent CWI, it can prompt necessary behavioral adjustments. Education and behavioral modifications are central to preventing CWI. Given the limited research on CWI prevention in military settings, despite the frequent occurrence of these injuries, there is a pressing need for further studies to evaluate effective preventive strategies within this specific operational framework.

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Introduction

Cold environments, marked by low ambient temperatures, high wind speeds, and unique terrains, often pose significant challenges to soldiers. During cold weather operations (CWOs), soldiers are exposed to the elements, but also to factors such as physical exhaustion and sleep deprivation, which may make them more susceptible to cold weather injury (CWI) [1]. This article's main objective is to offer an overview of preventive strategies for CWI within the context of a hierarchy of controls.

CWI can broadly be categorized into whole body hypothermia and/or peripheral CWI. Although individual responses can be highly variable, in general hypothermia is a state in which the body's core temperature (T_c) drops <35°C. It is categorized by severity: from mild hypothermia (T_c 32–35°C) which impairs operational effectiveness to moderate hypothermia (<32°C) and severe hypothermia (T_c <28°C), potentially resulting in death or long-term neurological damage [2–5]. It should be noted that these T_c thresholds relate to isolated hypothermia and may be higher in those with co-existent trauma. Peripheral CWI is more prevalent but not as life-threatening. However, they can result in acute and chronic functional impairment and in severe cases amputation affecting acute and long-term operational performance and effectiveness. Peripheral CWI is classified into two categories: freezing cold injuries (FCIs) and non-freezing cold injuries (NFCIs) [6,7]. The distinction between FCIs and NFCIs relates to the temperature of the exposed skin. FCIs, also

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Table 1. Overview of physiological cold defense mechanisms, impact, and their behavioral cold defense equivalent (i.e. activity or clothing-wise). SFT: subcutaneous fat thickness.

Thermogenic response	Impact (i.e. heat equivalent)	Source	Activity equivalent
Non-shivering thermogenesis	0 – 30 W	[19]	Fidgeting
Shivering thermogenesis	300 – 500 W	[20]	Moderate activity
Diet induced thermogenesis	6 – 20 W over 2 hours	[21]	Fidgeting
Maximal tissue insulative response	**Insulation equivalent**	**Source**	**Clothing equivalent**
At rest	0.10 $m^2K\ W^{-1}$ or 0.645 clo thin SFT	[22]	Summer wear
	0.32 $m^2K\ W^{-1}$ or 2.065 clo thick SFT		Winter attire
At high activity level	0.01 – 0.03 $m^2K\ W^{-1}$ or 0.065 – 0.194 clo	[22]	Underwear

known as frostbite, occur below the freezing point of tissue (<–0.55°C), whereas NFCIs occur when skin is exposed to low temperatures and often moisture for prolonged periods of time (several hours to days) [8–12]. Historically, NFCI has been referred to as "trench foot," is often seen in military settings, and has influenced the outcome of many military campaigns [10]. NFCIs also occur on other body regions, but hands and feet that are most commonly affected. NFCIs are characterized by an inability to maintain skin temperature often involving prolonged peripheral vasoconstriction. The exact mechanism behind NFCIs is poorly understood but is thought to include direct damage from cold, hypoxia or ischemia, and the liberation of reactive oxygen compounds during reperfusion [8–12], which variously affects small fiber nerves and microvasculature. While the mechanisms behind NFCIs are not fully understood, the overarching principle for preventing hypothermia, FCIs and NFCIs is to reduce the rate and degree of whole-body and local cooling.

CWI risk varies between individuals, and there is no "one-size-fits-all" solution for preventing CWI [8]. Predisposing factors for the development of CWI are extensively described and summarized in earlier work by Haman et al. [8], Castellani et al. [13], Giesbrecht and Wilkerson [14], and White and Sullivan-Kwantes [2], and can be categorized into environmental (e.g. temperature, wetness, windchill, exposure duration), mechanical (e.g. inadequate clothing and shelter, cramped positioning, tight boots), physiological (energy depletion, poor physical conditioning, body morphology), medical (e.g. Raynaud's, preexisting injuries, vasoconstrictive drugs), and psychological (e.g. severe mental stress) factors [15]. To optimize military operational effectiveness in the cold, being aware of, and using appropriate preventive strategies for development of CWI is essential [16,17]. Although the human body has several physiological mechanisms to counteract mild cold environments, either insulating (i.e. peripheral vasoconstriction) or metabolic (i.e. shivering) responses in an effort to prevent significant reductions in core temperature, it is crucial to understand that *relying on physiological cold defense mechanisms is unlikely to be a successful strategy to prevent CWI* [17,18]. A brief overview of the strength of physiological cold defense mechanisms and their behavioral equivalent (i.e. changing activity or clothing) is shown in Table 1. The table shows that behavioral cold defense has the greatest impact with a wider range of options than physiological cold defense mechanism [17].

To guide commanders in implementing the most effective preventive measures against CWI, it is beneficial to consider a suggested hierarchy of controls [23]. De Castro's hierarchy of controls categorizes risk control strategies to workplace hazards from the most effective at the top to the least effective at the bottom (Figure 1), which has been adapted to CWOs in this article. Understanding this hierarchy helps commanders make informed decisions and prioritize interventions. This article primarily covers evidence for the items that can be implemented in the lower part of De Castro's hierarchy of controls (Tier 4 alter and Tier 5 personal protective equipment). While not the strongest preventive measures, they are the ones most frequently utilized in tactical training and deployment.

- **Tier 1 Remove**: the most effective control is to completely remove the hazard. However,

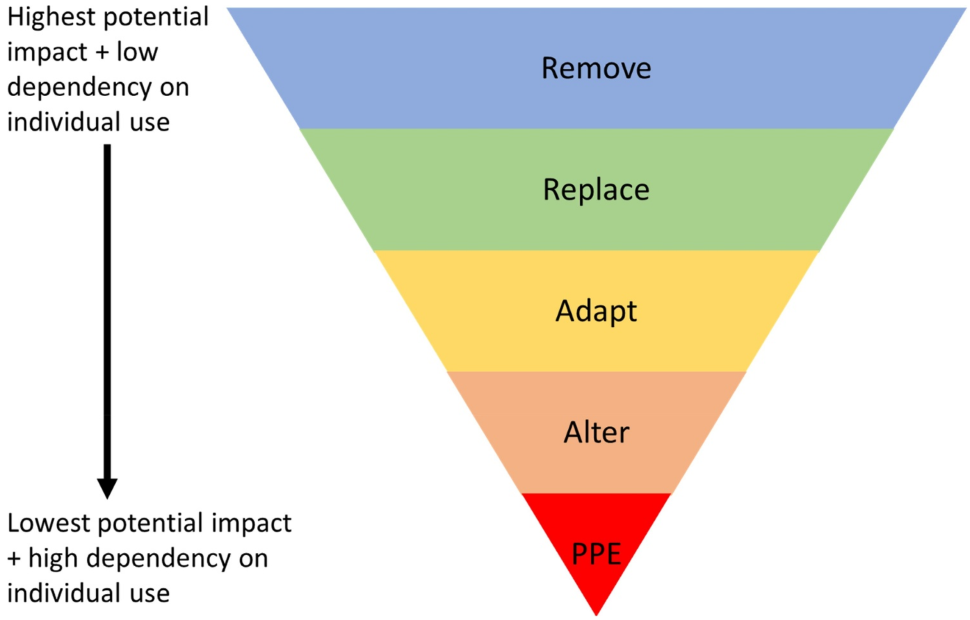

Figure 1. Graphical illustration of the hierarchy of controls, based on [23]. PPE: personal protective equipment.

in military operations, elimination of exposure to cold is often not possible. An example of elimination is that below a certain temperature, depending on each country's policy, routine training will stop and drop down to essential training only.

- **Tier 2 Replace**: in the context of CWOs, this might involve substituting a training that includes immersion during winter with one that does not, holding it in summer instead. The overriding principle is to replace an activity with another where risk is high and exposure to additional cold is not essential for training at that time.
- **Tier 3 Adapt**: these involve modifications to the environment or equipment. Examples include establishing windbreaks and using heated tents.
- **Tier 4 Alter**: this includes ensuring soldiers are well-educated and well-trained, fit, well-rested, well-nourished, hydrated, and behaviorally acclimated before and during training.
- **Tier 5 Personal Protective equipment (PPE)**: this is the last line of defense. It involves protective clothing and gear.

Mitigation strategies employed are frequently a combination of tier 4 and 5 strategies, despite these being the least effective, possibly because other options may not be militarily feasible. For example, providing clothing with appropriate insulative properties for a specific situation in combination with behavior modification. This article begins with a discussion on hazard and risk assessment. The practice of identifying hazard, assessing risk, and implementing control measures is itself an activity that falls within Tier 4. This should be taken into consideration when reading this article.

Hazard and risk assessment

Education and training

First and foremost, it is essential to ensure that all personnel have received an appropriate level of education and training on operating in the cold and identification and management of CWI. It is essential they can identify hazards and assess and mitigate risk at a level commensurate with their rank and role. Armed with this knowledge, military personnel are more capable of staying warm enough to operate effectively and subsequently reduce CWI. Education and training should include all factors known to impact performance in the cold such as the environmental, mechanical, physiological, medical, and psychological factors.

After identifying optimal strategies for maintaining warmth in specific roles, military personnel should practice in temperate climates and become proficient at certain activities, for example, conducting tasks while wearing gloves or mittens, before doing these tasks in a cold environment.

While preventive measures will vary between different corps (or units) and roles, some education and training can be centralized. However, it is crucial to provide customized training that aligns with each soldier's specific circumstances and mission. This training should be regularly reviewed and updated as each winter approaches and prior to cold weather deployments, especially for nations that do not have an Arctic climate. Education and training must also include CWO survival techniques and provide first aid for CWI. As Whayne expounded: "The prevention of cold injury is primarily a function of command from the highest to the lowest echelon. It requires the assumption of responsibility by all personnel, including the medical corps, which, though its role is purely advisory, must nonetheless assume the responsibility for making its advice forceful as well as correct" [24]. A short summary of all topics covered in this chapter and the next chapter on controls can be found in Figure 2.

Identify cold hazards

Before applying suitable and sufficient controls, it is important to identify the hazard and recognize soldiers at heightened risk. The windchill index is commonly used in cold weather environments to express the level of cold and the corresponding risk for FCIs that can be experienced (Figure 3) [26]. The works of Antarctic geographer Siple and geologist Passel are often credited as the beginning of the windchill index [27]. The current windchill index represents a person moving about $5\,km{\cdot}h^{-1}$ against the wind at face level [25] and indicates the risk of getting FCIs on bare skin of the cheek [25]. In practice, this chart is easy to use and can be brought along in military settings. It should be noted, however, that the windchill index does not account for solar radiation, protective gear, other body areas that are more susceptible to FCI, high activity levels or other individual characteristics that attenuate the susceptibility for CWI [8,25]. Nor does it take into account the wide range of weather conditions that can occur within a small area (other than making repeated readings). Tikuisis and Keefe also created a windchill table for exposed skin of the finger. While not currently widespread in use, it might be relevant for military operations [28].

Screening for individuals at risk (but not selecting)

As well as identifying hazard and assessing risk for the average soldier, it is also important to identify individuals who may be at a heightened risk for CWI. This allows for implementing additional measures to ensure effectiveness and safety. It has long been thought that individuals who "feel the cold" more than others may be at greater risk of cold injury than others, and because this is non-modifiable, researchers since the Second World War have been keen to understand whether this inherent propensity to feel cold confers a heightened risk of CWI. On the other hand, feeling the cold more could be protective if behavior is adjusted earlier and appropriately. Daanen et al. proposed a finger immersion test to gauge peripheral tissue's cold induced vasodilation (CIVD) response and the risk of CWI which follows the Yoshimura method [29]. CIVD is a phenomenon characterized by cyclic rewarming (i.e. few minutes) of the skin during cold exposure and is driven by vasodilation through the opening of arteriovenous anastomoses. The sudden vasodilation cycles could increase peripheral temperatures. This phenomenon is evident at the extremities including the face, ears, hands and feet [30] and seems at least to be dependent on core and skin temperatures, but potentially only in a certain range (i.e. sufficiently warm core). The exact underlying mechanism of the CIVD response is a topic of debate. This method showed that a less efficient CIVD response had a weak association with CWI incidence in military settings [31,32]. The Norwegian Army studied hand rewarming rates after a cold weather exercise to assess if cold exposure attenuated the CIVD response [33,34]. They found a tendency for slightly faster rewarming following CWOs.

Hazard and risk assessment

Education and training
Problem: Hazards may not be appropriately recognized, estimated, or addressed if personnel are inadequately trained.
Research add: Leadership and behavior are key to maintain operational effectiveness in cold environments, and these must be underpinned by sound knowledge.
Mitigation: Education and training should include all factors known to impact operational effectiveness in the cold.

Identify cold hazard
Problem: Are tools available to calculate FCIs, NFCIs and/or hypothermia risk?
Research add: The windchill index is a practical, evidence-based risk assessment tool for FCI, but is limited by variables such as clothing level, activity, and precipitation. It does not address risk of NFCIs or hypothermia.
Mitigation: The windchill index is a useful adjunct in assessing risk of CWI.

Identify individuals at risk
Problem: What do we know about individual risk factors for CWIs?
Research add: African race and female sex may confer a heightened risk of CWI, as can certain medical conditions such as Raynaud's phenomenon.
Mitigation: Identify susceptible individuals and operate heightened surveillance.

Alter (controls tier 4)

Fatigue
Problem: Can fatigue make personnel susceptible to CWIs?
Research add: Fatigue has been linked with CWI, but evidence for this association is weak.
Mitigation: Adequate rest improves thermoregulation and might mitigate the CWI risk.

Sleep deprivation
Problem: Sleep deprivation negatively impacts body temperature regulation, does this increase CWI risk?
Research add: Fatigue may play a part in CWI, but its effect is not clearly understood or quantified.
Mitigation: Ensure sufficient sleep to improve thermoregulation and potentially mitigate the CWI risk.

Fluid intake and temperatures
Problem: Hypohydration is common during CWO due to diminished thirst and increased urination +/- sweating. Does this increase vulnerability to CWI?
Research add: Dehydration affects performance but evidence for a relation with CWIs is weak.
Mitigation: Scheduled water breaks, methods to prevent freezing of fluids, provision of hot drinks, and reassurance about toilet breaks.

Caloric intake
Problem: Activities in the cold increase energy expenditure but compensatory caloric intake is often insufficient, does this increase individuals risk to CWI?
Research add: There is no direct evidence of correlation between caloric intake and CWIs. However, working in caloric deficit impairs thermoregulation and thus may be involved in risk of CWI. Protein balance can be maintained if individuals eat >40% of their caloric deficit and consume 1.6 $g \cdot kg^{-1} \cdot day^{-1}$ protein.
Mitigation: Emphasize the importance of eating well in cold environments, and ensure logistic support facilitates this.

Physical fitness
Problem: Exercise often contributes to thermoregulation in CWOs through metabolic heat production. Are those who are less fit and less able to sustain activity at heightened risk of CWI?
Research add: Evidence to prove that physical fitness relates to risk of CWIs is lacking.
Mitigation: Aerobic training pre-CWO may improve thermoregulatory capacity and reduce risk of cooling.

Fat and lean body mass
Problem: Are thinner people at higher risk of CWI?
Research add: Large bodies cool down slower, but evidence to prove that fat or lean body mass protects for developing peripheral CWIs lacks.
Mitigation: Starting CWO with a relatively high subcutaneous fat mass might be beneficial to prevent heat loss and maintain body temperature (it also an energy storage).

Cold acclimation
Problem: Is it possible to acclimatize to cold?
Research add: Laboratory acclimation requires an intense and prolonged protocol, and may paradoxically weaken thermal responses; it is not feasible in current military practice. .
Mitigation: Do not rely on physiological cold acclimation as a strategy.

Buddying up
Problem: Can 'buddying up' help in identification of incipient or actual CWI?
Research add: Buddies trained to look out for signs of CWIs such as difficulty with dexterous tasks, white patches on skin, clumsiness, mild confusion, and irritability does help in early identification of problems.
Mitigation: Train personnel in buddy checks and incorporate them into leadership strategy.

Physical activity
Problem: Do activity levels affect CWI risk?
Research add: Most CWI occur during periods of inactivity as the body cools more rapidly without the metabolic heat production associated with muscle use.
Mitigation: Regard being stationary in the cold as high risk and employ additional methods such as shelter, additional clothing, and bursts of activity to reduce risk.

Decision support tools
Problem: The risk of CWIs is dependent on complex interaction of factors and is hard to estimate.
Research add: Developed tools may help for rational decision making what clothes to procure and wear for certain exercises. Other tools predict the time before onset of CWI given the environment, activity, and clothing.
Mitigation: Decision support tools could elicit essential behavioral changes to prevent CWIs.

PPE (controls tier 5)

Clothing
Problem: What is the ideal clothing strategy for CWO?
Research add: Multi-layered clothing approach is recommended: at minimum an inner layer for moisture wicking and insulation, a mid-layer for added insulation, a third layer for protection against wind and water, and a potential fourth layer for camouflage. As individual physiological responses vary, clothing needs should be adjusted accordingly. Experience, training and good leadership is essential for effective use of clothing.
Mitigation: Ensure clothing is kept clean, prevent overheating, wear it loose and in layers, keep it dry, and make sure it fits appropriately. Training on proper cold-weather attire and understanding individual needs is crucial.

Gloves and mittens
Problem: How can hands best be protected?
Research add: Hands and fingers are prone to CWI, and hand protection is difficult due to balancing needs of insulation versus dexterity. Mittens trap air and allow heat transfer between digits and are warmer than gloves of the same insulative quality. Heated elements may have some use in CWO but there are technical challenges. **Mitigation:** Use gloves or mittens appropriate for the task and be cautious if opting for heated elements.

Shoes and socks
Problem: What is the ideal foot protection system?
Research add: Feet are prone to CWIs. Different conditions demand different footwear properties. Footwear should have a loose fit to allow for heat and moisture exchange but not too roomy to prevent pumping. Good knowledge of weather and terrain matched against footwear can reduce risk of cooling.
Mitigation: Applicability and suitability of footwear is context dependent and informed choices are essential.

Figure 2. Summary of risk assessment and controls in military cold weather operations in terms of problem, research add, and mitigation.

Air temperature (°C)

Wind speed (km/h)

Calm	10	5	0	-5	-10	-15	-20	-25	-30	-35	-40	-45	-50
10	9	3	-3	9	-15	-21	-27	-33	-39	-45	-51	-57	-63
15	8	2	-4	-11	-17	-23	-29	-35	-41	-48	-54	-60	-66
20	7	1	-5	-12	-18	-24	-31	-37	-43	-49	-56	-62	-68
25	7	1	-6	-12	-19	-25	-32	-38	-45	-51	-57	-64	-70
30	7	0	-7	-13	-19	-26	-33	-39	-46	-52	-59	-65	-72
35	6	0	-7	-14	-20	-27	-33	-40	-47	-53	-60	-66	-73
40	6	-1	-7	-14	-21	-27	-34	-41	-48	-54	-61	-68	-74
45	6	-1	-8	-15	-21	-28	-35	-42	-48	-55	-62	-69	-75
50	6	-1	-8	-15	-22	-29	-35	-42	-49	-56	-63	-70	-76
55	5	-2	-9	-15	-22	-29	-36	-43	-50	-57	-63	-70	-77
60	5	-2	-9	-16	-23	-30	-37	-43	-50	-57	-64	-71	-78
70	5	-2	-9	-16	-23	-30	-37	-44	-51	-59	-66	-73	-80
80	4	-3	-10	-17	-24	-31	-38	-45	-52	-60	-67	-74	-81

Frostbite risk

Figure 3. Windchill factor that indicates the risk of freezing injury on bare skin based on air temperature and wind strength. Blue shading indicates temperature at which frostbite can occur, based on [25].

Though a limited number of injuries occurred, in their military training Brändström and colleagues found that slower rewarming rates were evident in 4 of 5 CWI [32]. Other studies found the test nonspecific, with more CWI stemming from poor decisions, extreme cold exposure, or wet clothing [35]. There is evidence that a less efficient CIVD response may confer a heightened risk, especially in women and individuals of African race, but the magnitude of this risk in relation to sustaining CWI has not yet been defined [15]. It has also been postulated that the cold sensitivity test or CIVD response can be used as an entry standard for military service in cold regions, selecting out those who display a less efficient response. However, without a direct link to substantially increased risk of CWI and with significant intra-individual variability between tests, it is unlikely that the test would meet the requisite standards for employment law in many countries. Overall, the evidence suggests behavioral factors are more indicative of CWI risk than biological ones.

Controls

Alter

Preventing is better than curing and ensuring that soldiers are ready and capable of operating in cold weather is of paramount importance. Alter, tier 4 in De Castro's hierarchy of controls focuses on procedural and operational measures to ensure the best possible physical and mental condition of soldiers, ultimately reducing their susceptibility to CWI. Central to these controls is the emphasis on identifying hazards, comprehensive training, optimal fitness level, sufficient rest, proper nourishment, hydration, appropriate use of PPE that fits properly, and fostering behavioral acclimation to cold environments both prior to and during operations. Of important note, there are considerable individual differences in the mechanisms and processes mentioned in the previous sentence that will be described in more detail in the paragraphs that follow. A short summary of all topics covered in this chapter can be found in Figure 2.

Fatigue

Fatigue has historically been linked with NFCI [36,37], but although some studies support this association, few have clearly defined fatigue. ~~Commonly,~~ Fatigue is variously used as a term to describe sleep deprivation or exertional tiredness or both, and there have usually been other risk factors such as nutrition or hydration at play.

Sleep deprivation

One night of sleep deprivation (i.e. 29 hours total sleep deprivation) was found to reduce finger skin temperature (T_{sk}) and vascular conductance in a laboratory setting using cold water hand immersion [38,39]. In a more ecologically valid setting, Peng and Sullivan-Kwantes [40] found that CWI were not associated with sleep duration during a 5-d Canadian Arctic operation. Sleep duration varied from 4 to 8 hours daily and was reduced during the operation. There is a paucity of valid field studies on the isolated effect of sleep deprivation. Young and colleagues [41] looked at the combined effect of sleep deprivation (~4 h of sleep per day), exertional fatigue and insufficient caloric intake on cold thermoregulatory responses. Forty-eight hours after ceasing arduous work, the suppressive effect of sleep deprivation on the thermoregulatory system was almost abolished. What is becoming increasingly clear is that recovery time between periods of arduous training or deployment is important for overall health although again, this has not been definitively linked with incidence of CWI [40–42]. Collectively, sufficient sleep together with adequate rest appears to improve thermoregulation and may mitigate the risk for the development of both hypothermia and peripheral CWI.

Caloric intake

Caloric intake in the cold should increase in response to the significantly higher energy expenditure mainly elicited by the type of activities usually performed in the cold (i.e. walking in snow, skiing). Energy expenditure (i.e. corresponding to total metabolic rate) of soldiers in the cold seems to be ~10–40% higher and therefore caloric intake should be higher as well [43,44]. Previous studies show that energy expenditure during military operations can be as high as 5,000–10,000 kcal (20,000–40,000 kJ) per day [13,43–47] depending on how demanding the CWOs are and the activity levels. Irrespective of *need*, what has been found during research is that it appears extremely challenging to increase caloric intake over about 5000 kcal per day. Thurber and colleagues found evidence for an alimentary energy supply limit of ~2.5× basal metabolic rate [48]. Assuming a basal oxygen consumption of ~0.25 $L{\cdot}min^{-1}$ for men and ~0.2 $L{\cdot}min^{-1}$ for women and considering the human body burns 5 $kcal{\cdot}L^{-1}$ oxygen [49], the alimentary energy supply would be ~4500 $kcal{\cdot}d^{-1}$ for men and ~3600 $kcal{\cdot}d^{-1}$ for women. Contributory factors to this ceiling effect include not being hungry, no time to eat and the difficulty of preparing food in the cold and eating whilst wearing gloves [50,51]. The potential size of the energy deficit can be estimated using the difference between sustained metabolic scope (~3× basal metabolic rate [48]) and nutritional limit (Δ of ~0.5× basal metabolic rate) and would be 900 $kcal{\cdot}d^{-1}$ and 720 $kcal{\cdot}d^{-1}$ for men and women, respectively. With these deficits, it would take 8–9 d for men and 10–11 d for women to lose 1 kg of fat (7700 $kcal{\cdot}kg^{-1}$ [52]). Research by Margolis et al. [43,44] showed that over a three-to-seven-day period, caloric deficits were found to be as high as 3000 kcal per day. There have been efforts to identify nutritional interventions to minimize energy deficit. One study of Norwegian soldiers revealed that they chose not to consume ~34% of their rations [43,44,53], and supplementing these soldiers with additional carbohydrate (CHO)- or protein-based snacks was also ineffective since the soldiers consumed ~85% of the snacks but compensated for this by eating less from their rations. To allow for an increased caloric intake up to the energy supply limit, food intake should be trained and/or monitored by leadership, i.e. think of forced food breaks. The importance and benefits of leadership amongst others are emphasized by recent insights from the French Army [54–56]. Charlot and colleagues [54,55] intervened during a Greenland expedition using easy-to-use, highly palatable and familiar food supply and a planned schedule to stimulate spontaneous energy intake. A very promising observation was that soldiers reached neutral energy balance in <10 d. Noteworthy, as the expedition was not very demanding, this strategy should still be verified in more types of exercises.

Chronic negative energy balance impairs thermoregulation and impacts on inflammatory processes, and this inability to increase caloric intake proportionate to activity is very important [57]. As energy demands for maintaining T_c are high, caloric restriction has been shown to reduce T_c [58]. Soldiers able to manage energy intake close to energy expenditure have been shown to have a better protein balance and less inflammation compared to soldiers with a caloric deficit [43,44,53]. Recently, Margolis & Pasiakos summarized that protein balance can be maintained if individuals eat >40% of their caloric deficit and consume $1.6\,g\cdot kg^{-1}\cdot d^{-1}$ protein [59] (Unpublished data). Yet, and most important, direct evidence regarding the correlation between (just enough) caloric intake and risk for CWI lacks.

Fluid intake

Working in cold environments can lead to hypohydration through decreased thirst, cold-induced diuresis, sweating, and rations that tend to be high calorie but with low water content. It is estimated that when relying on cold weather rations, individuals need to drink up to an additional 1 L water per day to compensate for the lower water content compared to regular rations [13]. An added difficulty is that even though the water is needed, the person may not feel thirsty. The US Military have propounded scheduled water breaks where soldiers are required to drink, for example, half a canteen cup (0.25 L) with breakfast, lunch, dinner and before going to sleep and half a canteen cup every hour during the day, equaling ~5 L per day [60]. The Norwegian Armed Forces recommend similar measures, aiming for 0.6–1 L of water per hour during physical activity [61]. Furthermore, they advise water should be consumed in small and frequent quantities at a rate of 0.1–0.2 L every 10 min [61]. What must also be taken into account is that drinking at this rate produces added difficulties: water must be kept from freezing by keeping bottles next to the body or other methods, breaks are needed to encourage drinking, and there will inevitably need to be more toilet breaks which may be hazardous at night and in some situations there might be the need of adding extra salt. Sub-optimal hydration is likely to affect physical performance but evidence that it leads to CWI is weak. It is likely that any relationship in the mild dehydration generally found in soldiers exercising in the cold is coincidental rather than causative [62–64].

Drink and food temperature

Hot drinks are comforting and often thought to “warm people up.” However, to the author’s knowledge, the net effect of hot drinks on the thermoregulatory system (i.e. losing heat via whole-body vasodilation of the skin versus adding heat by drinking a hot fluid) has not been quantified in cold environments. Regarding moderate to warm environments, the effect of drink temperature on T_c has been established. Some studies found that cold drinks could attenuate the rise in T_c [65,66]. Others showed no changes in T_c, T_{sk} or heat storage as a result of cold or hot drinks [67,68]. However, based on anecdotal accounts, hot drinks are important for group cohesion, comfort, and general well-being. For food this principle would be valid too, but again this has not been quantified. Yet research has shown implicit wanting for warm dishes in a temperate (16°C) over a warm (32°C) environment [69]. The authors further emphasize the importance of food reward to reach energy balance which might be reached by allowing warm food preparation again by proper leadership.

Physical fitness

Improving physical fitness. It has been proposed that endurance training with commensurate enhancement of aerobic capacity could be a way of improving thermoregulation in the cold via increased metabolic heat production, higher T_{sk} and an earlier onset of shivering [70]. Also, high aerobic capacity subjects seem to use fat oxidation more than CHO (i.e. glycogen) in their total energy expenditure during exercise, as glycogen stores are used less quickly, and exercise can be maintained longer before exhaustion occurs. Importantly, glycogen is kept in reserve for heat production when needed [71,72]. This response has a sex-effect as women tend to oxidize more fat and less carbohydrates in general compared to men, both reported in controlled as well as field experiment settings [47,73–75]. Whilst this shows that those who are physically fit have a more efficient thermoregulatory response and tend to utilize fats more in energy production; it is tempting to suggest that this may reduce CWI. However, evidence to prove this is the case is lacking, and given the multifactorial nature of CWI and individual differences in response to the cold (i.e. some people cool much more quickly than others) it is unlikely to be a principle determining factor.

Increasing fat or lean body mass. High subcutaneous fat mass may be beneficial in military personnel operating in the cold by reducing surface-to-volume ratio and thus the ratio between heat loss and heat production. That is why individuals with a large surface-to-volume ratio demonstrated a greater decline in core temperatures compared to those with a smaller ratio [60]. Since the loss in muscle mass relates to the loss in fat mass after military training [73,76], starting with a relatively high fat mass can be beneficial to prevent lean body mass loss. However, high subcutaneous fat mass is generally associated with low physical fitness, which may be a disadvantage. Conversely, at rest, subcutaneous fat tends to be advantageous through insulative effects [22,77,78]. However, about 90% of body tissue insulation at rest is explained by nonfat tissues [79]. In line with this, a recent study showed that in resting subjects, a high lean body mass, and not a high fat mass, is the cause of the beneficial cold response [80]. During activity, insulative properties of the body are reduced once the muscle is perfused and then the thickness of the subcutaneous fat layer becomes the prime determinant of the tissue insulation [22,80]. Studies supporting this statement reported reduced heat loss in cold environments and less shivering in individuals with higher subcutaneous fat mass [81].

Cold acclimation

When preparing for cold exposure, individuals can physiologically habituate (i.e. reduced shivering or vasoconstriction, following days of exposure) and they can show an enhanced insulating and metabolic response (i.e. increased shivering and vasoconstriction, following weeks of exposure) [18]. Whilst much is spoken of these responses, an implementable and sustainable program for this has yet to be found. Physiological acclimation has been induced in laboratory conditions but requires an intense and extensive protocol, does not always produce benefits [18,82,83], and thus has limited potential for use in the military context on current evidence. There may also be drawbacks to cold acclimation as it seems to involve a downregulation of skin cold sensing and a commensurate reduction in metabolic response on exposure to cold [18,82,83], thus paradoxically increasing the conditions in which CWI is more likely to occur. What has been shown to be of great importance is behavioral adaptation to living and working in cold environments which links into the benefits of training for cold environments [18].

Physical activity

Inactive soldiering is arguably the most potent risk factor for CWI in CWOs for the military. When soldiers are inactive and still (e.g. standing on guard or in shooting position), cooling will progress, and mitigation measures will merely slow the rate at which this happens. Physical activity not only slows cooling, but also rewarms; muscles produce heat while generating power and even the coldest feet can be rewarmed with sufficient activity [84]. Increased blood circulation can occur several hours after physical activity [85,86] due to transport of metabolites and waste products from muscle. It is appreciated that exercise is not always militarily possible and may need to be reduced to small movements (i.e. exercise extremities by, for example, sticking heels into the ground or spinning arms), and that the individual must be adequately fed, hydrated and uninjured to use physical activity as a treatment for cold or indeed maintaining warmth for optimal performance.

Decision support tools

Decision support tools have recently been developed that may help in deciding what clothes to procure and wear for a particular exercise or deployment [87–90]. For example, CoWEDA is a tool that integrates human performance metrics, a thermoregulatory model (SCTM), and a database of biophysical properties of clothing [89]. The application then advises the number of hours that an individual can be exposed to a particular situation (environment, activity, clothing) before a potentially injurious temperature (body, hand, feet) is reached (Figure 4). However, a challenge is that decision support tools do not take the individual thermoregulatory differences into account.

To support proper decision-making, monitoring can be of great importance. Given that we have thresholds for development of hypothermia (T_c <35°C) and FCIs (T_{sk} <–0.55°C), monitoring of temperature (core and skin) appears an attractive risk mitigation strategy particularly if the monitoring is "real-time" and can thus warn people as they approach a potentially injurious temperature [87] but it is not without problem. Hence, monitoring T_c and T_{sk} has the potential to contribute to avoidance of CWI. However, the gold standard for T_c measurement is to use an esophageal probe [91] which is really only feasible in a laboratory or clinical setting; second best is a rectal probe but readings can be positionally variable and it is equally unsuited to a military setting. Other devices all have their drawbacks: telemetric pills are rather expensive, are influenced by nutrition, and come with logistical challenges (i.e. should be ingested at least ~1 hour prior to exercise) [92], heat flux sensors tend to be influenced by sweating [93], and tympanic measurements using infrared-based devices are dependent on ambient temperature (if canal is not insulated) [94] and ear canal morphology [95]. At this moment, telemetric pills appear to hold the most promise for monitoring T_c in the military. However, this area requires more research. T_{sk} monitoring is even less well established than T_c measurements. There are T_{sk} sensors available on the market (for example, cable free i-Buttons® or thermistors with cable), but the sensors are currently not capable of real-time monitoring. Other difficulties with these types of measurements are that the sensors may be uncomfortable in boots, produce hindrance in gloves, and make personal hygiene more difficult. Further, there is a risk that metal in the devices may freeze and cause local CWI, as well as the problem of rapid battery deterioration in the cold. Infrared imaging might have the potential for use in training recruits to learn that a certain feeling in the fingers relates to CWI risk. Showing the infrared images together with the actual T_{sk} could create more understanding and awareness. A NATO workgroup has addressed the issue of temperature monitoring. ("Enhancing warfighter effectiveness with wearable biosensors and physiological models") and came up with a list of requirements for monitoring of soldiers [96]: "Monitoring devices should be robust, waterproof, sustain a cold environment, should not allow condensation from temperature shock, have a long battery life, should be wireless, small, of low weight, easy to use, should produce low noise, have a large data capacity and should have no risk for increased cold injury and skin irritations."

Buddying up

In the military, soldiers are often directed to "buddy up," in other words, to work in pairs and keep an eye on each other for adverse symptoms and signs at an early stage; this can represent a key part of risk mitigation at work. In cold environments, they should be taught to look out for signs of peripheral CWI such as difficulty with dexterous tasks, white patches on skin, or early signs of hypothermia (e.g. clumsiness, mild confusion, irritability) [97–99]. Furthermore, social vigilance, such as buddy checks, not only reinforces awareness of emerging CWI symptoms but also encourages timely corrective actions.

Personal protective equipment (PPE)

PPE sits at the bottom of the hierarchy of controls and is, in theory, the least effective of them. However, circumstances do not always afford the opportunity to implement higher tiers of control, especially in the military, and in these situations wearing appropriate PPE may be the most effective measure available. PPE must be appropriate for the individual and the task as well being properly used and maintained [16,100]. Lajeunesse and Lackenbauer [101] stated that it is crucial to train military personnel on how to effectively use their PPE in the cold. Recently, the Norwegian Armed Forces have composed four animated videos in Norwegian, English and Ukrainian about the threat, prevention and symptoms of CWI [99].

Wearing appropriate clothing

Clothing is quintessentially important in combating cooling and CWI [7]. Typical cold weather clothing configurations consist of a three- or four-layered structure based on the principles of layering, insulation, and ventilation [13], with an inner layer that is in direct contact with the skin. This inner layer should preferably be lightweight and promote wicking of moisture to the outer layers where moisture can evaporate; fabric fibers should create a relatively thick air layer between skin and fabric. The second or mid layer should provide insulation required according to environmental conditions and activity. The third layer, the outer layer, should ideally allow the transfer of moisture to the air via evaporation, but protect against wind and rain. A fourth camouflage layer may be added to the clothing ensemble, common practice in many northern countries. During high-intensity training activities where sweating is likely, it is preferable that layers are removed, to avoid moisture collecting in the base and mid layers as it will lead to more rapid cooling when inactive. However, there is an acknowledgment that changing clothing layers during a real combat type scenario would be more complicated. Outer-layer clothing can also be designed to have zippers to promote ventilation and moisture removal.

Leadership can play a big part in the effectiveness of PPE. There is considerable variation in how individuals respond to the cold, some people cool more quickly than others. Therefore, it makes no sense to direct everyone to wear the same clothing. Subordinates should be encouraged to judge for themselves what their individual needs are to keep warm and, once educated on the use of PPE, combine this with experience to choose optimal layering. When training military personnel it can be useful to use acronyms to support learning. One used for clothing in cold environments is: "COLDFEET" (see also Figure 5): Keep it **Clean**, Prevent **Overheating**, Wear it **Loose** and in Layers, Keep it **Dry**, Appropriate **Fit**, **Exercise** your extremities, **Eat** your rations, **Tight** boots are terrible.

ISO11079 [102] provides several outputs on the required clothing insulation (IREQ) given the environmental conditions and activity level. For example, $IREQ_{neutral}$ is the required insulation for thermal balance and thermal comfort where $IREQ_{minimal}$ is the minimal required insulation to be able to work at least 8 h. Both are corrected for air movement by body or wind that effectively reduce the insulation provided by clothing. This information can be used as background knowledge to be applied in decision support tools as mentioned in paragraph 3.1.9.

Gloves and mittens

Hand protection is a particularly difficult problem to solve on CWOs. As insulation increases, dexterity tends to decrease as a result of the thickness of glove or mitten. Thus, there is always a balance to be found, and what must be guarded against is the instinct to remove handwear because a fine task is proving difficult. As with all clothing, it is the amount of air trapped that governs the insulative property of gloves and mittens. Thus, mittens which trap a lot of air and allow heat transfer between digits, tend to be warmer than gloves of the same insulative quality. Claw mittens have the thumb and forefinger separate allowing a little more movement for tasks, and other constructs have gloves with a mitten flap that covers the fingers when possible. External heating such as heated pads, gloves, and insole may have some use in combatting cooling [103–105], but may not be ideal because of weight, short battery life in cold settings, difficulties of recharging, and uncertain performance in wet conditions. Moreover, adding such equipment works against the "fight light" principle. Carrying this type of supportive equipment is feasible when vehicles are near to provide power and carriage. It may be that in the future, as technology advances, practical integrated heating systems may become available. A further argument against soldiers using heated pads is that they should learn how to successfully cope with the cold without technology as there is always a risk that heating devices could stop working. However, there are certain specific roles where they are useful now, such as medics keeping casualties warm through use of heated pads or heated blankets. In summary, each of these clothing items may be useful to some people in some settings, but their applicability and suitability are very context dependent.

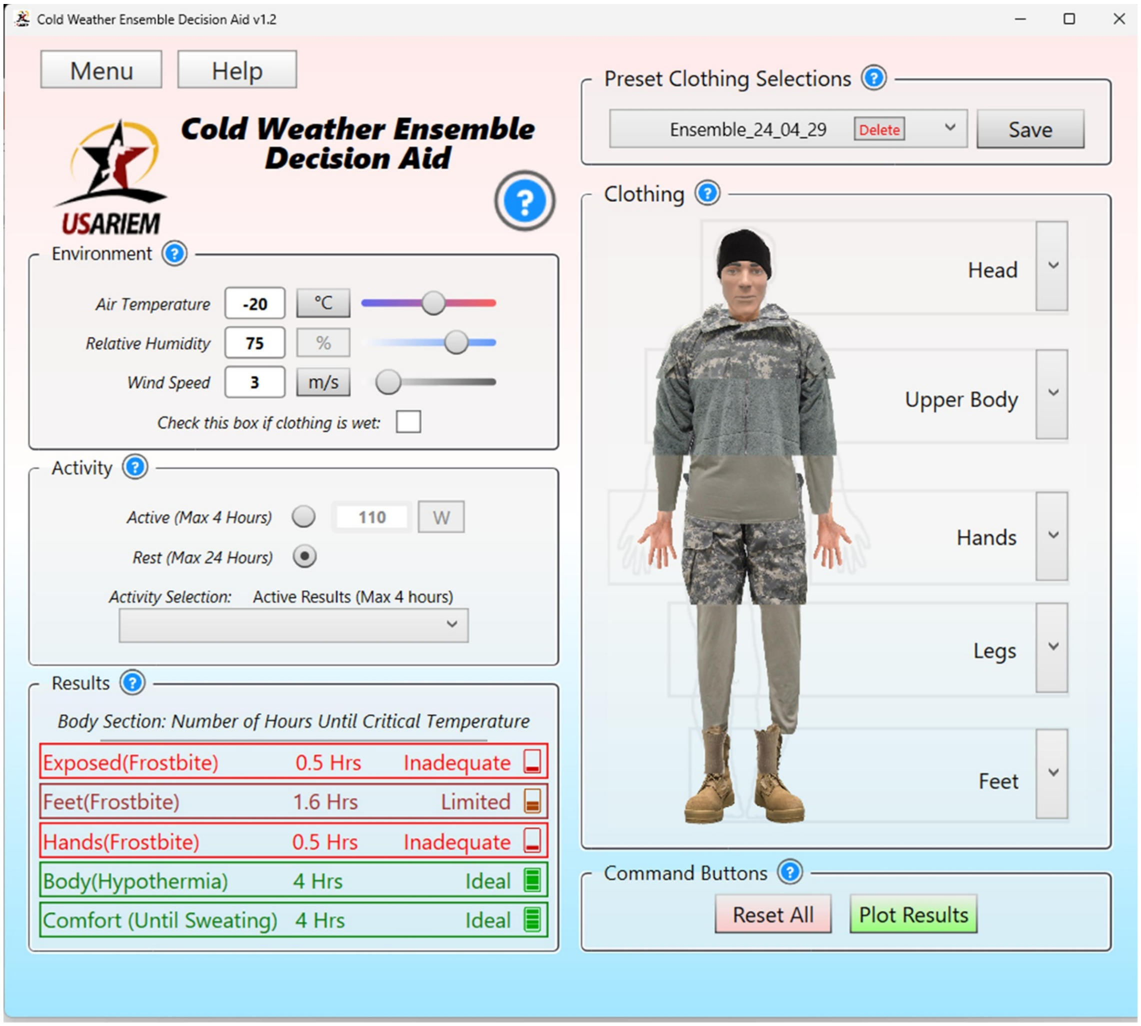

Figure 4. Example of a widely used decision support tool, cold weather decision aid (CoWEDA) that advises the number of hours that an individual can be exposed to a particular situation (environment, activity, clothing) before a potentially injurious temperature (body, hand, feet) is reached. Time to injury is based on skin temperatures reaching 5°C and core temperatures reaching 36°C.

Shoes and socks

Feet, like hands, are prone to CWI as they have a small muscle mass, and commensurately low levels of local heat production. Combined with a relatively large surface area, feet are susceptible to CWI. On top of that, since military duty involves both static as well as dynamic tasks, selecting appropriate footwear that will prevent CWI can be challenging. Footwear should ideally be insulated, waterproof (but vapor permeable), absorbing (but quick drying) and lightweight. It is difficult to encompass all these characteristics within a single boot. There is not a single solution for all circumstances, and conditions (i.e. environment, activity, duration of exposure) should dictate which characteristics to prioritize and the knowledge and experience of when to use the different footwear is very important. To meet the insulation requirement, the inside of footwear should be made from materials with low thermal conductivity. The outermost layer should in most cases be made from windproof, waterproof, and breathable [106] materials or leather with a water-repellent finish for the waterproof but vapor permeable requirement, yet the ideal outer layer depends on the environmental conditions and mission. In the northern countries in extreme cold, snowy, or wet conditions, for instance, woolen insoles and insulative polyester over boots are recommended. In addition, footwear should have a loose fit to allow for internal heat exchange by free air movement [86,107–109]. Neither should footwear be too roomy to allow for a pumping effect that promotes convective heat loss.

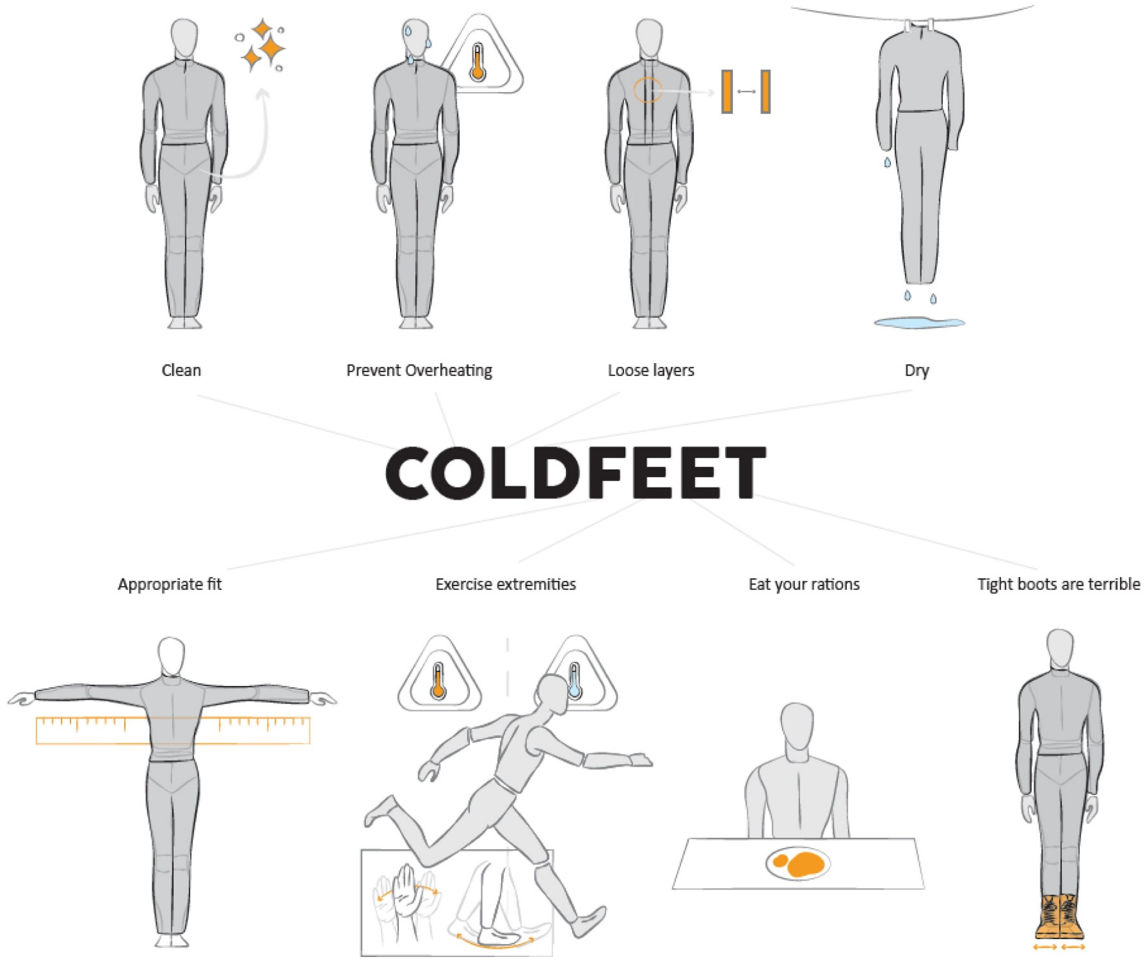

Figure 5. The acronym "COLDFEET" to prevent cold weather injury (CWI) explained. The acronym mostly refers to appropriate clothing and some other essential aspects in cold weather military operations. In more detail, "C" for keep it clean, "O" for prevent overheating, "L" for wear it loose and in layers, "D" for keep it dry, "F" for appropriate fit, "E" for exercise your extremities, "E" for eat your rations, "T" for tight boots are terrible.

It is further recommended to wear two pairs of socks; first, a thin layer to protect against blisters and a second insulative layer [110]. Two pairs of thin socks insulate better than one pair of thick socks [86,107,108]. There does not seem to be a single solution that fits all users and all conditions. Depending on activity level, certain material properties are recommended over others. When active, socks' desirable properties include wicking, insulation, and quick drying properties [86,107–109]. When static for long periods, based on anecdotal accounts, the northern countries recommend two layers of wool socks. Such recommendations of materials with conflicting nature highlight the importance of defining user conditions to be able to select appropriate clothing ensembles. Soldiers should make sure to always bring a pair of dry socks. Feet should be dried whenever possible and socks should be changed during breaks, post-exercise, and prior to sleep if they are damp or wet. If drying possibilities are restricted, it is recommended to "work wet but rest dry," for example, wearing waterproof and breathable socks when in a rest area. Finally, individuals should have their boots fitted wearing the socks they intend to use in the cold so that fit is optimal. Adherence to personal administrative routines is essential in the military field to help guard against CWI.

Mitigation strategies with a high risk

In the following paragraphs, we describe CWI prevention strategies that lack strong scientific supporting evidence, have significant adverse side effects, or may not be allowed in the military, depending on the actual setting (i.e. training or war). They are included for horizon scanning and potential future benefit.

Invasive treatments

Invasive treatments to enhance blood flow may have a protective effect against the development of CWI. An exhaustive list of such agents is not included here, rather a few of the more common interventions are highlighted as offering potential for further research. First, botulinum toxin injections may reduce cold sensitivity and maintain peripheral blood flow due to its “relaxation effect” [111,112]. A case study by Norheim and colleagues demonstrated reversal of frostbite symptoms 2 y after the injury, however this should be viewed with caution as there were no control cases and to our knowledge there is no other research evaluating the benefits of botulinum for prevention or treatment of CWI. The question raised is whether botulinum toxin given before cold exposure might reduce CWI risk through enhancing blood flow. The effect of botulinum toxin is relatively long-lasting (i.e. 8–14 wk). The required botulinum toxin dose varies per individual (up to a factor 1000) and must be calculated by a suitably qualified practitioner. Theoretically, botulinum injections could be administered at different skin sites such as feet, nose, and ears (i.e. common CWI sites). A potential problem associated with botulinum is the fact that cold sensitivity is reduced, and this lack of awareness may impair an individual’s thermoregulatory behaviors (i.e. wear more clothing, look for shelter, exercise). More importantly, caution should be taken when injecting botulinum toxin as the toxin may spread through diffusion or retrograde transport, there might be immunogenicity and could cause anhidrosis [113,114]. A second research area is galvanic current through the skin which has recently been shown to improve the vasodilatory response of individuals suffering from Raynaud’s phenomenon [115]. Could this be used to reduce CWI risk? To date, there is no evidence to show the same effect in healthy individuals. Thirdly, there is weak evidence that acupuncture may be of benefit in Raynaud’s phenomenon through enhanced capillary flow [116] and in recovering skin perfusion after freezing cold injury [117]. Due to the limited amount of randomized controlled trials and low quality of evidence, a meta-analysis only lends limited support for these statements [118]. Again, acupuncture could prove to be a preventive strategy against peripheral CWI in healthy individuals during cold exposure. Research to establish whether botulinum toxin injections, electrical stimulation, or acupuncture could guard against CWI in the military may be fruitful projects, but potential benefits of any such treatment would need to be carefully weighed against the disadvantages inherent in invasive treatments that need to be repeated over time.

Prophylactic drugs

Drugs that aid blood flow may offer protection against the development of CWI. This article does not endorse any drug preventive strategy, it seeks only to provide a summary of current knowledge of common drugs used in this context. Nonsteroidal anti-inflammatory drugs (NSAIDs) are the most frequently prescribed drugs in modern medicine and can be bought over the counter in many countries, for example ibuprofen. Considered vasodilators, NSAIDs and aspirin may theoretically offer protection against peripheral CWI in CWOs [119] but to date there is no evidence for this. Furthermore, long-term use of NSAIDs has been shown in some to harm organs such as the liver (especially in combination with alcohol) and abdomen. Hence, taking them for preventative reasons, especially for long periods of time could be dangerous and damaging.

Conclusions

Following a broader perspective on existing preventive strategies for CWI, the operationally most relevant strategies that were identified in this article are aligned. To start with, susceptibility for CWI should be identified. Prior to CWOs, military personnel should be highly educated about prevention of CWI in CWOs. Thereafter, when on a military operation in the cold, they should mainly focus on appropriate behavior, including using appropriate layered clothing system, understanding that stationary periods in the cold are especially high risk, eating sufficient calories, and staying hydrated. It is also important to monitor the environment using the windchill index and the physical state of the body. Monitoring itself does not prevent the development of CWI, but it could elicit essential changes in behavior accordingly. The most relevant preventive strategies for preventing CWI are education and behavior. As evidence for CWI preventive strategies in a military context is scarce, despite there being a high prevalence of CWI in the military context, there is an imperative to develop research that evaluates preventive strategies in a relevant context.

List of abbreviations

BSA (m^2)	Body surface area
CIVD	Cold-induced vasodilation
CHO	Carbohydrate
CWOs	Cold weather operations
CWI	Cold weather injury
(N)FCIs	(Non-) freezing cold injuries
LBM (kg)	Lean body mass
T_c (°C)	Core temperature
T_{sk} (°C)	Skin temperature
CIVD	Cold-induced vasodilation
IREQ	Required insulation
CoWEDA	Cold weather ensemble decision aid
SCTM	Six-cylinder model
VO_2max ($ml·min^{-1}·kg^{-1}$)	Maximal oxygen uptake
(N)ST	(Non-) shivering thermogenesis
SFT	Subcutaneous fat thickness
PPE	Personal protective equipment
BMI ($kg·m^{-2}$)	Body mass index
CHO	Carbohydrate
SFT	Subcutaneous fat thickness
Clo	Degree of thermal insulation
NSAIDs	Nonsteroidal anti-inflammatory drugs

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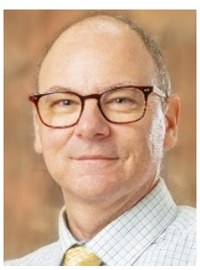

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References

[1] Milley MA, O'Keefe GB. Report: mountain warfare and cold weather operations. Headquarters department of the army Washington, USA; 2016.
[2] White M, Sullivan-Kwantes W. Examining methods to enhance and maintain peripheral blood flow to extremities in the cold: a literature review for at risk populations for cold weather injuries deliverable. Toronto, Canada: Defence Research and Development; 2019.
[3] Pozos RS, Iaizzo PA, Danzl DF, et al. Limits of tolerance to hypothermia. San Diego, CA: Naval Health Research Center; 1993.
[4] Moran DS, Heled Y, Shani Y, et al. Hypothermia and local cold injuries in combat and non-combat situations—the Israeli experience. Aviat Space Environ Med. 2003;74(3):281–284.
[5] Paton BC. Cold, casualties, and conquests: the effects of cold on warfare. Med Asp Harsh Environ. 2001;1:313–349.
[6] Imray CHE, Oakley EHN. Cold still kills: cold-related illnesses in military practice freezing and non-freezing cold injury. BMJ Mil Heal. 2005;151(4):218–222. doi:10.1136/jramc-151-04-02
[7] Heil K, Thomas R, Robertson G, et al. Freezing and non-freezing cold weather injuries: a systematic review. Br Med Bull. 2016;117(1):79–93. doi:10.1093/bmb/ldw001
[8] Haman F, Souza S, Castellani J, et al. Human vulnerability and variability in the cold: establishing individual risks for cold weather injuries. Temperature. 2022;9(2):158–195. doi:10.1080/23328940.2022.2044740
[9] Kuht JA, Woods D, Hollis S. Case series of non-freezing cold injury: epidemiology and risk factors. BMJ Mil Heal. 2019;165(6):400–404. doi:10.1136/jramc-2018-000992
[10] Tipton M, Eglin C. Non-freezing cold injury: a little-known big problem. Exp Physiol. 2023;108(3):329–330. doi:10.1113/EP091139
[11] Wright J, Massey H, Hollis S, et al. Peripheral sensory function in non-freezing cold injury patients and matched controls. Exp Physiol. 2023;108(3):438–447. doi:10.1113/EP090720
[12] Eglin CM, Wright J, Maley MJ, et al. The peripheral vascular responses in non-freezing cold injury and matched controls. Exp Physiol. 2023;108(3):420–437. doi:10.1113/EP090721
[13] Castellani J, Young A, Ducharme M, et al. American college of sports medicine position stand: prevention of cold injuries during exercise. Med Sci Sport Exerc.

2006;38(11):2012–2029. doi:10.1249/01.mss.0000241641.75101.64

[14] Giesbrecht GG, Wilkerson JA. Hypothermia, frostbite and other cold injuries: prevention, survival, rescue, and treatment. Seattle, USA: The Mountaineers Books; 2006.

[15] Castellani JW, Eglin CM, Ikäheimo TM, et al. ACSM expert consensus statement: injury prevention and exercise performance during cold-weather exercise. Curr Sports Med Rep. 2021 Nov;20(11):594–607. doi:10.1249/JSR.0000000000000907

[16] Sullivan-Kwantes W, Haman F, Kingma BRM, et al. Human performance research for military operations in extreme cold environments. J Sci Med Sport. 2021;24(10):954–962. doi:10.1016/j.jsams.2020.11.010

[17] Friedl KE, Hasselstrom H, Kingma BRM, et al. Introduction: training is more important than technology (for performance in the cold). Int J Circumpolar Health. 2023 Dec;82(1):2240572. 10.1080/22423982.2023.2240572

[18] Daanen HAM, Van Marken Lichtenbelt WD. Human whole body cold adaptation. Temperature. 2016;3(1):104–118. doi:10.1080/23328940.2015.1135688

[19] van Ooijen AMJ, van Marken Lichtenbelt WD, van Steenhoven AA, et al. Cold-induced heat production preceding shivering. Br J Nutr. 2005;93(3):387–391. doi:10.1079/BJN20041362

[20] Benzinger TH. Heat regulation: homeostasis of central temperature in man. Physiol Rev. 1969;49(4):671–759. doi:10.1152/physrev.1969.49.4.671

[21] Westerterp KR. Diet induced thermogenesis. Nutr Metab (Lond). 2004;1(1):5. doi:10.1186/1743-7075-1-5

[22] Veicsteinas A, Ferretti G, Rennie DW. Superficial shell insulation in resting and exercising men in cold water. J Appl Physiol. 1982;52(6):1557–1564. doi:10.1152/jappl.1982.52.6.1557

[23] de Castro ABB. 'Hierarchy of controls': providing a framework for addressing workplace hazards. AJN Am J Nurs. 2003;103(12):104. doi:10.1097/00000446-200312000-00030

[24] Whayne T, DeBakey M, Coates JJ, et al. Cold injury, ground type in world war ii (medical department, United States army). Washington DC: Office of the Surgeon General; 1958.

[25] Osczevski R, Bluestein M. The new wind chill equivalent temperature chart. Bull Am Meteorol Soc. 2005;86(10):1453–1458. doi:10.1175/BAMS-86-10-1453

[26] Siple PA, Passel CF. Measurements of dry atmospheric cooling in subfreezing temperatures. Proc Am Philos Soc. 1945;89(1):177–199.

[27] Lankford HV, Fox LR. The wind-chill index. Wildern Environ Med. 2021;32(3):392–399. doi:10.1016/j.wem.2021.04.005

[28] Tikuisis P, Keefe AA. Prediction of times of facial and finger freezing during cold air exposure. Toronto, Canada: Defence Research and Development; 2004.

[29] Yoshimura H, Iida T. Studies on the reactivity of skin vessels to extreme cold part I: a point test on the resistance against frostbite. Jpn J Physiol. 1950;1:147–159. doi:10.2170/jjphysiol.1.147

[30] Daanen HAM, Van de Linde FJG, Romet TT, et al. The effect of body temperature on the hunting response of the middle finger skin temperature. Eur J Appl Physiol Occup Physiol. 1997;76(6):538–543. doi:10.1007/s004210050287

[31] Daanen HAM, Van Der Struijs NR. Resistance index of frostbite as a predictor of cold injury in arctic operations. Aviat Space Environ Med. 2005;76(12):1119–1122.

[32] Brandstrom H, Grip H, Hallberg P, et al. Hand cold recovery responses before and after 15 months of military training in a cold climate. Aviat Sp Env Med. 2008;79(9):904–908. doi:10.3357/ASEM.1886.2008

[33] Norheim AJ, Borud E, Wilsgaard T, et al. Variability in peripheral rewarming after cold stress among 255 healthy Norwegian army conscripts assessed by dynamic infrared thermography. Int J Circumpolar Health. 2018;77(1):1536250. doi:10.1080/22423982.2018.1536250

[34] Rones N, Teien HK, Gulliksrud K, et al. FFI report 22/00661 - cooling and rewarming of the hands of military conscripts following a standardized cold challenge. 2022.

[35] Sullivan-Kwantes W, Moes K, Limmer R, et al. Finger cold-induced vasodilation test does not predict subsequent cold injuries: A lesson from the 2018 Canadian forces exercise. Temperature. 2019;6(2):142–149. doi:10.1080/23328940.2019.1574200

[36] Hughes B. The causes and prevention of trench foot. Br Med J. 1916;1(2890):712. doi:10.1136/bmj.1.2890.712

[37] Ungley CC, Channell GD, Richards RL. The immersion foot syndrome. Br J Surg. 1945;33(129):17–31. doi:10.1002/bjs.18003312903

[38] Keramidas ME, Botonis PG. Short-term sleep deprivation and human thermoregulatory function during thermal challenges. Exp Physiol. 2021;106(5):1139–1148. doi:10.1113/EP089467

[39] Sauvet F, Bourrilhon C, Besnard Y, et al. Effects of 29-h total sleep deprivation on local cold tolerance in humans. Eur J Appl Physiol. 2012;112(9):3239–3250. doi:10.1007/s00421-011-2297-1

[40] Peng H, Sullivan-Kwantes W. Sleep and associated risk for cold weather injuries during OP NUNALIVUT 2018. Scientific Letter, DRDC-RDDC-2019-L325. 2019.

[41] Young AJ, Castellani JW, O'Brien C, et al. Exertional fatigue, sleep loss, and negative energy balance increase susceptibility to hypothermia. J Appl Physiol. 1998;85(4):1210–1217. doi:10.1152/jappl.1998.85.4.1210

[42] Love RJ, Sullivan-Kwantes W Analysis of sleep and fatigue metrics of a subset of troops on arctic exercise GUERRIER NORDIQUE 2019. Scientific Letter, DRDC-RDDC-2023-L005). 2023

[43] Margolis LM, Murphy NE, Martini S, et al. Effects of supplemental energy on protein balance during 4-d arctic military training. Med Sci Sport Exerc. 2016;48(8):1604–1612. doi:10.1249/MSS.0000000000000944

[44] Margolis LM, Murphy NE, Martini S, et al. Effects of winter military training on energy balance, whole-body protein balance, muscle damage, soreness, and physical performance. Appl Physiol Nutr Metab. 2014;39(12):1395–1401. doi:10.1139/apnm-2014-0212
[45] Hamarsland H, Paulsen G, Solberg PA, et al. Depressed physical performance outlasts hormonal disturbances after military training. Med Sci Sport Exerc. 2018;50(10):2076–2084. doi:10.1249/MSS.0000000000001681
[46] Guezennec CY, Satabin P, Legrand H, et al. Physical performance and metabolic changes induced by combined prolonged exercise and different energy intakes in humans. Eur J Appl Physiol Occup Physiol. 1994;68(6):525–530. doi:10.1007/BF00599524
[47] Hoyt RW, Opstad PK, Haugen AH, et al. Negative energy balance in male and female rangers: effects of 7 d of sustained exercise and food deprivation. Am J Clin Nutr. 2006;83(5):1068–1075. doi:10.1093/ajcn/83.5.1068
[48] Thurber C, Dugas LR, Ocobock C, et al. Extreme events reveal an alimentary limit on sustained maximal human energy expenditure. Sci Adv. 2019;5(6):eaaw0341. doi:10.1126/sciadv.aaw0341
[49] Kenney WL, Wilmore JH, Costill DL. Physiology of sport and exercise. Champaign, Illinois, USA: Human kinetics; 2022.
[50] Westerterp-Plantenga MS. Effects of extreme environments on food intake in human subjects. Proc Nutr Soc. 1999;58(4):791–798. doi:10.1017/S002966519900107X
[51] Ahmed M, Mandic I, Lou W, et al. Comparison of dietary intakes of Canadian armed forces personnel consuming field rations in acute hot, cold, and temperate conditions with standardized infantry activities. Mil Med Res. 2019;6(1):1–16. doi:10.1186/s40779-019-0216-7
[52] Shirreffs SM, Maughan RJ. Rehydration and recovery of fluid balance after exercise. Exerc Sport Sci Rev. 2000;28(1):27–32.
[53] McClung JP, Martini S, Murphy NE, et al. Effects of a 7-day military training exercise on inflammatory biomarkers, serum hepcidin, and iron status. Nutr J. 2013;12(1):1–4. doi:10.1186/1475-2891-12-141
[54] Charlot K, Chapelot D, Colin P, et al. Daily energy balance and eating behaviour during a 14-day cold weather expedition in Greenland. Appl Physiol Nutr Metab. 2020;45(9):968–977. doi:10.1139/apnm-2019-0677
[55] Charlot K, Chapelot D, Siracusa J, et al. An augmented food strategy leads to complete energy compensation during a 15-day military training expedition in the cold. Physiol Rep. 2021;9(11):e14591. doi:10.14814/phy2.14591
[56] Charlot K, Coca M, Colin P, et al. Evaluation of the efficacy of a light ration adapted to cold weather during a 20-day expedition in Greenland. Physiol Behav. 2024;277:114497. doi:10.1016/j.physbeh.2024.114497
[57] Sanchez-Delgado G, Alcantara JMA, Acosta FM, et al. Energy expenditure and macronutrient oxidation in response to an individualized nonshivering cooling protocol. Obesity. 2020;28(11):2175–2183. doi:10.1002/oby.22972
[58] Landsberg L, Young JB, Bleich HL, et al. Fasting, feeding and regulation of the sympathetic nervous system. N Engl J Med. 1978;298(23):1295–1301. doi:10.1056/NEJM197806082982306
[59] Margolis LM, Pasiakos SM. Performance nutrition for cold-weather military operations. Int J Circumpolar Health. 2023;82(1):2192392. doi:10.1080/22423982.2023.2192392
[60] Young AJ, Roberts DE, Scott DP, et al. Sustaining health and performance in the cold: environmental medicine guidance for cold-weather operation. Natick, USA: Army Research Institute of Environmental Medicine; 1992.
[61] Royal Norwegian armed forces. UD 6-81-8E Instruction In Winter Service: Nutr In Cold Conditions. 2011.
[62] Kenefick RW, Mahood NV, Hazzard MP, et al. Hypohydration effects on thermoregulation during moderate exercise in the cold. Eur J Appl Physiol. 2004;92(4–5):565–570. doi:10.1007/s00421-004-1079-4
[63] O'Brien C, Frykman PN. Peripheral responses to cold: case studies from an arctic expedition. Wildern Environ Med. 2003;14(2):112–119. doi:10.1580/1080-6032(2003)014[0112:PRTCCS]2.0.CO;2
[64] O'Brien C, Montain SJ. Hypohydration effect on finger skin temperature and blood flow during cold-water finger immersion. J Appl Physiol. 2003;94(2):598–603. doi:10.1152/japplphysiol.00678.2002
[65] Mündel T, King J, Collacott E, et al. Drink temperature influences fluid intake and endurance capacity in men during exercise in a hot, dry environment. Exp Physiol. 2006;91(5):925–933. doi:10.1113/expphysiol.2006.034223
[66] Burdon C, O'Connor H, Gifford J, et al. Effect of drink temperature on core temperature and endurance cycling performance in warm, humid conditions. J Sports Sci. 2010;28(11):1147–1156. doi:10.1080/02640414.2010.489197
[67] Barwood MJ, Goodall S, Bateman J. The effect of hot and cold drinks on thermoregulation, perception, and performance: the role of the gut in thermoreception. Eur J Appl Physiol. 2018;118(12):2643–2654. doi:10.1007/s00421-018-3987-8
[68] Lee JKW, Maughan RJ, Shirreffs SM. The influence of serial feeding of drinks at different temperatures on thermoregulatory responses during cycling. J Sports Sci. 2008;26(6):583–590. doi:10.1080/02640410701697388
[69] Coca M, Besançon L, Erblang M, et al. Twenty four-hour passive heat and cold exposures did not modify energy intake and appetite but strongly modify food reward. Br J Nutr. 2024 Apr;1–18. doi: 10.1017/S0007114524000825
[70] Bittel JH, Nonotte-Varly C, Livecchi-Gonnot GH, et al. Physical fitness and thermoregulatory reactions in a cold environment in men. J Appl Physiol. 1988;65(5):1984–1989. doi:10.1152/jappl.1988.65.5.1984

[71] Haman F. Shivering in the cold: from mechanisms of fuel selection to survival. J Appl Physiol. 2006;100(5):1702–1708. doi:10.1152/japplphysiol.01088.2005
[72] Rintamäki H. Predisposing factors and prevention of frostbite. Int J Circumpolar Health. 2000;59(2):114–121.
[73] Vikmoen O, Teien HK, Raustøl M, et al. Sex differences in the physiological response to a demanding military field exercise. Scand J Med Sci Sports. 2020;30(8):1348–1359. doi:10.1111/sms.13689
[74] Tarnopolsky MA. Gender differences in substrate metabolism during endurance exercise. Can J Appl Physiol. 2000;25(4):312–327. doi:10.1139/h00-024
[75] Lamont LS. Gender differences in amino acid use during endurance exercise. Nutr Rev. 2005;63(12):419–422. doi:10.1111/j.1753-4887.2005.tb00116.x
[76] Vikmoen O, Teien HK, Tansø R, et al. The effects of a 10-day military field exercise on Body composition, physical performance, and muscle cells in men and women. Med Sci Sports Exerc. 2023;56(4):682–696. doi:10.1249/MSS.0000000000003340
[77] Savastano DM, Gorbach AM, Eden HS, et al. Adiposity and human regional body temperature. Am J Clin Nutr. 2009;90(5):1124–1131. doi:10.3945/ajcn.2009.27567
[78] Rennie DW, Covino BG, Howell BJ, et al. Physical insulation of Korean diving women. J Appl Physiol. 1962;17(6):961–966. doi:10.1152/jappl.1962.17.6.961
[79] Ducharme MB, Tikuisis P. In vivo thermal conductivity of the human forearm tissues. J Appl Physiol. 1991;70(6):2682–2690. doi:10.1152/jappl.1991.70.6.2682
[80] Nahon KJ, Boon MR, Doornink F, et al. Lower critical temperature and cold-induced thermogenesis of lean and overweight humans are inversely related to body mass and basal metabolic rate. J Therm Biol. 2017;69:238–248. doi:10.1016/j.jtherbio.2017.08.006
[81] Toner MM, McArdle WD. Human thermoregulatory responses to acute cold stress with special reference to water immersion. Compr Physiol. 2011;2(89):379–397.
[82] Cheung SS, Daanen HAM. Dynamic adaptation of the peripheral circulation to cold exposure. Microcirculation. 2012;19(1):65–77. doi:10.1111/j.1549-8719.2011.00126.x
[83] Castellani JW, Young AJ. Human physiological responses to cold exposure: acute responses and acclimatization to prolonged exposure. Auton Neurosci. 2016;196:63–74. doi:10.1016/j.autneu.2016.02.009
[84] Rintamäki H, Hassi J, Oksa J, et al. Rewarming of feet by lower and upper body exercise. Europ J Appl Physiol. 1992;65(5):427–432. doi:10.1007/BF00243509
[85] Kenny GP, Chen AA, Nurbakhsh BA, et al. Moderate exercise increases postexercise thresholds for vasoconstriction and shivering. J Appl Physiol. 1998;85(4):1357–1361. doi:10.1152/jappl.1998.85.4.1357
[86] Kuklane K. Protection of feet in cold exposure. Ind Health. 2009;47(3):242–253. doi:10.2486/indhealth.47.242
[87] Lee JKW, Tan B, Kingma B, et al. Biomarkers for warfighter safety and performance in hot and cold environments. J Sci Med Sport. 2022;26:S71–S78. doi:10.1016/j.jsams.2022.12.006
[88] Kingma BRM, Steenhoff H, Toftum J, et al. Climapp—integrating personal factors with weather forecasts for individualised warning and guidance on thermal stress. Int J Environ Res Public Health. 2021;18(21):11317. doi:10.3390/ijerph182111317
[89] Xu X, Rioux TP, Gonzalez J, et al. A digital tool for prevention and management of cold weather injuries—cold weather ensemble decision aid (CoWEDA). Int J Biometeorol. 2021;65(8):1415–1426. doi:10.1007/s00484-021-02113-0
[90] Potter AW, Looney DP, Santee WR, et al. Validation of new method for predicting human skin temperatures during cold exposure: the cold weather ensemble decision aid (CoWEDA). Inf Med Unlocked. 2020 Jan 1;18100301. doi:10.1016/j.imu.2020.100301
[91] Taylor NAS, Tipton MJ, Kenny GP. Considerations for the measurement of core, skin and mean body temperatures. J Therm Biol. 2014;46:72–101. doi:10.1016/j.jtherbio.2014.10.006
[92] Notley SR, Meade RD, Kenny GP. Time following ingestion does not influence the validity of telemetry pill measurements of core temperature during exercise-heat stress: The journal Temperature toolbox. Temp. 2021;8(1):12–20. doi:10.1080/23328940.2020.1801119
[93] Brajkovic D, Ducharme MB. Confounding factors in the use of the zero-heat-flow method for non-invasive muscle temperature measurement. Eur J Appl Physiol. 2005;94(4):386–391. doi:10.1007/s00421-005-1336-1
[94] Strapazzon G, Procter E, Avancini G, et al. Thermistor probe for measurement of tympanic temperature: influence of ambient temperature. Resuscitation. 2013;84:S93. doi:10.1016/j.resuscitation.2013.08.236
[95] Daanen HAM. Infrared tympanic temperature and ear canal morphology. J Med Eng Technol. 2006;30(4):224–234. doi:10.1080/03091900600711613
[96] NATO. HFM RTG-260 - enhancing warfighter effectiveness with wearable bio sensors and physiological models. 2019.
[97] Heil KM, Oakley EHN, Wood AM. British military freezing cold injuries: a 13-year review. J R Army Med Corps. 2016;162(6):413–418. doi:10.1136/jramc-2015-000445
[98] Rathjen NA, Shahbodaghi SD, Brown JA. Hypothermia and cold weather injuries. Am Fam Physician. 2019;100(11):680–686.
[99] Teien HK, Rones N, Renberg J. Training videos to prevent cold weather injuries. Int J Circumpolar Health. 2023;82(1):2195137. doi:10.1080/22423982.2023.2195137
[100] Nindl BC, Billing DC, Drain JR, et al. Perspectives on resilience for military readiness and preparedness: report of an international military physiology roundtable. J Sci Med Sport. 2018;21(11):1116–1124. doi:10.1016/j.jsams.2018.05.005
[101] Lajeunesse A, Lackenbauer PW. Canadian armed forces arctic operations, 1941-2015 lessons learned,

lost, and relearned. New Brunswick, Canada: Gregg Centre; 2017.
[102] ISO11079 - ergonomics of the thermal environment - determination and interpretation of cold stress when using required clothing insulation (IREQ) and local cooling effects. 2007;
[103] Hickey CA Jr, Woodward AA Jr, Hanlon WE. A pilot study to determine the thermal protective capability of electrically heated clothing and boot inserts. Aberdeen, Scotland: Army Research Lab; 1993.
[104] Song W, Lai D, Wang F. Evaluating the cold protective performance (CPP) of an electrically heated garment (EHG) and a chemically heated garment (CHG) in cold environments. Fiber Polym. 2015;16(12):2689–2697. doi:10.1007/s12221-015-5409-4
[105] Wang F. Evaluation of the performances of electrically heated clothing. [Licentiate Thesis, Ergonomics and Aerosol Technology]. Tryckeriet i E-huset, Lunds universitet; 2010.
[106] Howard E, Oakley N. The design and function of military footwear: a review following experiences in the South Atlantic. Ergonomics. 1984;27(6):631–637. doi:10.1080/00140138408963535
[107] Kuklane K, Geng Q, Holmér I. Effect of footwear insulation on thermal responses in the cold. Int J Occup Saf Ergon. 1998;4(2):137–152. doi:10.1080/10803548.1998.11076386
[108] Kuklane K, Kaced Y. Footwear for cold weather conditions. In: D. Francis, editor. Handbook of footwear design and manufacture. Sawston, UK: Woodhead Publishing; 2021pp. 323–360.
[109] Wang F Textiles for protective military footwear. In: A. Luximon, editor. Handbook of footwear design and manufacture. Sawston, UK: Woodhead Publishing; 2013pp. 318–340.
[110] Thwaites C, Gore WL Cold-weather clothing. In: E. Wilusz, editor. Military textiles. Sawston, UK: Woodhead Publisher; 2008pp. 158–182.
[111] Dressler D. Clinical pharmacology of botulinum toxin drugs. Botulinum Toxin Ther. 2021;263:93–106.
[112] Norheim AJ, Mercer J, Musial F, et al. A new treatment for frostbite sequelae; botulinum toxin. Int J Circumpolar Health. 2017;76(1):1273677. doi:10.1080/22423982.2016.1273677
[113] Samizadeh S, De Boulle K. Botulinum neurotoxin formulations: overcoming the confusion. Clin Cosmet Investig Dermatol. 2018;Volume 11:273–287. doi:10.2147/CCID.S156851
[114] Braune C, Erbguth F, Birklein F. Dose thresholds and duration of the local anhidrotic effect of botulinum toxin injections: measured by sudometry. Br J Dermatol. 2001;144(1):111–117. doi:10.1046/j.1365-2133.2001.03961.x
[115] Tapia-Haro RM, García-Ríos MC, Toledano-Moreno S, et al. The complementary effects of galvanic current electrical stimulation associated with conservative treatment to increase vasodilation in patients with raynaud's phenomenon: a randomized trial. Clin Rehabil. 2020;34(5):595–606. doi:10.1177/0269215520907652
[116] Appiah R, Hiller S, Caspary L, et al. Treatment of primary Raynaud's syndrome with traditional Chinese acupuncture. J Intern Med. 1997;241(2):119–124. doi:10.1046/j.1365-2796.1997.91105000.x
[117] Norheim AJ, Alræk T. Acupuncture for frostbite sequel—A case report. Eur J Integr Med. 2018;17:102–106. doi:10.1016/j.eujim.2017.12.003
[118] Zhou F, Huang E, Zheng E, et al. The use of acupuncture in patients with Raynaud's syndrome: a systematic review and meta-analysis of randomized controlled trials. Acupunct Med. 2023;41(2):63–72. doi:10.1177/09645284221076504
[119] Bushra R, Aslam N. An overview of clinical pharmacology of ibuprofen. Oman Med J. 2010;25(3):155. doi:10.5001/omj.2010.49