Invited review

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Cold operational readiness in the military: from science to practice

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ABSTRACT

Cold weather operations are logistically difficult to orchestrate and extremely challenging for soldiers. Decades of research and empirical evidence indicate that humans are extremely vulnerable to cold and that individual responses are highly variable. In this context, it may be necessary to develop personalised strategies to sustain soldiers' performance and ensure overall mission success in the cold. Systematic cold weather training is essential for soldiers to best prepare to operate during, and recover from, cold weather operations. The purpose of this review is to highlight key aspects of cold weather training, including (1) human responses to cold, (2) nutrition, (3) sleep and (4) protective equipment requirements. Bringing science to practice to improve training principles can facilitate soldiers performing safely and effectively in the cold. Cold weather training prepares soldiers for operations in cold, harsh environments. However, decreases in physical, psychological and thermoregulatory performance have been reported following such training, which influences operational ability and increases the overall risk of injuries. When optimising the planning of field training exercises or operational missions, it is important to understand the soldiers' physical and cognitive performance capacity, as well as their capacity to cope and recover during and after the exercise or mission. Even though the body is fully recovered in terms of body composition or hormonal concentrations, physical or cognitive performance can still be unrecovered. When overlooked, symptoms of overtraining and risk of injury may increase, decreasing operational readiness.

WHAT IS ALREADY KNOWN ON THIS TOPIC

⇒ Cold weather training and operations provide a great opportunity to acquire the operational, survival and tactical skills necessary to operate in such environments.
⇒ Systematic cold weather training is essential to best prepare soldiers to operate during, and recover from, cold weather operations.

WHAT THIS STUDY ADDS

⇒ The purpose of this review is to highlight key aspects of cold weather training, including (1) human responses to cold, (2) modelling the impact of cold on humans, (3) sleep and (4) nutrition.
⇒ A better understanding of soldier responses to training practices during winter warfare, as well as their environment, can lead to optimisation of their capacity to master cold weather warfare.

HOW THIS STUDY MIGHT AFFECT RESEARCH, PRACTICE OR POLICY

⇒ Closing the gap between research and training in the field allows for improved effort coordination to better prepare soldiers, including updating training strategies.

INTRODUCTION

Cold environments, such as the ones in Arctic and sub-Arctic regions, expose soldiers to a variety of additional stressors, including sleep deprivation, high energy deficits and extreme weather conditions. The result of the combination of these multiple stressors makes military operations in cold climates and Polar Regions particularly challenging, as these extreme environments and operational demands can be both physically and psychologically taxing.

Extreme weather conditions, in particular cold, can have a strong effect on soldiers' performance, due to the weight of cold weather clothing and other equipment. Dismounted cold weather military operations require sustained low-to-moderate intense physical activity while traversing difficult terrain.[1] The sustained physical exertion associated with cold weather military operations results in exceedingly high daily energy expenditures, which may reach as up to 7000 kcal/day.[2–4] Due to limited food supply, curtailed time to eat, suppressed appetite and logistical difficulties of eating under cold weather conditions, it becomes exceedingly difficult for service members to consume an adequate amount of energy to match energy demands.[1] Insufficient energy intakes to meet energy expenditures during cold weather operations results in severe energy deficits, ranging from 40% to 70% of total energy needs.[4] The severity of energy deficit during cold weather military operations is associated with decreased body mass and nutrient status, alterations in substrate metabolism and increased inflammation, leading to declines in physical performance.[5–7]

Over the last century, tremendous advancements in heating, sheltering and clothing technologies have occurred to allow humans to live, work and thrive in cold climates. However, military exercises in cold climates remain extremely challenging and hazardous. The cold impairs the ability of people to work effectively, notably due to reduced dexterity and involuntary shivering.[8] Beyond performance degradation, the cold also poses significant health risks, such as acute issues like frostbite and chronic conditions such as trench foot.[9] The extremities,

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particularly the fingers and toes, are highly susceptible to cold injury[10] due to their limited blood flow as a result of vasoconstriction in response to cold. From an operational standpoint, simple solutions for improving cold tolerance are essential to ensure feasibility and compliance.

Effective preparation and behaviour can mitigate health and performance risks associated with cold exposure. Currently, military behavioural doctrines are aimed at providing overarching one-size-fits-all solutions and models to help minimise the effects of cold and maintain performance. Nevertheless, research clearly shows that modelling human cold responses is extremely difficult as cold responses are highly variable among individuals even of similar origins and morphologies.[11] In this context, efforts must be made to better bridge the gap between scientific findings and cold weather operations. Logistics and equipment choices are often predetermined in military settings, making anticipating the environment crucial. It became clear already in 1941 that wind exacerbated cold air temperature conditions, leading to the development of the windchill index, which has been updated by Joint Action Group for Temperature Indices since.[12]

Traditionally, preparation to cold weather operations has focused primarily on teaching the skills necessary for cold protection, including learning about adequate clothing solutions, cold-specific nutrition and behaviours, as well as fire and shelter making. However, maintaining physical and mental performance in the cold requires an integrated global approach that focuses not only on efficient operational strategies but also safe preparation and adequate recovery.

Cold acclimation: optimisation of cold tolerance

Efficient operational strategies

As tropical animals, humans display a particularly high vulnerability to cold.[11] The furless human body combined with long appendages and highly vascularised skin is by far better suited for dissipating heat in warm climates.[13] In this context, behavioural and decision-making adaptations are the main line of defence as physiological responses to reduce heat loss and increase heat production are extremely limited. Of great concern is the substantial and consequential drive to redistribute blood flow to the core and away from extremities (hands, feet and facial features). While this response reduces overall rate of heat loss, it increases the risk of cold weather injuries (CWIs) including freezing (FCIs) and non-freezing cold injuries (NFCIs). Currently, mitigation strategies for peripheral CWI are mainly focused on improving insulation and artificial heating to extremities. However, this also (1) increases the risks of wetness which accentuates the rate of heat dissipation by conduction if not well managed and (2) reduces hand dexterity with the thickening layer of thermal protective material. On the other side of the body temperature maintenance equation, heat production in humans is maintained primarily through shivering thermogenesis (ST) and, to a lesser extent, by non-shivering thermogenesis (NST). While ST can increase heat production by up to five times, it remains highly debilitating and uncomfortable in comparison to NST.[14] In other word, ST provides the necessary heat in an attempt to maintain core temperature (T_{core}) but in comparison to NST, its activation reduces cold tolerance.

An additional concern is the high variability of cold tolerance and responses between individuals based on variations in (1) body mass, (2) level of cold acclimation and (3) muscle shivering recruitment pattern.[15] These variations are also found among morphologically similar individuals generalising on cold tolerance extremely difficult but emphasising the importance of individualised cold training and preparation (Table 1). Adding to the complexity of cold weather operations, and cold itself, research has convincingly shown that cold tolerance is greatly affected by negative energy balance and lack of sleep.[11] Feeding and sleeping strategies remain highly difficult to implement during cold weather operations. Feeding and sleep can be deprioritised in the context of operational needs, in particular those related to complexities of moving in snow.

Safe preparation

In contrast to physical training, far less is known about the best way to improve and build up cold tolerance. The effects on cold tolerance of cold exposure frequency, intensity, time and type (air vs water) have not been well documented. While some experimental work confirms that cold acclimation can improve cold tolerance,[16] no information is available on the impact of specific cold acclimation programmes on performance during cold weather operations. Cold training should focus on (1) reducing cold shock response, (2) improving thermal comfort at the whole-body level, as well as hand and feet, (3) reducing shivering, (4) maintaining physical and cognitive capacity, (5) improving sleep and feeding capacity. In case of accidental and unexpected immersion in water between 0°C and 15°C, individuals must learn to control the stress response, float and reduce the

Table 1 Cold operational resilience indicators

Indicator	Operational definition	Operational importance
Shivering	Shivering or cold-induced involuntary muscle contraction is a strong indicator of cold tolerance and cold performance	Shivering decreases heat loss and increases metabolic heat production. Important indicator to the individual of the need for warm-up.
RCWIs	RCWI can indicate the risk of freezing and non-freezing cold injury, which can occur with wet cold conditions already in 15°C.	Individual knowledge of previous injuries and symptoms to prevent new cold weather injuries.
Cognitive capacity	Cognitive capacity indicates the underlying cognitive skills of vigilance, reaction time, working memory and reasoning	Cold can have declining effect on cognitive capacity. Important to know the individual effects.
Mood	Mood indicates the emotional state of mind	Cold can have declining effect on mood. Important to know the individual effects.
Thermal comfort	Thermal discomfort indicates the limit of cold tolerance	Thermal discomfort is an indicator to increase clothing or ways to warm-up the body.
Fatigue	Fatigue indicates the level of perceived exhaustion	Fatigue and cold can lead to decreased performance.
Physical performance	Physical performance is of one of the key indicators of physical and tactical performance, and may include high power bouts, sustained work or marksmanship	Good physical performance can help individual to tolerate cold and make right decisions under operational stress in the cold.

RCWIs, Risk of cold weather injuries.

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cold shock response. Cold shock training can reduce the intensity of the response even after 14 months post-training.[17] Using two acclimation protocols (1 month compensable and 7-day non-compensable), Gordon *et al*[16] showed that ST response can be reduced by 20–40% while improving thermal comfort. In addition, exercising in the heat alone has been shown to improve finger temperature during cold exposure which may reduce the risk of CWI.[18] Of key importance, however, individuals must learn to embrace the cold and feel comfortable in performing and making appropriate decisions in any cold condition they might face.

Impact of severe energy deficits during cold weather military operations

To better understand metabolic adaptations to cold weather operations, Karl *et al*[5] assessed changes in metabolomics profiles, measuring 737 metabolites, before and after a 4 day, 51 km ski march, which induced a 55% energy deficit in 25 male Norwegian soldiers. Of the 737 metabolites, 478 changed during the training, with the majority of the altered metabolites being within lipid metabolism.[5] There was an 88% increase in free fatty acid metabolites, a 91% increase in acylcarnitine metabolites and an 88% decrease in monoglycerol and diacylglycerol metabolites. Reductions in monoglycerol and diacylglycerol and elevated concentrations of acylcarnitine metabolites suggests increased uptake of fatty acids for fuel use, as the latter primarily functions to facilitate transport of fatty acids across mitochondrial membranes during beta-oxidation.[19] In agreement, there was a >30-fold increase in the ketone body 3-hydroxybutyrate, a metabolite of fatty acid oxidation, indicating changes in lipid metabolites reflected increases in fatty acid mobilisation and oxidation, likely to compensate for low energy availability during the ski march.[5]

While increased fatty acid oxidation is an appropriate metabolic response to severe energy deficits during cold weather operations, this metabolic adaptation may also be a contributor to negative physiological consequences following cold weather operations.[2] Acylcarnitine metabolites share common pathways with branched-chain amino acid (BCAA) metabolites,[20] where there is a concurrent increase in the concentration of BCAA and acylcarnitine metabolites, signifying increased protein catabolism.[21] Greater protein breakdown, signified by increased concentrations of BCAA metabolites, is likely due to greater reliance on BCAAs for oxidative purposes to meet energy demands with severe energy deficits during cold weather operations.[22] This is corroborated by a more negative protein balance (eg, protein breakdown>protein synthesis) with greater severity in energy deficits during cold weather operations.[4] Furthermore, acylcarnitine metabolites have been associated with increased inflammation, with a dose-dependent increase in proinflammatory cytokine interleukin-6 (IL-6) production observed with greater acylcarnitine concentrations in cell culture models.[23] Increased inflammation with elevated acylcarnitine metabolites may, in part, contribute to decreased iron status during cold weather operations.[6,7] Specifically, increases in IL-6 during cold weather operations increase concentrations of the iron regulatory protein hepcidin, which reduces absorption and distribution of iron within the body.[6,7] Increases in hepcidin during cold weather operations have been linked to decreases in haemoglobin and haematocrit status due to reduced dietary iron absorption.[6,7] Interestingly, the severity of energy deficit was associated with higher concentrations of hepcidin during a cold weather operation.[6] Collectively, these data may indicate that increased acylcarnitine metabolites during cold weather military operations under energy deficit conditions may contribute to greater protein catabolism and increase systemic inflammation. Minimising the severity of energy deficits during cold weather operations is likely necessary to diminish the rise in acylcarnitine metabolites and subsequent negative physiological effects.

Sleep health prior, during and after cold weather operations

Good sleep health is essential to sustain performance and to mitigate risk associated with fatigue. Good sleep health is characterised by subjective sleep satisfaction (ie, sleep quality), appropriate timing, regular, adequate duration, high efficiency and thus promoting sustained alertness during waking hours. Despite several initiatives to improve the sleep across NATO forces, on average, service members sleep less and poorer than the general population.[24] Insufficient and poor sleep appears to be particularly prevalent immediately before deployment and during deployment. Prior to deployments, sleep is often deprioritised in lieu of other social and operational needs. Interestingly, longer sleep is associated with lower risk of injury and may help protect cognitive capacities that underlie most cognitive processes during subsequent sleep loss.[25] Preserving sleep prior to mission may therefore be an important health and performance enhancement intervention.

During cold operations, even in the context of an adequate sleep opportunity, several physical environmental factors can impact the restorative power of sleep.[26] These factors include environmental factors such as air quality, surface comfort, temperature and humidity, noise and light. Lack of ventilation (higher exposure to air pollutants and increased CO_2), thermal discomfort (hot or cold), poor ground insulation, noisy and lit sleeping environment can disrupt sleep.[26] During cold weather operations, tents are often heated using a central stove requiring a fire-watch that can severely reduce the overall sleep opportunity of the unit and increase the risk of accidental carbon monoxide poisoning.[27]

It is worth mentioning that sleep not only represents an opportunity to rest but it is also a period of energy conservation. Sleep deprivation in cold environment has been linked to a slight increase in cutaneous heat loss and in metabolic heat production.[28] Sustained military operations in the cold with minimal sleep can lead to greater declines in core temperature.[29] During polar sailing expeditions, circadian disruption due to the lack of daylight can lead to dissociation between sleep and the circadian core body temperature.[30] Early studies carried out by Buguet and colleagues[31] showed that sleeping in extreme cold environments leads to a reduction in REM sleep and activation of stress hormones.[31,32] Conversely, experimental studies have shown that sleeping more than the habitual amount (ie, banking sleep) increases tolerance to an extreme cold stimulus. Taken together, these studies highlight the need to allocate an adequate sleep opportunity, be cognisant about the impact of the environment on the circadian system, and the need to use optimal sleep systems that ensure heat retention and comfort.

During deployment in cold weather and Arctic environments, sleep is important not only for learning and memory consolidation but also to reduce the risk of accidents and improve decision-making-related risky cold, unsafe behaviour. These behaviours, for example, could include the decision to wear gloves or not during a particular situation, not following procedures around frozen water, jet skiing, etc. Poor sleep health can broadly impact physical performance, motivation and social cohesion, all of which are important determinants of mission success.[33] At a unit level, better leader's sleep prioritisation can impact unit's performance, providing an avenue for educational interventions.[34] It is reasonable to hypothesise that the complex interplay of factors that predict resilience during cold operations likely includes preserved sleep as an important factor. Understanding the determinants that shape sleep during cold operations remains essential to develop mitigating and adaptation strategies.

Adequate recovery

Generally, little focus is given to post-cold weather operations assuming that activities can continue normally. However, high energy demands, negative energy balance and sleep deprivation post cold weather trainings have been shown to reduce cold tolerance substantially for up to 4 months.[35] In addition, reductions in post-cold weather operations physical performance have been shown by many researchers. Care should be given to proper recovery methods to avoid detriments in the cold exposure response. Good restorative sleep is associated with several physiological processes such as muscle repair, brain plastic changes, appetite regulation and inflammatory modulation to name a few.[36] To date, there are no science-based guidelines related to sleep and rest following cold weather operations.

Modelling of extremity temperature in extremely cold weather

Since the development of wind chill in 1941, our understanding of the interplay between cold environments and human physiology has grown significantly. This evolution has led to more comprehensive models, incorporating factors such as physical activity, clothing, and more recently, individualised modelling.[37,38] Models now predict operationally relevant parameters such as core temperature, required clothing insulation and extremity temperatures. Despite their increasing complexity, all models fundamentally quantify the body's heat losses and gains. Some notable examples of models with increasing complexity are the Required Clothing Insulation (IREQ), the finger temperature model and Cold Weather Ensemble Decision Aid (CoWEDa).[38]

The IREQ quantifies the heat balance of the human body by calculating convective, evaporative and radiative heat losses to the environment and heat production from physical work. From this, the model calculates the required amount of insulation from clothing to prevent hypothermia. Models like IREQ could support in clothing ensemble selection and acquisition by identifying the thermal requirements of the mission or operational area. On a smaller scale, the finger temperature model calculates the heat balance and physiological response specifically for the extremities. Predicting the temperature of the extremities can inform whether conditions will be safe, but also what equipment is required for optimal performance, for example, no loss in dexterity. Extremities are important in assessing injury risk, since they are susceptible to CWI and use of them is necessary to perform various operational tasks. Finally, the most advanced of these models are similar to the model underlying the CoWEDA tool. It is based on a six cylinder—human represented by six cylinders—thermoregulatory model and is able to predict core temperature and skin temperature, including that of extremities, in a wide range of conditions. As a trade-off, an increasingly complex model requires more detailed input and so becomes harder to use in operational settings. In recent years, there has been a trend to connect complex models to a graphical user interface (GUI), thereby bridging the gap between complexity and operational viability. The CoWEDA tool includes a GUI.

Although predictive models can help enhance safety, they are not a replacement for adequate monitoring. Models make simplifications and rely on data which may prove to be inaccurate (eg, weather data). Instead, modelling and monitoring should supplement each other; modelling is used to anticipate risks and develop mitigation strategies, while monitoring ensures the risk assessment was accurate and the chosen mitigation strategies are effective. Ultimately, models provide additional information which can be leveraged to enhance safety through better informed mission planning, clothing and equipment selection, and awareness.

FUTURE DIRECTIONS

A challenge yet ahead of us is the ability to allow the bigger public to make use of these models in a way where the input remains limited in complexity yet the output is accurate and interpretable. Better understanding the impact of behavioural trainings, better use of high-quality protective equipment and the use of mathematical prediction might help developed individualised approaches that might better fit the needs of cold weather operations. This would make these models not just theoretically interesting but also practically applicable as decision-support tools, a transformation that could be a significant leap in our ability to operate safely and effectively in harsh cold environments.

CONCLUSION

As a summary, the previous literature has shown that aerobic and anaerobic endurance, as well as neuromuscular performance, are decreased in cold weather environment. Similarly, energy expenditure is increased, in the context of operational conditions that do not allow proper feeding and sleep. These factors are important to consider when planning operations in Arctic climates. Our improved understanding of the human body in extremely cold environments and increasing ability to mathematically predict these effects can be leveraged to make better-informed decisions regarding training, mission planning, and clothing and equipment requirements.

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