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Review

Human performance research for military operations in extreme cold environments☆

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ABSTRACT

Objectives: Soldier performance in the Arctic depends on planning and training, protective equipment, and human physiological limits. The purpose of this review was to highlight the span of current research on enhancing soldier effectiveness in extreme cold and austere environments.
Methods: The practices of seasoned soldiers who train in the Arctic and cold-dwelling natives inform performance strategies. We provide examples of research and technology that build on these concepts.
Results: Examples of current performance research include evaluation of equipment and tactics such as the bioenergetics of load carriage over snow in Norwegian exercises; Canadian field monitoring of hand temperatures and freezing cold injuries for better protection of manual dexterity; and Dutch predictive modeling of cold-wet work tolerances. Healthy young men can respond to cold with a substantial thermogenic response based on US and Canadian studies on brown adipose tissue and other mechanisms of non-shivering thermogenesis; the potential advantage of greater fat insulation is offset in obese unfit subjects by a smaller thermogenic response. Current physiological studies are addressing previously unanswered problems of cold acclimation procedures, thermogenic enhancement and regulation, and modulation of sympathetic activation, all of which may further enhance cold survival and expand the performance envelope.
Conclusion: There is an inseparable behavioral component to soldier performance in the Arctic, and even the best equipment does not benefit soldiers who have not trained in the actual environment. Training inexperienced soldiers to performance limits may be helped with personal monitoring technologies and predictive models.

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1. Introduction

> "The line between surviving and operating is subtle in the Arctic. With only a small misstep, a unit or individual can transition from fighting for a tactical goal to fighting for survival."
>
> Observations recorded after a joint Canada-US "Exercise Guerriere Nordique"Captain Nathan Fry[1]

The Arctic region, shared by Canada, United States, Denmark, Norway, Sweden, Iceland, Finland and Russia[2] is one of the extreme environments on earth. This region has some of the coldest temperatures, strong winds, fog, ice blizzards, crevasses and depending on the season, 24 h of light or darkness. In addition to the challenging environment, the Arctic circle is a large area encompassing ~6 % of the earth and over 21 million km^2. In this area beyond the tree line, infrastructure is extremely limited requiring air transport in response to emergencies (medical, industrial, tourism, natural

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☆ This paper represents a synthesis of presentations and discussion in a thematic session on Arctic operations. This is also a work product of NATO panel 310 which met at the same conference, with overlapping membership in this session.

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disaster or search and rescue).[2,3] Depending on the type of event, emergency response can take anywhere from hours to days or even longer due to geographic location, weather, terrain, and availability of aircraft and response personnel.[1,4,5]

Interest in the Arctic is increasing due to global warming and the melting of the arctic ice resulting in the opening of new ocean routes, increasing access to mineral and oil reserves and exploitation of other potential Arctic resources.[2,6] A growing interest in the Arctic region increases the likelihood that it will be more frequented and contested. This heightens the need for an effective Arctic response capability for conflicts, emergencies, safety, and environmental concerns. Soldiers must be highly specialized, well trained, well equipped and self-sufficient to operate successfully and survive in this remote and extreme environment. Military preparedness in recent years has focused on hot climates but Norway and Canada have now established dedicated Arctic units that are establishing tactics, techniques and procedures for Arctic operations.[1]

For this brief review, we chose six deep dive topics that span the problem set for human performance in Arctic Operations. We bring forth perspectives of soldiers who train in the Arctic, military performance researchers working on improved materiel and tactics for arctic operations, and field and laboratory-based integrative physiology investigations focused on cold weather performance problem solving. In addition, we discuss our respective laboratories' efforts in understanding how the extreme cold affects human performance, culminating in a discussion that highlights the importance of treating human performance as the product of multiple factors working as an integrated system that can permit a person to thrive in the extreme cold or leaves them vulnerable to injury.

2. Preparation and field training exercises: what are the issues?

In the 1940s, a set of military exercises in the Canadian Arctic highlighted advances as well as continuing challenges and deficiencies in equipment, training, communication, and tactics.[1,7,8] Many of the problems identified are continuing issues for military operations in the Arctic today. Improved personal protective equipment (PPE) and training in its proper use still leads the list of challenges. Cold weather protective clothing is still cumbersome, and the hobbling effect of bulky and restrictive clothing increases energy costs for the soldiers by at least 10%.[9,10] This is further complicated when personal protective equipment for CBRNE or body armor is also required.[11] Hands and feet are particularly vulnerable to performance impairment and injury in the cold.[12–16] Soldiers want a better hand protection system that provides thermal protection but permits greater dexterity; large mittens alone do not suffice.[13] Protection of the hands in extreme cold has been the subject of many studies but control of peripheral vasoconstriction is still elusive. Norwegian studies of cold-induced vasoconstriction indicate large variability in reperfusion of the fingers in healthy normal soldiers.[17] This may be a predictor of risk, as Swedish soldiers slowest to recover perfusion of their fingers were at higher risk for CWI during 15 months of field training,[18] while cold pressor tests measuring more systemic responses did not predict CWI in Swedish cadets and Canadian soldiers.[19,20] Moisture is a special problem in the cold, increasing risks of hypothermia and serious medical threats such as trench foot, produced by extended exposure to damp cold conditions in a boot.[21] Cold-wet issues can be mitigated by better equipment design but, most importantly, involve training to prevent these problems, such as work pacing and proper self-management. Key research and technology problems related to equipment and training are summarized in Table 1.

Table 1
Research and technology wish list for human performance enhancement in Arctic operations.

1	Increased hand protection, enabling manual dexterity and reducing freezing cold injury risk (including methods to increase peripheral blood flow to warm extremities)
2	Sweat management system/fabrics in clothing and boots
3	Biologically-based thermogenic strategies to prevent hypothermia (e.g., effective protocol for cold acclimatization; dietary supplements that increase nonshivering thermogenesis)
4	Wearable physiological monitoring that functions in extreme cold
5	Non-fog goggles and better face protection
6	Virtual reality team training for safe indoctrination of novice soldiers to Arctic operations and the concept of "comfortably cold"
7	Protective shelters with low thermal signatures and new heater/stove technology for rapid and efficient warming, heating water, and drying of clothing (with reduction of fire and CO risk)
8	Medical treatment protocols and medical equipment for traumatic care in the Arctic

Arctic military training is multi-faceted and consists of teaching basic Arctic survival techniques, creating a survival plan, wearing and maintaining personal protective equipment, building shelters, guidance on how to keep warm as well as to avoid overheating, avoiding cold injuries, first-aid, and being prepared for the psychological and mental challenges of being in the Arctic. Arctic warriors require a reset of expectations with a mental preparation to be "comfortably cold," and an understanding of the difference between discomfort and critical signals that require prompt corrective action. For Canadian Arctic troops, these are part of a standard training curriculum which is required before deploying to the Arctic. Preparation for exercises such as Guerrier Nordique (Nordic Warrior) require equipment shakedowns, tent set up, stove craft, and extensive hands on training. Decades of lessons learned have taught the military that "the average untrained soldier is worse than useless in harsh Arctic conditions."[1] This observation was reenforced in a recent Arctic exercise where unprepared soldiers had to be evacuated due to multiple injuries and inability to operate in the extreme cold in the first days of the exercise resulting in abandoning the exercise to focus on basic training ([name redacted], unpublished observations, 2019). Unlike almost any other environment into which soldiers may be sent, the Arctic is unforgiving and unprepared soldiers will not be able to perform and may not survive.

Leadership is required to ensure that proper preparation is not sacrificed in a hasty attempt to meet the operational objectives—doing so in the unpredictable Arctic conditions can quickly result in mission failure, injury, or death. Leadership is also critical to enforce appropriate behaviors (e.g. buddy checks for frostbite and prompt reporting of emergent problems); an emerging problem must be dealt with on the spot to prevent a much more serious issue thirty minutes later.[22] In this context, pre-deployment preparations also require the transmission of knowledge as they relate to the sociology, psychology and biology of cold weather operations.[22] For example, body size, ethnicity, and sex may affect performance, increase the vulnerability to injury and affect decisions about equipment and training requirements.

If there is one thing that has been learned from multiple military Arctic training exercises, it is that soldiers require training from experts, especially experienced native cold-dwellers such as the Inuit in the Canadian Rangers, and personal experience to learn how to effectively use their PPE in the extreme cold.[1] This training will give them the knowledge and understanding on how the clothing interacts with their own physiology, especially during periods of high activity or low activity where clothing layering is extremely important to avoid either sweating or getting too cold. This training will also inform them on what pieces of personal protective kit works better for them as some people require more protective kit than others or different style of kit. It is only through multi-day experience in the field in the Arctic that the level of experience required to safely and successfully operate in the Arctic can be gained.[23]

3. Assessment of current performance problems and risks for cold weather injury

Successfully operating in the Arctic requires complex planning, training and superior PPE equipment to help prevent cold-weather injuries (CWI) as temperatures in the winter can reach as low as −60 °C[12] resulting in bare skin freezing in less than one minute.[24] These factors are critical enablers for operating and performing their duties optimally as soldiers are faced with varying cold conditions with changing levels of activity (from riding snowmobiles to building snow shelters or constructing tents) requiring one to dress in multiple layers which can be shed or added to avoid sweating or freezing, both which could result in a CWI.[25]

In one study of 215 US and Canadian soldiers in a joint Arctic exercise at -21 °C (with windchill of -44 °C) that included airborne operations, the incidence of self-reported frostbite was 17%, and with physician assessment, as high as 21%.[26] Sullivan-Kwantes and Moes conducted a subsequent project relating PPE selection and risks of CWI, comparing issued and non-issued PPE worn by Canadian Armed Forces (CAF) in the Arctic. A total of 511 military personnel completed a survey to document the type of clothing selected and worn by deployed CAF members. Surveys also included self-reported official diagnosis of a CWI (hypothermia, frostnip, and frostbite) by the medical officer during the operation (unpublished observations). These CWI surveys recorded the injury, equipment worn during the time of the injury, and the mechanism of injury. Results from this study indicated that a high proportion of participants reported using non-issued liner gloves (72%), mittens (56%), hat (47%), socks (42%), thermal underwear (40%), boots (39%) and goggles (42%) either alone or in combination with issued kit. The predominant contributors to CWI were wet clothing, fatigue, dehydration, clothing items not providing adequate protection, snowmobile riding, and removing hand protection for increased dexterity for certain tasks. In sum, CWI incidences occur for several unrelated reasons, and to the extent that the issued equipment may be at fault, soldiers commonly augment their kit with store bought, and presumably untested, kit.[27] This highlights the need for common standards of protective clothing.

It is important to note that injuries like frost nip, frostbite, non-freezing cold injuries, and hypothermia can have immediate impact on the capability of a unit and can result in long term health implications or a permanent disability for the soldier [3,4,28] Training to recognize the warning signs of impending CWI is key to prevention with increased physical activity such as, changing damp clothing, adding protective equipment, or movement to heated shelter. High rates of CWI and under-reporting of CWI is common in current Arctic exercises.[28,29] Reasons for underreporting varied and included pride, not realizing they had an injury, and intentionally hiding the injury to avoid being pulled from operations.[17]

One consideration for the future is to include temperature and moisture sensing in some of the protective equipment to both alert novices to prompt action required as well as to continue to gain insights into how to improve the clothing, gloves, boots, and face protection. Wearable sensing could mature into real time physiological monitoring feedback to individuals and leaders to prevent CWI and sustain performance.[30] Development of physiological monitoring technologies that will operate in extreme cold field conditions and will not hamper safety and performance of the individuals presents a special set of challenges. This is part of the lessons learned over several years of experiments with Arctic troops monitored for glove and boot temperatures, where batteries failed, wires froze and broke, and there was a risk of injury from direct skin contact by cold metal sensors ([Name redacted], unpublished observations, 2018).

Specialized clothing designed around the needs of the extreme cold weather warfighter will be a performance enhancer to soldiers who have trained to use it to maximum advantage. A new U.S. Cold Temperature and Arctic Protective System (CTAPS) has been developed based, in part, on soldier user feedback following US National Guard participation in the Canadian Guerrier Nordique 2019 exercise; simplified layers, consideration to moisture problems, hood design, and external pocket access are vital new features. This improves on the design of the Extended Cold Weather Clothing System III (ECWCSIII) implemented for cold weather operations in 2007 which is excellent for cold weather but does not fully serve Arctic needs. Biophysical comparisons of US Army and Marine, Norwegian, and Canadian cold weather ensembles suggest a narrow range of strategies in preferred designs, preferred use of natural fabrics, and common requirements across countries.[31] The current major challenge in cold weather clothing is management of sweat and external moisture; this was highlighted in a comparison of three generations of Finnish cold weather uniforms where comfort is improved with the right combination of fabrics and layers to reduce friction and enhance moisture transfer in the inner layers, and also protect from external wetness.[32] A new boot system for Arctic operations (-20 to −60 °C) moves away from the old vapor barrier design and uses new insulation technology, addressing a critical need in foot protection as discussed in the cold-wet modeling portion of this paper. Native cold region dwellers such as the Inuit and Saami people rely heavily on animal fur for optimal Arctic protection, including ground cloths under sleeping bags and in mittens. As an example, wolverine fur ruffs on hoods help create a protective microenvironment around the face so far not duplicated by artificial fabrics, and there is an important science basis to support this traditional knowledge; a cold face causes vasoconstriction of the hands.[33,34]

4. Mobility and load carriage issues

Mobility in the Arctic can be particularly challenging, and movement is particularly hampered by snow requiring varying levels of energy expenditure depending on the terrain.[35] The various Arctic countries differ in temperatures and terrain and depending on the military operation, military movement over land may consist of snow vehicles, such as snowmobiles or soldiers traveling on skis or snowshoes; both require special training and equipment to be successful. Designs can be optimized for specific conditions and operations; for example, snow shoe choice can be based on snow conditions, intended movement, and loads with different energy costs.[36] In Canadian Arctic exercises, heavy equipment, fuel, and frozen ice for water is transported in traditional Inuit komatik sleds. In Norway, the dismounted soldiers in the squad usually use backpacks for the equipment and supplies that they need to transport and sometimes a pulk that the soldiers pull behind them, alternating the task between team members. The pulk is a shorter version of the ahkio used by some armies; both are a form of sled without runners. In a flat landscape, it is an advantage to have pulk compared to a backpacks.[5] However, in more hilly terrain this is not so obvious. Therefore, it is of importance to understand how the soldiers in a squad manage to move through more hilly terrain with a pulk each and with no backpacks. Here we summarize the results of a previously reported test.[37]

Eight soldiers from two different squads, four from each made two different groups. They participated in the two days study and Group 1 was skiing with pulk the first day and with backpack the next and Group 2 the other way around (Fig. 1). Previously they had been on a field exercise over 6 days, mainly skiing with packing. They followed a track in hilly terrain along the Russian border in Norway close to Elvenes. The weather conditions were good with temperature about -6 to −8 °C, wind below 5 m/s and no precipitation. Heart rate, core temperature, and skin temperature (chest) were measured (Equivital Hidalgo Ltd) and also distance, average speed, weight of pulk/backpacks and vertical movement. Soldiers were also surveyed about their preference.

Average speed for the two groups was 1.7 and 1.0 km/h (pulk) and 2.3 and 1.4 km/h (backpack) with corresponding mean weights of 47 ± 7(±SD) and 34 ± 5 kg (pulk) and 28 ± 3 and 21 ± 2 kg (backpack). The mean vertical movement for the two groups with pulk were 410 m uphill (ascent) and 340 m downhill (descent) and the corresponding results for backpack were 435 m and 375 m, respectively. Average heart rates combined for both groups ($n = 8$) were increased from 107 ± 5 (backpack) to 117 ± 9 (pulk) (paired t-test, $p < 0.05$). Average core temperature combined for both groups were 37.7 °C + 0.2 ($n = 6$, pulk) and 37.6 °C ± 0.2 ($n = 7$, backpacks) (N.S). Figure 1 shows an example of heart rate and core temperature over the two days for one soldier. Chest skin temperature was significant lower for pulk compare to backpacks (~3 °C) ($p < 0.05$). The result from the survey (questionnaire) showed that 67% of the soldiers preferred the pulk, 33% preferred a combination of pulk and backpacks, and nobody wanted a solution only based on backpacks.

Based on the monitoring in the field in this study the soldiers with the pulk could take about 50% more weight with them compared to backpacks; however, speed decreases by ~25-30%. Based on heart rate responses, physical load increased by ~10%. Chest skin temperature decreased by ~3 °C probably due to increased ventilation in the clothing. It was easier to open up the lining of the upper body when walking with a pulk compared to a backpacks. Most soldiers prefer the pulk. For Arctic operations, some kind of sled (ie., pulk, ahkio, or komatik) is useful and efficient for transporting loads.

5. The cold-wet problem – the bane of arctic warriors

Management of sweat in cold environments is a key trained behavior important to prevention of cold injury.[38] In Arctic operations, this involves smart pacing of physical work, managing clothing layers, and paying attention to damp socks and gloves. Better understanding of cold wet tolerance limits is important for predictive models of cold tolerance for military planning or real time performance limits. This is produced in the form of predictive models that can be used by military planners or in real time. One example of useful cold predictive models, is the wind chill index which is widely used for guidance in operational settings on risk for frostbite of exposed skin.[39,40] For more elaborate guidance, heat balance models can be used that require input on clothing level, activity level and environmental conditions to provide output on duration limit to performance loss, duration limit to hypothermia, as well as the required clothing insulation to prevent hypothermia or sweating.[41,42] In general guidelines are aimed at keeping clothing dry – or assume clothing is dry.[43] However, wet clothing can greatly increase the impact of cold weather conditions.[44] Moreover, during military operations clothing can get wet by both internal and external factors such as sweating, rainfall or wading through water. Therefore, it can be operationally relevant to have an indication of the impact of wet *vs.* dry clothing on safe duration of exposure.

At the ICSPP 2020 meeting, the Wet Equivalent air Temperature (WET) was proposed.[45] WET is the steady state effective air temperature for dry clothing which results in equal heat loss to exposure to the actual air temperature for wet clothing. With respect to interpretation it is comparable to a 'feels-like'-index that can be used as input in other models as a proxy to estimate the effect of wet clothing. The dry and wet duration limits provide a bandwidth of safe operation time. For instance, existing guideline IREQ-ISO-11079 provides insight on required insulation and safe exposure duration (DLE) but assumes the clothing is dry. The wet DLE can be estimated by substituting air temperature with the WET-index. For instance, a guard standing in an 18 °C, 50% relative humidity, 1.0 m/s wind environment, the DLE is greater than 8 hours. However wet clothing can cause an equivalent heat loss as if air temperature were WET = 8 °C, and that significantly reduces the wet DLE to 2 hours. WET is calculated by adapting the heat balance model described in Parsons.[46,47] Wetness of clothing influences the heat balance in three ways: clothing insulation decreases by replacing air with water; evaporation from skin tissue becomes negligible if there is no air medium for evaporation to take place; and clothing temperature decreases due to increased evaporation at the clothing surface.

To account for these effects, clothing wetness (wcl) is used as analogous to skin wetness.[44] Dry clothing assumes the value 0 ($wcl = 0$) and wet ($wcl = 1$). Based on an empirical study wet clothing insulation ($wcl = 1$) is linearly interpolated with 40% reduction in dry clothing insulation for fully wet clothing.[46] Evaporation of skin tissue is scaled with clothing wetness ($Esk_{wet\_clothes} = (1\text{-}wcl)\ Esk_{dry\_clothes}$). Evaporation from wet clothing is formulated analogous to evaporation of sweat from the skin, using wcl instead of wsk. Fig. 2 shows an individual example of measured mean skin temperature (4 positions ISO, neck, scapula, abdomen and calf) and predicted mean skin temperature of the model for three levels of clothing wetness. The individual is dressed in BDU and standing in a 19 °C, 40% relative humidity, 0.1 m/s air speed environment.

The application of this conceptual biophysical model to Arctic conditions needs to be explored next. Rapid freezing of sweat within the clothing adds yet another level of modeling complexity. Another modeling challenge is to predict risk of trench foot injury from the interaction of temperature, water, and duration of skin exposure in a boot.[48]

6. How important is body morphology and composition in insulation?

A basic understanding of how human thermal physiology may differ according to body morphology and composition is useful in estimating the performance of soldiers operating in cold climates. Body size and shape influenced by adaptation to hot and cold environments have been the subject of many published studies, including many centered on the Bergmann and Allen rules that cold-dwellers have larger and rounder bodies to preserve heat.[49] With further study, these relationships are more complicated, influenced in modern times by other factors.[50] Body fat insulation follows more complicated rules as well; specifically, Inuits, have been reported to have lower body fat content in relation to body size.[51] In non-human species such as elephant seals, a high

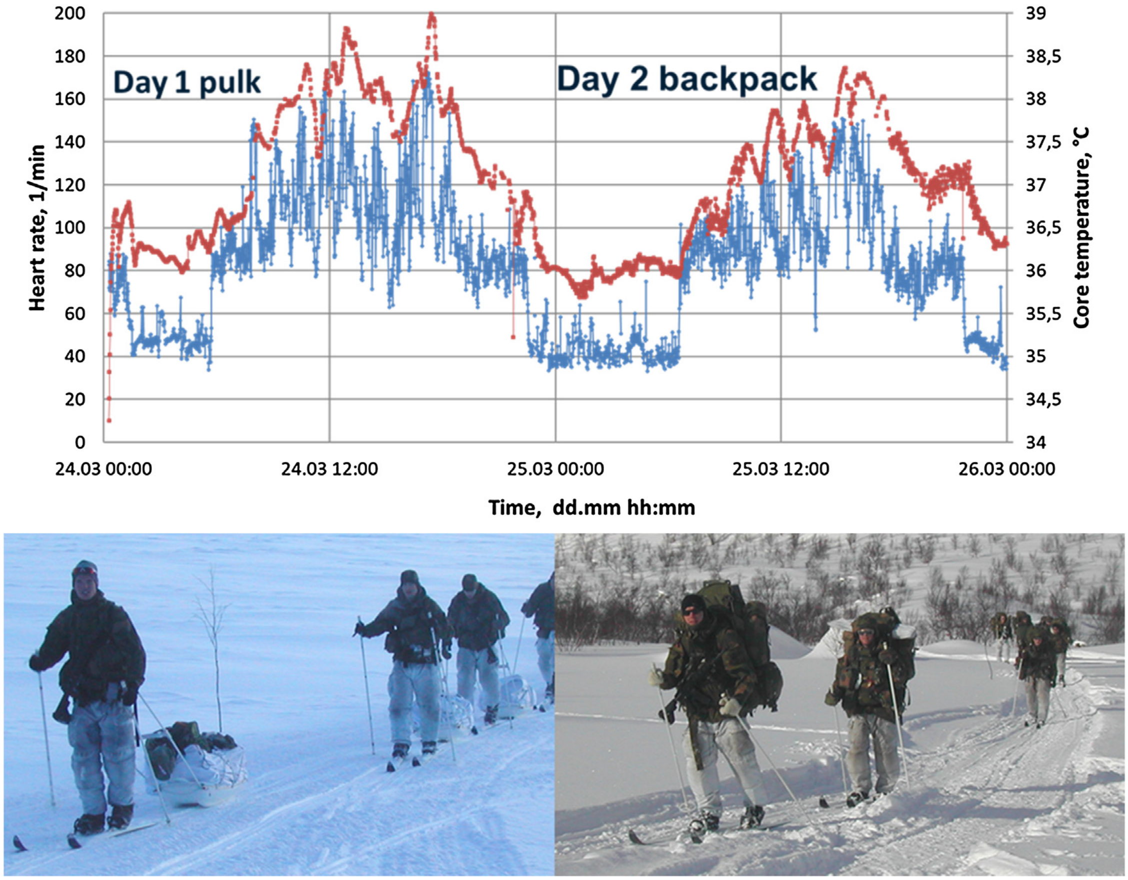

Fig. 1. Norwegian soldiers with pulks (left panel) and backpacks (right panel). Typical heart rate (blue dots) and core temperature (red dots) response during the two day study is shown for one soldier (top panel).

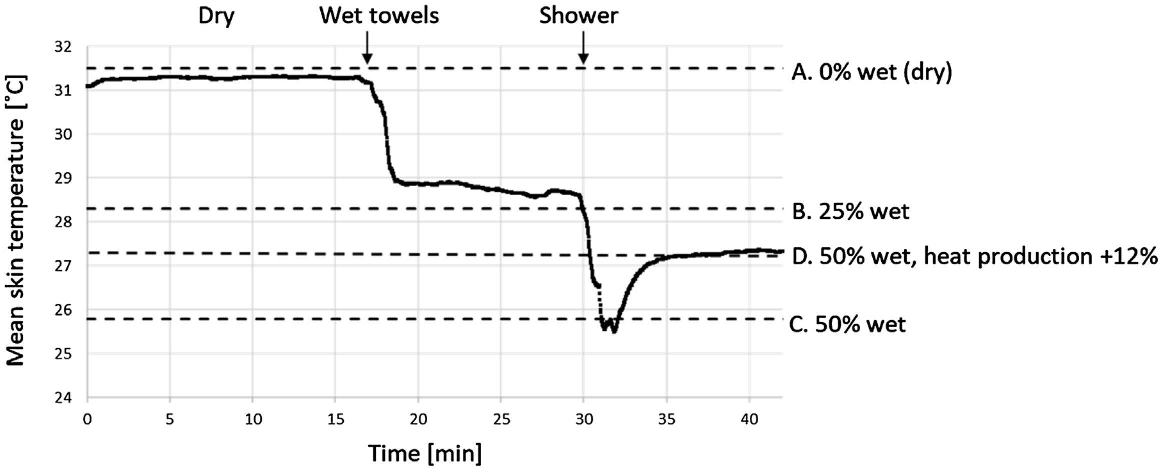

Fig. 2. Measured mean skin temperature (solid line), and simulated mean skin temperature (dashed line) for A) 0% clothing wetness, B. 25% clothing wetness, C. 50% clothing wetness, D. 50% clothing wetness with 12% increase in metabolic heat production to reflect cold-induced thermogenesis (e.g., muscle tension, brown adipose tissue, or other). Measured water temperature is 17 °C.

fat content appears to include an important subcutaneous insulative role for protection in cold environments.[52] One could ask “do higher body fat troops have a similar performance edge as Arctic warriors?” In a recently published study, Brychta and colleagues investigated the question with a 13-day protocol in an environmentally-controlled setting.[53] Using a whole-room indirect calorimeter, resting energy expenditure was measured in 12 lean and 9 obese healthy, young (25 ± 6 years old), lightly clothed (0.36 clo), fasted men on each day during a 5 h exposure to a different constant ambient temperature, randomized between 16-31 °C. Skin and core body temperature, muscle activity, and other physiological responses were also measured as well as subjective scales of thermal comfort. The volume and activity of brown adipose tissue (BAT) was also measured with 18F-Fluorodeoxyglucose positron emission tomography-computed tomography (PET-CT) after exposure to an individualized coldest tolerable ambient temperature.

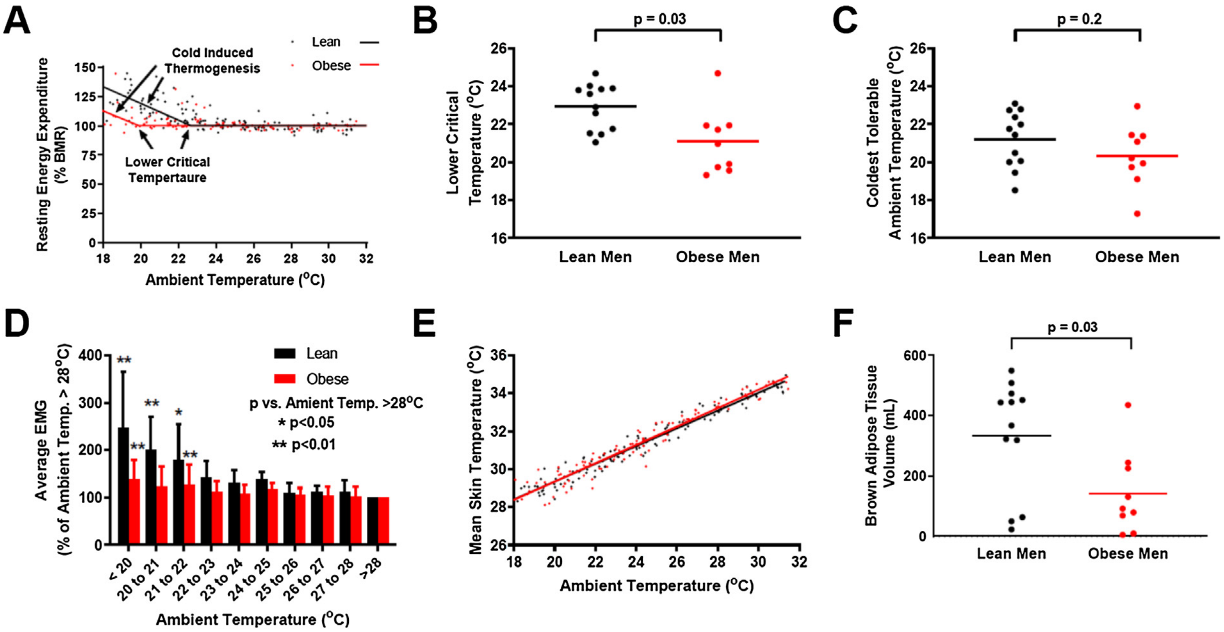

Fig. 3. A. Resting energy expenditure normalized to basal metabolic rate (BMR) as a function of ambient temperature with group branched-regression models for 12 lean men (black) and 9 obese men (red). B-C. Lower critical temperature is warmer in lean men than obese men (B), but both groups have similar coldest tolerable temperature before overt shivering (C). D. Nonvoluntary muscle activity, as quantitated by the root mean squared (RMS) surface electromyogram (EMG) averaged from four muscle groups (Pectoralis Major, Trapezius, Biceps Brachii, and Rectus Femoris) during motionless periods, at the indicated ambient temperature and expressed as a percentage of average EMG activity at ambient temperature >28oC. E. Linear regression models of the weighted mean skin temperature as a function of ambient temperature were similar for lean and obese men. F. Brown adipose tissue volume was greater for lean than obese men. Source: Brychta et al.[53]

This study demonstrated that all subjects had a temperature range where resting energy expenditure was minimal, defined as the basal metabolic rate (BMR, Fig. 3A). The temperature below which cold-induced thermogenesis occurred, the lower critical temperature, was colder in obese than lean men (21.1 ± 1.7 vs. 22.9 ± 1.2 °C, p = 0.03, Fig. 3B) but both groups reached similar coldest tolerable temperatures (20.3 ± 1.6 vs. 21.2 ± 1.5 °C, p = 0.2, Fig. 3C). At the coldest tolerable temperature, the additional heat produced above BMR for defending core temperature was less in obese than lean men (125 ± 146 kcal/day or 6 ± 7% of the BMR vs. 300 ± 218 kcal/day or 17 ± 11%, p = 0.01). Muscle electrical activity confirmed that shivering initiated at the lower critical temperature for both lean and obese men (Fig. 3D). Core and weighted-mean skin temperatures (Fig. 3E) varied similarly with ambient temperature in both groups, but obese men had cooler proximal and warmer peripheral skin temperatures in the cold. Cold-activated BAT volume was lower in the obese vs. lean men (130 ± 121 vs 334 ± 162 ml, p = 0.03, Fig. 3F), but did not correlate with the individual cold-induced thermogenesis. This suggests that BAT activation was not a critical factor in the differences in heat production between obese and nonobese subjects.

The findings that obese men did not tolerate colder temperatures better than lean men suggests that any additional insulation provided by greater body fat was offset by less cold-induced thermogenesis in the obese men; this did not, however, examine placement of the fat between visceral and subcutaneous distributions. It further revealed that muscle activity began to increase at the lower critical temperature, and shivering became overt at temperatures only 1-1.8°C colder in non-acclimatized men during 5 hours of exposure.

7. Physiological (and behavioral) acclimation is actually possible

When Scholander reported his physiological studies of cold-dwelling natives (Saami) in the 1950s, he described a “semi-tropical” microenvironment in the study participants because of their protective clothing.[54] But, in other studies of humans exposed to cold it became clear that there are human strategies to adjust chronically (acclimate) to cold exposure, notably a rise in non-shivering thermogenesis and an improvement in physiological insulation.[55] In non-exercising individuals, total cold-induced heat production is obtained from the activation of nonshivering thermogenesis and shivering thermogenesis. Hypotheses about increased subcutaneous insulation in extreme cold water swimmers have been tested in Ama and Haenyeo diving women. The adaptive differences were not in body fat but in the metabolic responses, with increased thermogenesis and a hypothermic tolerance, with tolerated oral temperatures typically below 35 °C and as low as 30 °C, lower than classic studies of naked aborigines and channel swimmers.[56,57]

In adults, shivering is by far the greatest contributor of heat and activates almost 80% of total muscle mass.[58] While shivering is important to produce heat, it remains particularly uncomfortable and affects thermal comfort and work capacity by impairing motor skills and coordination.[59] Over the last decades, many researchers have attempted to identify the best way to increase nonshivering thermogenesis in order to decrease the relative contribution of shivering and muscle recruitment. Using a cold acclimation protocol comprised of 31 days, 8 h per day at ∼12 °C, Davis reported an 80% decrease in shivering intensity and a 15% decrease in total heat production compared to men acclimatized to summer conditions.[60] Almost half a century later, Blondin and his colleagues showed that shivering could be reduced by 20% when non cold acclimatized were exposed to 10 °C at 2 h

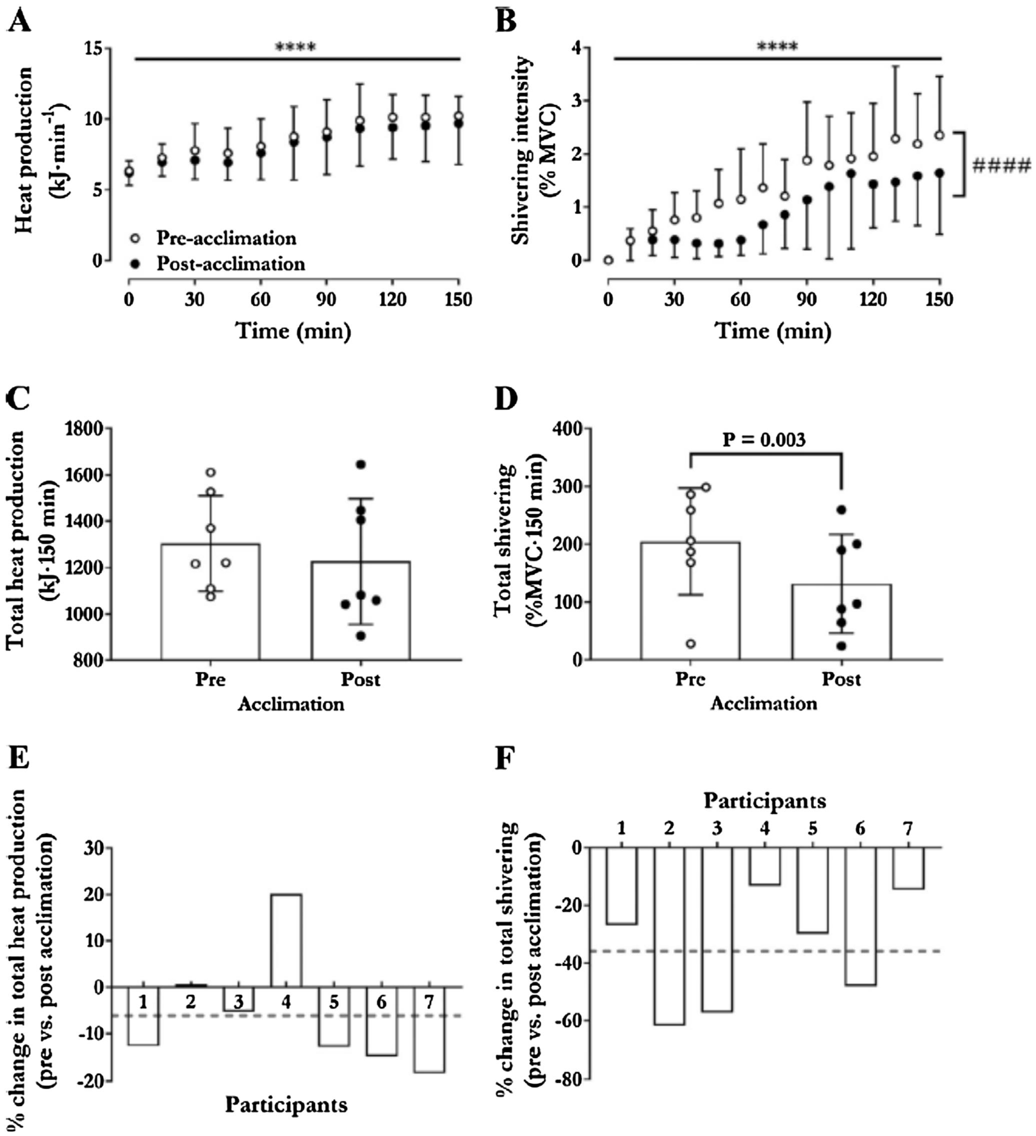

Fig. 4. Thermogenic responses to acute cold exposure before and after cold acclimation. Changes in rate of metabolic heat production (kJ/min) (A), shivering intensity [% maximum voluntary contraction (MVC)](B), total heat production (kJ·150 min)(C), and total shivering (%MVC·150 min)(D) during an acute cold exposure at a mean skin temperature of 26 °C. Percent change in heat production (B) and shivering intensity (F) from before to after cold acclimation for each participant. Source: Gordon et al.[59]

per day and 5 days a week for 4 weeks.[61] In the latter study, it was also shown that BAT volume and thermogenic capacity could be increased by 45% and 182%, respectively. This confirmed that BAT activation and the stimulation of other NST processes could modulate shivering activity in humans. However, Young suggested that the greatest cold acclimation effects could be obtained using uncompensable cold exposure where core temperature is reduced repeatedly.[62] To test this hypothesis and in an attempt to optimize cold tolerance response in a shorter amount of time, Gordon exposed non cold-acclimatized men to 7 consecutive days to 14 °C water for 1 h or until core temperature decrease to a maximum of 35.5 °C.[59] Results confirmed that substantial improvement in cold tolerance and a 36% decrease in shivering intensity (Fig. 4). Clearly, completing such a cold acclimation protocol requires great motivation but the outcome could be extremely beneficial for mission success and potentially, cold survival. In addition, this would expand the envelope of tolerable cold in military operations but especially for extreme cold in Arctic environments, taking advantage of cold acclimation mechanisms.

In addition to physiologically induced acclimatization, other strategies to promote nonshivering thermogenesis (and reduce the relative contribution of shivering to total heat production) have been investigated. Pharmacological enhancement has shown thermogenic benefits, notably the synergistic effects of caffeine (adenosine antagonist) and ephedrine (beta adrenergic agonist).[63,64] Pharmacologically-induced increase in brown adipose tissue appears to be possible, as demonstrated in a recent study with one month of high dose mirabegron administration.[65] The mechanism is being further investigated, with evidence that in humans the effect of this beta-3 adrenergic agonist is actually occurring through crossover activation of more conventional beta-2 adrenergic receptors.[66] Whether or not BAT content can make any important difference to cold weather performance for humans is yet to be determined. Comparison of the effect on cold induced thermogenic responses that might be produced by cold acclimatization strategies and by pharmacological enhancement remains an important question. Other suggestive but yet unproven concepts for research exploration include dietary and trained voluntary control of thermogenesis. Dietary supplements emerging from lab studies and others suggested from observations of native practices (e.g., consumption of seal liver high in retinoic acid) remain to be tested for performance enhancing benefits to Arctic warriors. Voluntary control of thermogenesis as practiced by Tibetan monks ("Tum-yo" yoga) is an area of investigation that would require an understanding of the brain regions involved in order to develop biofeedback targets for a soldier virtual reality training tool, in order to train voluntary control of thermogenesis that has been mastered by Tibetans only through years of practice.[67]

8. Conclusion

The Canadian Rangers have an Inuktitut word for operating in the Arctic: ihuma. Ihuma translates into wisdom, reason and knowledge and is taken to mean achievement of individual competence in Arctic survival along with the ability to lead others in the Arctic.[1,68] The various perspectives presented in this thematic session during the International Congress on Soldier Physical Performance 2020 address challenges faced by the military in the Arctic and, together, bring us closer to optimizing human performance in extreme conditions. However, a fuller appreciation of the factors that contribute to human performance, survival and thriving during military operations depend on our ability to integrate those perspectives to create a holistic understanding of how the human, the environment, training, leadership and the equipment interact to either facilitate the success of missions or put them at risk for failure. Paying attention to lessons learned and using a scientific approach to understanding the challenges of Arctic operations go a long way to generate knowledge through an application of measurements and reason. The last piece, wisdom, includes an understanding that others have valuable knowledge and practices that, while not necessarily based in science, have centuries of proven effectiveness by those who apply them. The lessons learned and practical guidance from the Inuit and other indigenous people who live in the Arctic have significant place among the equipment, techniques, and tactics our militaries have developed to handle extreme temperatures.

Disclaimer

The views and opinions presented in this manuscript are solely those of the authors and do not necessarily represent any official policy or position of the represented agencies.

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