Chapter 6: Rationalizing the Approach to Mitigate Soldier Physical Burden

Are Iron Man or Captain America the Magic Bullet?

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Rationalizing the Approach to Mitigate Soldier Physical Burden: Are *Iron Man* or *Captain America* the Magic Bullet?

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Throughout history, the dismounted soldier has had to carry heavy combat loads while marching long distances under very demanding terrain and environmental conditions. While they can doff their packs and much of their sustainment load once they arrive at their objective, they must still be fit to fight while wearing significant assault or fighting loads. As General Marshall noted, the infantryman is "a beast of burden" but his chief function in war does not really begin until he delivers that "burden" on the objective.[1] This chapter introduces this section's topic of "easing the burden," presenting the enduring problem of soldier physical overload, characterizing its prevalence, severity, causes, and consequences, and then examining the potential for Human Performance Enhancement (HPE), deliberately increasing human potential, beyond that accomplished naturally, to help mitigate the problem. In contrast to many other chapters in this volume, this chapter suggests many alternative, perhaps simpler, more cost-effective, and more readily acceptable solutions that could, and probably should, be exploited before HPE is developed sufficiently to successfully mitigate physical overload, at least for the dismounted soldier in the near-term.

HISTORICAL AND ENDURING PROBLEM OF OVERLOAD

Soldier loads have increased throughout the ages,[2] so concern about soldier overload is not new. Studies to determine maximum soldier loading go back over a hundred years and, based mostly on physiological response, conclude that the soldier should not carry loads of more than one-third of their body weight.[3] Most militaries recommend slightly lower doctrinal fighting loads of 30 per cent of body weight, recognizing that load carrying ability will be compromised by operational stressors,[4] and allow for higher marching or administrative move loads at 45 per cent of body weight for the average soldier.[5] The question of how much load a soldier can, or should, carry is a complex one to answer and depends on so many soldier system factors: the soldier's own capabilities, the clothing and equipment worn and carried, their missions and tasks, and the environment in which they must operate. The question is therefore unlikely to be answered with a single number reflecting percent of body weight.[6] It is interesting to note that load limit guidelines for mules and horses (actual "beasts of burden") are limited to less than these typical soldier doctrinal soldier loads[7] when their energy expenditure to carry loads is significantly less than that of humans,[8] and they, unlike soldiers, are not required to go into battle when they have delivered their loads to their objective.

THE PRESENT-DAY OVERLOADED SOLDIER

The "beast of burden" analogy[9] persists in the terminology used today; overload of soldiers due to equipment weight has been associated with the term "soldier burden" across many allied nations,[10] and scientific literature refers to load weight almost exclusively when burden is discussed. The authors believe that this term should be defined much more broadly than equipment weight. It should integrate combined and cumulative impact of all stressors, physical or psychological, imposed on the dismounted combatant, if only to draw attention to the myriad of contributors and potential mitigating strategies for soldier burden. Stressors include: environmental, such as extremes in temperature, humidity, altitude, precipitation; metabolic, due to work performed; load or equipment properties, not limited to mass, but also considering mass distribution, coverage, bulk, stiffness, breathability, thermal resistance; as well as psychological, such as mental workload, fatigue, and combat stress. The focus of this chapter is on physical stressors and physical burden mitigation, though it is recognized that these will certainly be exacerbated by the simultaneous presence of the psychological stressors faced by our soldiers on operations.

The loads carried by soldiers today are at record highs.[11] Figure 6.1 shows the typical load carried by dismounted Canadian infantry soldiers, by role, during recent operations in Afghanistan. Required items of equipment or supplies were determined through consultation and consensus building with a group of six multi-deployment-experienced staff and instructors serving at the Canadian Army's Infantry School (at the Combat Training Centre, Gagetown, New Brunswick). Data in figure 6.1 refer to a short-range patrol scenario of less than four hours duration, under temperate conditions.

Clearly, soldier loads are well above the established maximum loads of 30 per cent and 45 per cent of average body weight for fighting/assault loads and approach march loads, respectively. For perspective, the percentage body weight values translate to 26.04 kg and 39.06 kg, based on the average Canadian male combat arms soldier body weight of 86.8 kg.[12] In figure 6.1, the Section Commander's load is at 65 per cent of the average soldier's body weight, more than double the recommended maximum. However, not all soldiers are average, so even these load limits, if followed, would further burden all those soldiers who are below the average body weight. While clothing and much personal protective equipment (PPE) may be sized to soldiers, and therefore lighter in weight for smaller soldiers, many of the heavier items carried – such as weapons or ammunition – do not cater to the variability in soldier size and load-carriage capacity. To make matters worse, soldiers rarely train for operations with loads representative of those carried on operations. This often leads to soldiers dealing with serious physical overload for the first time in an operational theatre along with many other new operational stressors. It is no wonder that many allied nations are trying to tackle the problem of soldier burden with high priority.

WHY SUCH HEAVY LOADS?

A number of factors have likely contributed to the increase in combat loads over time. While perhaps counterintuitive, technological innovation is more likely to have added to the soldier's load than reduced it, because of the new capabilities offered.[13] Soldier modernization programs have fielded important new technologies and capabilities down to the individual soldier level (e.g., GPS, soldier radios, night vision equipment, weapon-mounted sensing, aiming and illumination aids, underslung grenade launchers, breaching equipment, or electronic

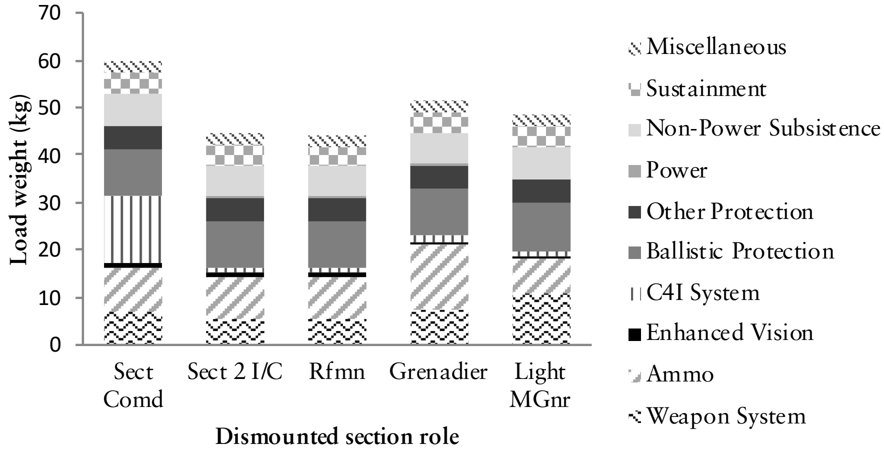

Figure 6.1 Consensus on Canadian dismounted infantry loads, by dismounted infantry section role, for a typical Afghanistan mission.

*Horizontal lines represent maximum recommended or doctrinal loads for the average soldier weight (86.8 kg): the upper blue line represents 45% of average body weight for administrative moves or marching order, and the red line represents 30% of body weight for patrolling, advance to contact missions or fighting order. (Sect Comd = Section Commander, Sect 2 I/C = Section Second in Command, Rfmn = Rifleman, Light MGnr = Light Machine Gunner).

countermeasures). Most of these new capabilities require power, and since batteries are not standardized across equipment procurements, soldiers must now carry and manage multiple types of batteries, adding to their burden. The nature of counter-insurgency and adaptive dispersed operations can make re-supply difficult, particularly in immature theatres of operation. Sustainment loads of consumables (such as ammunition, batteries, food, and water) may be higher than ever due to a lack of confidence in re-supply, real or imagined. Potable water loads are also higher due to the hydration requirements imposed by hot climates, as experienced on recent operations. Finally, our soldiers are wearing more PPE, or body armour, as a result of the emergence of new threats such as Improvised Explosive Devices (IEDs). While intended to enhance survivability, the PPE is burdensome by nature, adding significant weight, restricting movement, increasing ensemble bulk, and interfering with normal heat dissipation.

The overload situation may well be due to many other long-standing reasons that others have identified,[14] including: lack of appreciation for the dangers of and how to mitigate against overload; concerns about injuring soldiers in peacetime by undertaking more operationally realistic training; fear of not having critical supplies in the rare event they might be needed; anxiety over having to justify making a balanced risk decision and ordering men to reduce their protective posture when conditions really do warrant this; lack of sufficient airlift or ground transport; or failure in leadership to do proper mission-specific load planning or to provide clear guidance and monitor its enforcement.

Several nations have PPE that is designed to be modular or scalable in nature, as well as doctrine that permits adoption of armour protection levels with varying degrees of encumbrance[15] to take into account mission, environment, terrain, and threat conditions (METT-C). The extent to which other nations' soldiers actually modify their protective posture to balance protection with the risk of burden-related injuries or performance decrement is not well-documented, with the exception of one United States Marine Corps (USMC) command and staff college paper.[16] That paper supports what we have heard in focus groups with Canadian soldiers – that armour protection level decision-making in recent counter-insurgency operations was not typically delegated down to tactical units, and that orders were typically to maximize protection at all times. This may reflect lack of awareness of the consequences of overprotecting, and lack of appreciation for the fact that passive protection should be one's last resort in terms of integrated survivability. While some authors argue that overload can be dealt with through effective leadership (i.e., better load planning and enforcement of mission loads)[17] (Marshall 1950, Ezell 1992, Townsend 1994), it may well be that there is insufficient knowledge about the causes and impact of overload and burden, the trade-offs between loads, task performance, injury risk, operational impact, and the strategies needed to effectively deal with these.[18]

WHAT ARE THE RISKS OF OVERLOAD?

Soldier load carriage has been studied for more than a century so there is much evidence of the impact and risks of overload. Scientific literature is replete with evidence of increased physiological strain in response to increasing soldier load weight (for a summary see Knapik and Reynolds 2012). Whether loads are carried in packs, worn on the torso, or carried in the hands, as load weight increases, so too do many indicators of physiological strain, including: the metabolic or energy cost,[19] heart rate,[20] respiration rate,[21] muscle activity,[22] and blood lactate levels.[23] Increases in physiological strain can lead to more rapid onset of fatigue, degraded performance, and increased risk of over-exertion or musculoskeletal injury. There may also be increased risk of heat casualties, if soldiers are carrying loads while operating in challenging conditions such as high heat and humidity, altitude, steep, uneven or soft terrain,[24] or at a fast pace, especially if encumbered by PPE.[25]

Load carriage literature also reveals significant impact on movement biomechanics with increasing soldier load weight (for reviews, see Orr, Johnston, et al. 2012; Knapik and Reynolds 2012) regardless of how loads are carried (in backpacks, on the torso, or borne by the extremities). Any load-related changes to gait or movement biomechanics are important as they can not only impair mobility performance, but also lead to increased discomfort, musculoskeletal injuries,[26] as well as the longer-term risk of osteoarthritis.[27]

Several detailed reviews[28] summarize the following medical implications of load. After foot blisters, the most common load-related injuries are musculoskeletal, affecting the lower limbs (e.g., localized pain, strains, sprains and stress fractures, and several nerve compression injuries that cause numbness, tingling, pain, weakness or temporary paralysis).[29] The back is the next most common site for load-induced injury, with low back problems likely related to exaggerated body lean angles associated with heavy pack loads, as well as the asynchrony with which heavy loads move with the body.[30] Rucksack palsy, a common debilitating injury associated with backpacks, results from entrapment of the brachial plexus by the lower shoulder strap in the armpit.[31] Body armour may also contribute to increased risk of overexertion[32] or heat illness[33] due to its weight, coverage of the body with non-breathable materials that hinder heat dissipation, and inherent stiffness, requiring increased effort to overcome restrictions to movement.[34] Soldier overload has contributed to spiralling numbers of musculoskeletal injuries, resultant disability payment costs,[35] loss of combat-readiness, and perhaps even casualties or fatalities.[36] The incidence and severity of the problem is unknown, since medical records rarely record the context of operational or occupational injuries in sufficient detail to relate to equipment worn or loads carried.

The literature provides unequivocal evidence of impairments to military-relevant physical task performance with increasing load weight,[37] regardless of how that load is carried by the body. Significant performance decrements with increasing load have been demonstrated for operationally relevant mobility tasks such as marching,[38] distance running,[39] high intensity explosive sprints or agility runs,[40] and obstacle or combat mobility course completion.[41] More recently, performance for more tactically relevant movements such as bounding rushes, manoeuvre under fire (MANUF), or break contact drills has been shown to be significantly affected by load weight.[42]

An early study[43] and several recent reviews[44] concluded that for every kilogram of load, one can expect to see approximately 1±0.5 per cent decrement in mobility performance (straight runs, mobility/agility or obstacle courses). This decrement is surprisingly consistent considering the range of task methods, load conditions, and participants involved in those studies. This may not seem like much of a decrement, unless one considers by just how much soldier loads exceed recommended limits, and just how vulnerable soldiers may become when slowed down while under enemy fire. Several researchers have demonstrated, at least in a few limited scenarios, that load-induced mobility decrements significantly affect soldier susceptibility to enemy fire.[45] Intuitively, at least, this seems linked to ultimate survivability on the battlefield and perhaps even mission success.

Even perceptual and cognitive task performance could be impacted by physical overload. Although less equivocal than studies of the physiological, biomechanical, medical, or physical task performance impacts of load, several studies have indeed demonstrated that, with increasing physical load, decrements in perception (i.e., of threats), or impaired cognition (i.e., understanding or retention of orders) are indeed possible,[46] contributing to the risk that overload could have on soldier survivability or mission outcome.

IS SOLDIER AUGMENTATION OR ENHANCEMENT THE SOLUTION?

Might human performance enhancement (HPE), as defined and described by the editors and previous chapter authors, offer the solution to the problem of soldier burden and overload? Let us first examine the potential for biochemical HPE, as categorized in chapter 3.

There probably isn't an international level sport that isn't concerned about the use of performance-enhancing substances by its athletes looking to gain the decisive edge needed to win. Can and should such substances be exploited for official military use to increase soldier capabilities beyond what is achievable naturally? Anecdotally, soldiers may already be using steroids and other substances on their own in spite of policies and health warnings that discourage the abuse of such substances.[47] Some countries actively invest in research to develop or better understand the performance and health implications of ergogenic aids. The U.S. Army, for example, makes available to its soldiers "Hooah" caffeine gum to counter the effects of fatigue on operations.[48] It is one thing, however, to turn a blind eye to individual use of performance enhancing substances, or to make available a commonly ingested substance such as caffeine in a readily ingestible form. It is quite another to develop, produce, issue, and require the use of performance-enhancing substances by armies to achieve the decisive performance edge needed in battle. Unfortunately, even systemic use by the military of life-saving pre-treatments or antidotes has proven controversial and not without risk (e.g., use of potentially life-saving nerve agent pre-treatment tablets has been associated with Gulf War Syndrome; anti-malarial treatments with psychoses; anti-mosquito permethrin treatments of fabric with other health issues).

What about the potential for more invasive, more permanent HPE such as that employed in the movies to create Captain America? Biotechnology and genetic engineering approaches, discussed in the previous section of the book, offer the opportunity to create "super human soldiers" who are more effective on operations, better able to carry loads, further, faster, longer, with perhaps less potential for acute musculoskeletal injury and more resilient to the stresses of combat[49] though it is doubtful that bioengineering future soldiers could ever be seriously considered as a solution for overload given the likely myriad of associated legal, medical, moral, and ethical issues previously presented by at least one author[50] and discussed throughout this book, and specifically in chapters 10 and 11.

Surely less invasive and less-permanent HPE alternatives should be considered as the solution to soldier overload and burden. For example, for over a century, scientists and engineers have been developing exoskeletons in an effort to augment or enhance human movement,[51] and interest in their application to mitigate soldier burden has increased dramatically in the past ten years or so, as highlighted in chapters 2 and 7. As described in chapter 3, exoskeletons arose from rehabilitative medicine (to assist injured or disabled wearers regain normal limb function and mobility) and they are now being exploited to assist able-bodied wearers perform mobility tasks beyond normal human capabilities. Once considered science fiction and depicted only in movies such as "Iron Man," this technology has made its way into mainstream science. Typically highly customized, close-fitting, wearable assistive devices that may or may not be powered, exoskeletons, sometimes called exosuits[52] or dermoskeletons,[53] are intended to act in concert with the wearer's movements, to augment wearer performance, enhance their load-carrying capacity, strength and/or endurance.[54] They may have rigid framing elements, intended to transfer external loads to the ground[55] or they may be soft, compliant, biologically inspired "exosuits" and assist normal muscular action through actuated cables.[56] Might an "Iron Man"-like suit[57] or exoskeleton be the solution, the "magic bullet," to the problem of soldier overload?

Well-funded U.S. government research programs are exploring the potential for exoskeletons to help soldiers carry their extreme loads more effectively, or help them carry more, and thereby improve soldier mobility and effectiveness on the battlefield whilst reducing potential for musculoskeletal injury. The U.S. Special Operations Command Tactical Assault Light Operator Suit (TALOS) program aims to dramatically improve the protection of special forces personnel (i.e., maximize coverage of the body with armour) through the use of powered exoskeletons.[58] The U.S. Defense Advanced Research Projects Agency (DARPA) Warrior Web program, supported by the U.S. Army Research Laboratories (ARL), on the other hand, is developing a low-powered soft suit, intended to be worn underneath the uniform, to augment soldier load carrying capabilities and allow them to carry up to 100 pounds of equipment without risking joint and back injuries.[59] Multiple examples of exoskeletons exist worldwide, including but not limited to: Warrior Web;[60] Human Universal Load Carrier (HULC);[61] UPRISE;[62] Knee Stress Releaser Device (K-SRD);[63] Exo-buddy;[64] EXOS 2;[65] BLEEX;[66] or Hercule.[67] Many international defence research organizations are currently investigating the potential of such example exoskeletons for increasing soldier performance beyond that which is currently or naturally possible.

To date, many attempts to enhance human motor abilities with exoskeletons have failed. While there have been many claims of the potential of exoskeletons to reduce the energy cost of walking,[68] many cases have only compared energy costs of walking between powered and unpowered modes, and have not compared to the energy cost of walking without the exoskeleton. In other words, the systems have not been able to fully overcome the energy cost associated with carrying the extra weight of the system itself, so therefore, when worn, they actually *increase* the energy cost of walking.[69] As well, they induce significant changes to gait biomechanics,[70] which can lead to injury and even osteoarthritis, as mentioned in a previous section of this chapter. When wearing loads of twenty, forty, and fifty-five kg, use of one exoskeleton prototype actually increased energy costs to unsustainable work rates, even for healthy, young males.[71] While trial participants have perceived that exoskeletons make load carrying easier,[72] it is only very recently that researchers have been able to demonstrate real energy savings over unassisted walking on level treadmill walking with a soft unpowered exosuit,[73] hence the recent heightened excitement amongst defence organizations over their potential.

Challenges remain if exoskeletons are ever to become mainstream, particularly for dismounted soldier application, including: weight; power demands (though there is certainly potential for exoskeletons to also support power generation to a limited degree); uncomfortable interfaces; reliability and maintainability issues; requirement for customized fit; compatibility with wide range of soldier sizes, equipment, and tasks; and cost, to name a few.[74] Certainly, and as a minimum, exoskeletons will need to prove themselves under rigorous testing, a framework for which is described in chapter 7. It has been suggested that widespread implementation of worn assistive devices for burden mitigation in dismounted operations is at least a decade or more away,[75] though they may be implemented sooner for specific operators (i.e., special operations, infantry heavy weapons sub-units)[76] or in limited scenarios with frequent repetitive manual material handling, as in logistics functions, since they are now already being tested for their potential to reduce muskulo-skeletal injuries for lifting heavy load in commercial retail applications.[77]

If "Iron Man" or "Captain America" aren't going to solve these burdens, at least not in the short-term, what is the solution? The authors contend that the enduring problem of soldier burden will only soon be successfully mitigated through small incremental gains across a whole range of interventions. There is no magic bullet to this enduring hard problem; a soldier-centric, holistic, systems approach is needed.[78]

PROPOSING A SYSTEMS APPROACH TO BURDEN MITIGATION

Across many domains and applications, a systems approach considers the following to be the main interacting components of a complex, human-centric, socio-technical system, such as "The Soldier System"[79]: Technology/Tools, comprising all the technology, clothing, equipment worn, carried, consumed, or operated by the soldier; the User(s), representing the immense variability in the soldier population in terms of physical, physiological, or psychological characteristics and capabilities; the Tasks that soldiers must perform, whether physical, perceptual, or cognitive, in training or on operations; and the Environments in which soldiers must operate, including physical environments (temperature, humidity, precipitation, terrain, altitude, etc.) as well as organizational environments (policy, doctrine, leadership, discipline, organization, reward structures, etc.). Representative, though non-exhaustive, burden-mitigating strategies will be exemplified for each of these interacting "TUTE" system components in turn and are summarized at figure 6.2.

Tools or Technology Solutions

Whenever possible, getting the load off the soldier should be the primary goal. Alternatives to exoskeletons include: off-loading technologies such as carts,[80] manned or unmanned tactical carriers, vehicles, or robots.[81] Wheeled carts, whether attached to the soldier,[82] or simply assisted by the soldier,[83] have been studied, though they are not without challenges in terms of load stability and ability of the soldier to respond appropriately to threats when attached or handling them. A carrier, manned or unmanned, could carry section loads and combat supplies plus provide a source of power, recharging capability, casualty transport, and information collection (ISR), to name a few functions.[84] Autonomous follower load-carrying robots offer great potential for burden mitigation in the mid-term, presumably with less demand for soldier attention and intervention.[85] As is the case with exoskeletons, many of these high-tech off-loading solutions have challenges to overcome for the near to mid-term, particularly related to portable power, stealth, and ability to traverse very complex terrain under harsh weather conditions.

Advances in material science could lead to reductions in the weight (or bulk or stiffness) of individual soldier system components (e.g., caseless ammunition), although there is consensus that the most that can be expected is about 6–10 per cent.[86] Without accompanying doctrine and leadership, there is also concern that soldiers will simply offset any weight reductions by carrying more combat supplies such as water and ammunition. Incremental weight reductions

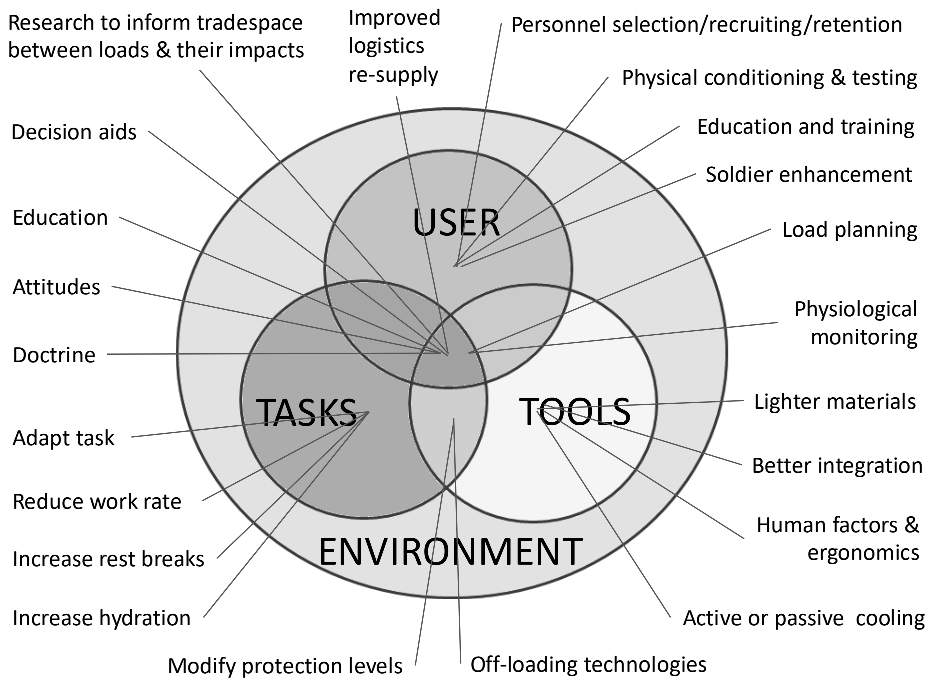

Figure 6.2 Summary of Interventions for soldier burden mitigation using a systems approach.

should be mandated for any acquisition of new equipment that replaces current capabilities, even if the replacement item has more functionality or capability. Recommended weight limits and centre of mass guidelines have been empirically developed for some soldier system components such as integrated headwear[87] or soldier assault weapons,[88] that reduce sub-system weight in order to reduce burden, and minimize discomfort or injury potential while ensuring acceptable combat task performance.

Alternative approaches to soldier equipment design and integration offer the potential to reduce the burden parameters of weight, bulk, and stiffness. Body armour weight burden may be reduced by 10–20 per cent by refining body armour requirements, improving testing reliability, and requiring more tailored, better-fitting armour.[89] Enhanced fit will also reduce ensemble bulk and stiffness. Modularity and scalability of armour protection can achieve as much as 20–45 per cent weight reduction,[90] if implemented along with doctrine, training, leadership, and validated decision supports to ensure its effective use. Additionally, while armies may save money by designing and buying one design or solution for all soldiers and all missions, this may actually compromise real potential for burden mitigation. Equipment that is specific to dismounted infantry and those soldiers most vulnerable to the risks of overload should be acquired with burden mitigation and optimized performance in mind, even if it comes at greater initial or through-life cost. Finally, where thorough work domain and task analysis show that it is warranted, consideration should be given to integrating multiple capabilities or functionality into one item, to avoid having a "Christmas Tree" approach to soldier system integration. If all soldiers need multiple capabilities for most missions, those capabilities should be integrated into one item to realize weight and bulk savings in housings, power supply, and controls (e.g., integrated laser aimers/illuminators).

Even simple load carriage equipment design and packing changes can help reduce burden (for a summary, see Joseph J. Knapik and Katy Reynolds, "Load Carriage in Military"[91]). Energy costs can be reduced for loads carried closer to the body's centre of mass, loads that are symmetric, or loads that move in concert with the body.[92] There are advantages of internal over external framed packs, as well as the use of pack hip belts.[93] Pack suspension strap design can help to reduce peak underlying tissue pressures[94] or shear forces on the spine.[95] Incorporation of stiffness elements into load carrying equipment can help transfer more of the load to the hips.[96] Any or all of these can reduce the incidence and severity of load-related health issues, such as rucksack palsy or lower back pain.

Mitigation of thermal strain through equipment design is paramount. Increasing air permeability of clothing and equipment (through materials, ventilation options, or modularity) will increase tolerance to heat by permitting more passive sweat evaporation.[97] Personal micro-climate cooling options have been successfully implemented for military personnel operating within vehicles or crew spaces[98]; technologies include active liquid- or air-cooled systems, and passive systems that employ phase change materials such as ice or salt,[99] or systems that transfer heat to the outside of the armour through conduction.[100] Few are currently suitable for dismounted operations due to a wide range of challenges: high power demands; requirement to be tethered to the cool air/liquid source and power supply; excessive system weight; inefficiency or short duration of effectiveness; and burden imposed by the cooling vest or carrier when not active.[101] However, intermittent cooling, an option for soldiers supported by a carrier or robot, may be highly effective for situations where workloads are intense and where tethered systems are inappropriate.[102]

To facilitate mission-specific load planning, military commanders and soldiers would benefit from decision support tools that allow them to readily understand the many contributors to burden and their impacts. Commander's guidance documents[103] and soldier aide-memoires are a good start, but given the rise in computing technology on the battlefield, there is an opportunity to provide decision support that is much more powerful. Load and mission planning tools have and continue to be developed[104] that could allow the user to enter or download soldier information, mission factors, select items of equipment needed for the mission. There is an opportunity to provide decision assistance models, based on research, that would inform decisions regarding: load weights, recommended distribution of loads across the section, energy costs of movement with loads,[105] implications of loading on an individual and/or section/platoon performance, risk of over-exertion or heat illness, hydration or work/rest schedules, or even recommend alternative routes that would be optimized for the user's prioritized goal (speed, energy cost, stealth, etc.). Much more research is needed to improve the accuracy and reliability of the complex models underlying such decision support tools.

Physiological monitoring systems also show potential. Focus groups with soldiers reveal insufficient understanding of the signs, symptoms and risks of heat illness. Physiological monitoring might be acceptable for use in training so that soldiers and leaders can learn individual responses to heat, overload, and other training stressors.[106] Real-time remote monitoring of soldier burden indicators, readiness, casualty risk, and actual injuries might eventually be achieved, and when networked with above-mentioned decision-support tools, help leaders, commanders, and their supporting medical chain on operations.

A significant challenge is the weight of batteries needed to sustain modern combat missions.[107] Better power system integration is being pursued by Canada and her allies, including: standardization of power sources to minimize the number of different battery types carried by each soldier, better distribution and management of power on the soldier, automatic charging whenever the soldier is seated in the carrier, as well as generation of power, by capturing solar energy or the energy harvested during normal human gait[108] to recharge batteries on the soldier on the move.

Finally, targeted air-drop and the increasing use of blue-force tracking by all friendly forces will lead to improved accuracy, timeliness, and reliability of combat re-supply. Increased confidence and trust in re-supply could lead to better load planning practices by leadership that balance risks between enemy and burden-related losses, and could reduce loads by tempering soldiers' natural inclination to pack for all possible worse-case situations.

User Interventions

Fitness measures correlate highly with load carrying capacity and performance[109] as well as reduced load-induced injuries.[110] Lean body mass (or low percent body fat) is probably the strongest predictor in terms of marching[111] and it also relates to heat tolerance.[112] Muscular strength and endurance are the next most predictive of marching performance under loads,[113] followed by aerobic fitness.[114] Important fitness correlates of obstacle course performance, on the other hand, appear to be muscular strength and endurance measures such as maximum number of sit-ups or push-ups in a prescribed time, or composite Army fitness scores,[115] with aerobic fitness to a lesser degree.[116] Load carrying experience is also important to either task.[117] It has long been recognized that regular physical training that includes aerobic exercise, resistance exercise and road marching can improve extended load carriage marching performance,[118] though there is wide variability in the approach and training regimen. A 2010 narrative review[119] recommended specific load carriage training, two to four times per month, with loads sufficient to elicit aerobic fitness development, ensuring that duration and distance gradually progress to avoid acute and overuse injury risks. In a more recent systematic review,[120] the greatest effect size was seen with progressive resistance training (focused on the upper body), combined with aerobic training and performed three times per week over at least four weeks, augmented with progressive load carrying exercise once weekly. There is growing evidence that performance of high-intensity combat mobility tasks such as rushes, fire, and movement, or break contact drills, is also related to physical fitness and can be improved through targeted physical conditioning and practice of those combat movements.[121] Authors of these studies stress the importance of a shift from purely endurance running, typical fitness training undertaken by most combat units, to a more sprint-based speed-training approach, in order to improve performance on these tasks so critical to battlefield survivability.

It is critical that soldiers train as they will fight, by wearing and working in realistic operational loads, clothing, and equipment configurations. The weight, bulk, and stiffness characteristics may change the way soldiers must complete tasks and, in life and death situations, these actions must be automatic, only possible through extensive practice and muscle memory. While physiological heat acclimation can happen in a couple of weeks of exercise and exposure to environmental conditions,[122] getting used to the discomfort associated with local high skin temperatures and sweating that cannot be compensated under non-breathable armour, so that it is not a distraction from performing other important perceptual and cognitive tasks, will require much longer exposure and experience. If modular, scalable protection is introduced, it will be essential to exercise alternative armour configurations over a wide range of missions, tasks, environments, soldiers, and leaders in order to build sufficient experience for leaders and soldiers to confidently decide on the best configuration for a given scenario.

Mission, Task, or Environment Adaptation

While units cannot always choose to undertake a mission or task, a number of mission or task attributes can be adjusted to modify the impact of burden on the well-being and performance of soldiers, including: scheduling the mission for a cooler time of day; slowing pace of work[123]; introducing more frequent or longer rest breaks[124]; more frequent hydration; reducing protective posture (enabled by a modular, scalable protection system); sharing a task or load amongst more soldiers; or off-loading a task to another sub-unit or a non-human (carts, mules, tactical vehicles, or robots). Similarly, soldiers will rarely be able to alter the physical environment in which they operate. However, they can make choices in terms of their micro-environment, choice of tactics and use of ground. Maximum use of clothing ventilation, shading covering exposed skin, or reducing protective posture, are behaviours that occur naturally. Keeping stealth considerations in mind, they can also choose routes to minimize exposure to hazardous or challenging conditions. They might choose a route with overhead tree canopy to avoid exposure to precipitation or blazing heat. They might choose terrain that is flat versus hilly, hard-packed versus rough, or terrain that offers more cover, minimizing the requirement to get into prone firing postures during rushes. These decisions will be facilitated by a system that provides networked communications, situation awareness, terrain visualization, as well as mission and route planning tools and provides these tools to soldiers and leaders in training, not just on operations, so that their use becomes familiar and their reliability improves. Confidence in their utility will be instilled through lessons learned and experience.

Soldiers and units often have choices about the environment in which they rest. Enforcing good operational and sleep hygiene practices will be important as the cumulative stresses of combat and exposure to challenging environmental conditions often lead soldiers to take shortcuts (e.g., not bothering with preparation of shelters, heating rations, etc.) which can affect mood, well-being, and impact on resilience and performance.

Organizational and System-Level Strategies

The importance of educating soldiers, leaders, and all stakeholders involved in the soldier system about burden cannot be overstated. Knowing the causes and factors contributing to burden, having a thorough understanding of the implications, risks, and outcomes associated with burden, and being exposed to the range of potential mitigating strategies, will be critical to ensure that every opportunity is taken to identify and implement incremental improvements across all lines of development (e.g., equipment, doctrine, training, organization, infrastructure, policy, etc.). However small these increments may appear, the collective impact that can be achieved within a culture focussed on burden mitigation may be very significant.

It has become readily apparent, through focus groups and interactions with soldiers and sub-unit leaders, that few understand the health, injury, performance, or survival implications of every kilogram carried into battle. Soldiers speak of heat stress due to body armour without realizing that the more discretionary loads they choose to carry may contribute equally if not more to their physiological stress. Figure 6.1 provided some insights; for most section members, load proportions are highest for ammunition, then weapon system, non-power subsistence (water, food, and food preparation equipment), then ballistic protection (armour and helmet), before other protection and sustainment loads. Soldiers almost unanimously prefer to get rid of protection to take more ammunition. While armour is heavy, uncomfortable, bulky, and hot, and does indeed hamper mobility, it saves lives. On the contrary, soldiers do not appear to question the high proportion of subsistence (water, food, food preparation equipment) and sustainment gear (load carrying equipment, overnight gear) they carry for such a short mission. The greatest contributor to their loads is typically ammunition, yet among the hundreds queried very few soldiers said they had ever expended – moreover very few even knew of any other soldier who had ever expended – a full load of ammunition during a firefight. Similarly, no one had ever heard of a failure in resupply. There certainly must have been more occasions when these occurred, however, this behaviour and attitude lends support to the concern about high ammunition loads that has been repeatedly expressed by senior officers in the literature reviewed.[125] They attribute much of the overloading problem to a failure in leadership and insist that leaders need to do better specific-to-mission load planning, give proper direction, and monitor compliance in order to balance the risks between casualties due to burden and those due to enemy action. By taking a systems approach, however, mitigating strategies are many and certainly include proper load planning by leaders, but additionally include: re-evaluation of doctrine that dictates load lists, particularly minimum ammunition loads, to discourage overload; appropriate implementation of physiological monitoring systems[126] that inform (validated) decision support tools; routine exercising of the logistical resupply chain alongside combat unit training so that problems are ironed out in training rather than operations and to instill confidence in resupply[127]; and a focus on improving the quality and frequency of marksmanship training to ensure that aimed shots hit their mark with fewer rounds,[128] to name a few organizational, system-level strategies.

Burden mitigation should remain a research and development priority. Research has not always reflected the extreme loads and conditions (tasks, environments, human variability, etc.) reflective of operational reality. Many studies examining the impact of soldier clothing, equipment, and loads, or any burden mitigating strategies, may need to be repeated in a more ecologically relevant context.

Knowledge gaps remain and include identification of important predictors of operational task performance, and then modelling the complex relationships amongst all burden contributors (not just load weight), so that soldier clothing and equipment design interventions may be appropriately identified, prioritized, and implemented. Soldier burden research to date has focused, almost exclusively, on the impacts of external load weight; this is perhaps not too surprising, since weight appears to be the biggest driver in terms of mobility effects (70 per cent according to[129]). However, given how difficult it has been for armies to successfully reduce soldier loads, consideration should at least be given to the contributions of other soldier equipment mass properties to help identify other solutions. As a first step, researchers are developing more accurate and reliable methods to characterize encumbered soldier and soldier equipment mass properties such as bulk,[130] PPE coverage,[131] and stiffness,[132] or restriction to range of motion.[133] These mass properties (in addition to weight) are also being evaluated in terms of their contribution to mobility task performance,[134] to help prioritize where future investments should be directed in terms of soldier clothing and equipment design to mitigate burden (e.g., should we invest in thinner or more flexible armour solutions?).

There also remains a serious lack of understanding of the trade-space between what soldiers wear and carry, their physiological readiness, heir operational task performance, and the impact of these on their individual and their military unit's overall operational effectiveness in terms of mobility, vulnerability, lethality, and integrated survivability. Once these trade-offs are quantified and adequately modelled, a whole range of analysis tools and decision aids can be developed, refined through experience and systematic data collection to improve their accuracy and reliability, and implemented so that all stakeholders – from researchers through those responsible for soldier system capability development, to soldiers and their entire chain of command – are enabled to make evidence-based decisions that will together achieve success in terms of soldier burden mitigation.

More detailed, context-specific data are needed to understand the cause factors contributing to injuries, whether operational or occupational. Knowing the specific clothing and equipment worn, loads carried, environmental conditions, in addition to usual information gathered about what the soldier was doing when an injury occurred, can help to identify and replace injurious equipment (e.g., poor rucksack design) or practices (e.g., overloading soldiers on training courses to "toughen" them up). Strategically, investments should be made to build and validate equipped soldier virtual modeling and analysis tools and capability so that future alternative equipment and loading options can be assessed more quickly, accurately and cost-effectively in a Virtual Soldier Proving Ground.[135] This would certainly not replace soldier-in-the-loop testing, but would enable efficient objective assessment of many more iterations of concepts and designs.

Applying an evidence-based user-centred focus in the specification, design, testing, and acquisition of soldier equipment will ensure that proper attention is given to equipment implications on soldier physiology, biomechanics, injury risk, performance, and operational effectiveness. In a National Research Council report on *Making the Soldier Decisive on Future Battlefields*,[136] several report recommendations speak to the importance of principles typically espoused by Systems Engineering and Human Systems Integration specialists, including the need for: a metrics-driven system of systems engineering environment with sufficient seniority, influence, and authority responsible for developing methods and analytical tools to evaluate and acquire total system solutions for soldiers and small tactical units; maintenance and evolution of a comprehensive set of measures of performance, effectiveness, and outcome (MOPs, MOEs, MOOs) for assessing capability improvements to the soldier system and regular assessment of the soldier system as it changes over time; investment in analysis architecture and infrastructure including the full range of human-system, engineering, and operational research modelling and analysis tools to enable "what-if" and sensitivity analyses to help prioritize burden mitigating strategies and support development of trade-off decision-making tools; and assembly of a consortium of multi-disciplinary cross-functional experts and stakeholders to implement analyses of the Soldier System, leverage existing research and development, and consider all intervention types (technology, doctrine, tactics, personnel, policy, etc.) in order to develop, identify, and seize opportunities for soldier burden mitigation, performance improvement, and to gain the decisive edge on the modern battlefield.

CONCLUSION

It won't be "Captain America" or "Iron Man" that will ensure the survival and effectiveness of dismounted soldiers, at least in the foreseeable future. The invasive HPE approach used to create Captain America is probably a non-starter given the myriad of legal, moral, and ethical considerations likely to delay its acceptability. Even less permanent pharmacological HPE is unlikely in the near-term, until long-term use of ergogenic aids, including their use in combination with other typical battlefield stressors, has been proven to be safe, and until they are accepted for widespread use in society. Considering their low technology readiness level, integration challenges, and complexity, at least in the short term, Iron Man-like exoskeletons, though relatively non-invasive when compared to bioengineering HPE, may pose more risk than opportunity for dismounted soldiers whose lives depend on simple, robust, reliable technology and their ability to move and perform combat tasks with speed and agility on the battlefield. Just as the factors contributing to soldier burden are multi-faceted, so must be the strategies for mitigating burden. The complete spectrum of technology, user, task, environment, and system-level interventions must be considered by all stakeholders at all stages of the soldier and the soldier system life cycle. Aiming for incremental gains across all of these opportunities is our best shot at significantly reducing soldier physical burden and ultimately ensuring the survival and effectiveness of our dismounted soldiers in the near-term and into the future, when HPE options become more realistic.

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