Integrated Physiological Monitoring

Craig Burrell
Ryan J. Love
Stergios Stergiopoulos
DRDC – Toronto Research Centre

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Abstract

Background: Wearable physiological monitors provide real-time information about many aspects of a person's physical state. They can provide biofeedback to assist tactical breathing and arousal control, core/skin temperature, breathing rate, heart rate, oxygen saturation, or quantification of sleep/fatigue, along with a range of other measurable physiological parameters. These measures can be useful to improve the effectiveness of training, or to prevent injury in the training area or on the battlefield.

Methods: Several data collection approaches were used in the writing of this report. In order to better understand the attitudes and outlook within the Canadian Armed Forces (CAF) with respect to our topic, we consulted numerous individual stakeholders within the CAF through questionnaires and focus groups, including members of the Infantry, combat medics, the Directorate Land Requirements (DLR), the Canadian Army Land Warfare Centre (CALWC), Canadian Forces Health Services (CFHS), and the Directorate of Fitness (DFIT). Furthermore, we attempted to learn as much as possible about the activities and interests of other nations in this technology domain by soliciting feedback through The Technical Cooperation Program (TTCP) Technical Panel 19 (Human Systems Performance (Land)) and North Atlantic Treaty Organization (NATO) RTO HFM-260 (Enhancing Warfighter Effectiveness with Wearable Biosensors and Physiological Models).

Results: We have found there to be widespread interest in physiological monitoring devices internationally. However, the United States military (Army) is currently the only nation that is moving forward with operationalizing the technology; other nations are using the technology primarily as a research tool at this time. Our CAF consultations revealed that there is interest and a high degree of comfort with using physiological monitoring devices as a training aid in the near future, and potentially during operations once significant confidence and experience with the technology is obtained. We have also found that there is currently a significant gap between data output from Commercial Off-the-Shelf (COTS) devices and the information required by commanders and/or medical staff. A substantial R&D effort is required to reduce the data from the physiological monitoring devices and present it to commanders and/or medical staff in the form of a dashboard containing only the most vital information.

Conclusions: This report explores potential applications of this technology within the CAF, with a focus on the Army, and reviews the recent activities of other nations in this technology domain.

Significance to Defence and Security

The core of the CAF is the personnel, and through we have thousands of sensors for information on our vehicles, ships, aircraft and other assets, we currently do not monitor the intricate workings of the human body when it is engaged in highly complex tasks. Wearable physiological monitoring devices have been said to be a revolutionary breakthrough for individual soldier enhancement, and the capability of these devices is expanding at a rapid pace. Small and lightweight physiology monitors provide instantaneous information about many aspects of a person's health status and may be useful to improve the effectiveness of training, or to prevent injury in the training area or on the battlefield.

Résumé

Contexte. Les dispositifs de surveillance physiologique corporels fournissent des données en temps réel sur divers aspects de l'état physique d'une personne. Ils permettent d'obtenir une rétroaction biologique favorisant la surveillance de paramètres physiologiques mesurables comme la respiration tactique et la gestion de l'état d'alerte, la température centrale ou superficielle (peau), le rythme respiratoire, la fréquence cardiaque, la saturation en oxygène, la quantification du sommeil / de la fatigue, ainsi qu'un éventail d'autres paramètres. Ces mesures peuvent servir à accroître l'efficacité de l'entraînement ou prévenir les blessures dans le secteur d'entraînement ou sur le champ de bataille.

Méthodologie. Plusieurs méthodes de collecte de données ont été prises en compte dans la rédaction du présent rapport. Pour mieux comprendre l'attitude et la perception des membres des Forces armées canadiennes (FAC) en regard du sujet en question, nous avons consulté, par le biais de questionnaires et de groupes de discussion, de nombreux intervenants des FAC, notamment des militaires d'infanterie, le personnel médical de combat, la Direction des besoins en ressources terrestres (DBRT), le Centre de guerre terrestre de l'Armée canadienne (CGTAC), les Services de santé des Forces canadiennes (SSFC), et la Direction – Conditionnement physique (DCP). De plus, nous avons tenté d'en apprendre le plus possible sur les activités et les intérêts d'autres nations relativement à ce domaine technologique en les invitant à nous fournir leur rétroaction dans le cadre du Programme de coopération technique (TTCP), Groupe technique 19 (Performances des systèmes humains [opérations terrestres]), et à la lumière du rapport RTO HFM-260 (« Enhancing Warfighter Effectiveness with Wearable Biosensors and Physiological Models ») de l'Organisation du Traité de l'Atlantique Nord (OTAN).

Résultats. Nous avons constaté un intérêt général pour les dispositifs de surveillance physiologique à l'échelle internationale. Toutefois, à l'heure actuelle, seules les Forces armées des États-Unis ont décidé d'aller de l'avant avec l'opérationnalisation de cette technologie; d'autres nations utilisent cette technologie principalement comme outil de recherche, pour le moment. Nos consultations avec les FAC ont révélé un grand intérêt et une grande aisance à l'égard de l'utilisation de dispositifs de surveillance physiologique comme outils d'aide à l'entraînement, dans un proche avenir, et possiblement pendant les opérations, lorsqu'un niveau de confiance et d'expérience significatif à l'égard de cette technologie sera atteint. Nous avons également constaté qu'il existe, à l'heure actuelle, un écart important entre les données produites par des dispositifs commerciaux (en vente libre) et les données requises par les commandants et/ou le personnel médical. Il convient donc de déployer des efforts considérables en matière de recherche et de développement pour réduire la quantité de données produites par les dispositifs de surveillance physiologique et de ne présenter aux commandants et/ou au personnel médical qu'un tableau de bord renfermant seulement les données essentielles.

Conclusions. Le présent rapport fait état des applications possibles de cette technologie au sein des FAC, plus particulièrement au profit de l'Armée de terre, ainsi que des activités récentes menées par d'autres nations dans ce domaine technologique.

Importance pour la défense et la sécurité

Le personnel est l’élément central des FAC, mais nous n’exerçons à l’heure actuelle aucune surveillance du fonctionnement complexe du corps humain lorsqu’il doit se livrer à des tâches hautement complexes, alors que nous disposons de milliers de capteurs pour relever des données sur nos véhicules, navires, aéronefs et autres biens. On dit des dispositifs de surveillance physiologique corporels qu’ils constituent une technologie de pointe révolutionnaire pour améliorer les capacités de chaque soldat; les possibilités offertes par ces dispositifs évoluent rapidement. De petits appareils légers de surveillance physiologique fournissent des données en temps réel sur divers aspects de l’état physique d’une personne et peuvent servir à accroître l’efficacité d’un entraînement ou à prévenir les blessures dans le secteur d’entraînement ou sur le champ de bataille.

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1 Introduction

Physiological status monitoring of soldiers has been called "one of the truly revolutionary breakthroughs in individual Soldier enhancement" (Friedl and Allan 2004, p. 36). Small and lightweight wearable physiological monitors can provide real-time information about many aspects of a soldier's health status. This report explores potential applications of this technology within the Canadian Armed Forces (CAF), with a focus on the Army, and also, in an effort to gain an international perspective, reviews recent military activities in this technology domain in other nations.

The rate of public uptake of wearable technology over the past three decades has been dramatic (Orange 2014). In the current wave of technological devices, we are seeing more "Smart" watches with pulse oximeters (for heart rate and blood oxygen quantification), accelerometers, gyroscopes, barometers, global positioning systems (GPS), magnetometer, ambient light sensors, and UV sensors. The data that one can now inexpensively collect on oneself is extensive, and there is a well-established market for integrated physiological monitoring systems (i.e., fitness watches) among athletic enthusiasts that has driven the research and development of the commercial off-the-shelf (COTS) devices (Orange 2014). These devices all seamlessly connect to other peripheral devices, such as cellular phones, and many have fast processors that can perform sophisticated data reduction and analysis on or off-line.

CAF personnel are likely to purchase these devices for their own personal use, and will wear these devices during training and operations unless it is specifically forbidden to do so. Considering that several of the more advanced physiological monitoring devices currently on the market have GPS, GLONASS, and even weather monitoring capabilities, we predict a high likelihood of these devices eventually impacting decision making during training and operations.

In addition to personally motivated use of such devices, there are reasons why the use of wearable physiological sensors could be strategically advantageous for the CAF. Military personnel often carry out operations in extreme environments in which the ability to monitor physiological status could inform tactical decision-making (Friedl et al. 2016). In situations where soldiers are at risk of injury, physiological monitoring may be able to contribute to improved safety (Hoyt et al. 2002), and when battlefield injuries occur medics could benefit from remote access to soldiers' vital signs to optimize medical triage. In training contexts also the ability to monitor physiological status during live exercises or during fitness assessments could improve overall awareness of the physical readiness of troops. At the same time, military use of such monitoring technologies imposes special technical challenges not always present in civilian contexts, such as a heightened requirement to provide low-noise, accurate data from portable, comfortable, and durable devices that can operate securely over prolonged periods with minimal maintenance.

We have focused this overview on specific considerations relevant to training and operations in the CAF, and especially in the Canadian Army. We describe the basic capabilities of wearable physiological monitors, outline the principal desirable features of such monitoring devices, and explain the architecture of a body-worn physiological monitoring system. We provide an overview of international efforts to apply wearable biosensors within a military context. Based on these findings and on consultations with numerous stakeholders within the CAF, we then discuss key potential applications of this technology that could be of significant benefit to the safety and effectiveness of Canada's soldiers. We conclude with a summary and a set of recommendations to guide future activities on this topic.

1.1 Methodology

Several approaches were used in the writing of this report. First, in order to better understand the attitudes and outlook within the CAF with respect to our topic, we consulted stakeholders within the CAF, including individual members of Directorate Land Requirements (DLR), Canadian Army Land Warfare Centre (CALWC), Surgeon-General, and Directorate of Fitness (D-FIT), organizations within the Department of National Defence targeted for their relevance to our topic of interest. Participation was individually solicited based on the prospective participant's knowledge of soldier systems and the relevance of his or her sphere of responsibility. Each participant completed an informal questionnaire designed to elicit his or her views on a number of issues related to the use of wearable physiological monitors in the military, including both advantages and disadvantages, obstacles to acceptance, privacy and security concerns, and related issues. The number of participants—just one from each organization—was too small to permit robust scientific conclusions to be drawn from the questionnaires, but they did accomplish their intended purpose, which was to stimulate reflection on this technology and to sample the scope of attitudes toward the technology within the CAF. The questionnaire was distributed via email, and is presented in Appendix A. Because the questionnaire pertained directly to the duties and responsibilities of each respondent's job, it was decided by program management that the questionnaire did not constitute public opinion research and so did not require ethics approval. The feedback received from our respondents has been integrated as appropriate into this report.

We also participated in several focus group discussions with CAF members in which part of the discussion concerned the use of wearable physiological monitors. These included a focus group with infantry held at CFB Meaford, a discussion with Army subject matter experts (SMEs) at CALWC, and a focus group with combat medics held at CFB Petawawa. The number of participants in each focus group was approximately 10.

Finally, we attempted to learn as much as possible about the activities and interests of other nations in this technology domain. To this end, we solicited feedback through several international forums, including TTCP Technical Panel 19 (Human Systems Performance (Land)) and NATO RTO HFM-260 (Enhancing Warfighter Effectiveness with Wearable Biosensors and Physiological Models). Our findings are concentrated in Section 3, with lessons learned for the CAF integrated throughout the report.

Based on these inputs, we identified numerous ways in which physiological monitoring might be used within the CAF, and these applications are described and discussed in Section 4.

2 Wearable Physiological Sensors

2.1 Basic Capabilities

Wearable sensors are capable of measuring and monitoring a large variety of physiological metrics. In this section we review the principal metrics monitored by COTS sensors, and comment on capabilities of more speculative or research-grade technologies. We also discuss how physiological data can be combined and interpreted to provide insight into health status, readiness, work strain, and other high-level indicators.

The most commonly measured physiological parameters are:

- **Heart rate** is a key indicator of physiological status, being correlated with energy expenditure, stress level, and even core temperature (Buller 2013). It is typically measured with electrocardiograph (ECG) electrodes embedded into a chest strap (Cuddy 2008, Tharion 2013) or close-fitting undershirt (Carre 2016, Montes 2015, Villar 2015) but can also be measured in other locations, such as the wrist (Thomas 2014) or ear lobe (Ma 2014). Some devices provide a simple numerical indicator of heart rate in beats per minute, while others can provide a complete ECG trace; the latter can be useful for computing heart rate variability (HRV), which has been implicated as a psychophysiological indicator of mental workload and emotional stress (Dishman 2000, Nickel 2003).
- **Respiratory rate** (breaths/min) is typically measured via a chest strap that expands during inhalation, and can be an important indicator of workload, stress level, and other physiological status measures. Some devices can also estimate **respiratory volume,** usually in litres (L). Ma and colleagues proposed to measure respiration rate using a temperature sensor positioned near the mouth (Ma 2014), but this is likely not practical for most military personnel. A novel method has also been proposed to measure respiration rate using a standard smartphone camera (Chon 2014).
- **Oxygen saturation.** Wearable pulse oximeters monitor arterial blood oxygenation using non-invasive light-emitting diodes. Traditionally oxygen saturation is measured at peripheral locations such as the earlobe or fingertip using a standard pulse oximeter. However, some devices now monitor oxygen saturation using a wrist strap (Thomas 2014), which is more convenient in a military or athletic context, or on the forehead, which might be feasible if embedded into a headband that may or may not be contained in a helmet (Nitzan 2014).
- **Skin temperature** is usually monitored via a thin skin patch or temperature probe in contact with the skin. In hot environments or within the microclimate created by protective personal equipment (PPE), skin temperature may be an effective indicator of heat strain, and in cold environments it can indicate risk of frostbite when assessed peripherally (Heil et al. 2016).
- **Core temperature** is an important parameter for assessing physiological status in extreme environments, and in particular for estimating risk of hyperthermia or hypothermia. It can be measured directly using ingested radio pills, and there is some evidence that it can be inferred from less invasive measures such as heart rate (Buller 2013).

- **Activity level** can be monitored using an accelerometer. These small instruments are included in many wearable fitness-tracking devices. Accelerometer-based devices (commonly referred to as actigraphs) have been used extensively to count steps, estimate caloric output, and assess sleep quality.
- **Body orientation** can be monitored with a three-axis accelerometer included in many COTS devices. The accelerometer indicates whether the wearer is stationary or in motion, and whether standing or lying down. If such data can be communicated to a commander it can potentially inform tactical or medical decision-making. For instance, interpretation of vital signs can rely on knowledge of body posture (Witting and Gallagher 2003).
- **Location** can be tracked using GPS technology which is now embedded into many COTS wearable physiological sensors. Real-time location tracking provides useful information about relative position and speed, and could be of particular tactical value if shared between members of a military section. A wearable **altimeter** would provide complementary information about the effects of mild hypoxia upon cognitive and physical performance.
- **Brain activity** is monitored with electroencephalographic (EEG) electrodes in contact with the skin of the head. Relatively few COTS devices provide such monitoring. Analysis of EEG signals is especially pertinent to assessments of mental vigilance and sleepiness.
- **Blood pressure** is among the standard vital signs. It is normally measured non-invasively with an arm-cuff, but this would likely be inconvenient for continuous monitoring of a soldier. Novel methods of measuring blood pressure include monitoring the radial artery pressure waveform at the wrist (Williams 2011, Thomas 2014), but such methods are currently in the investigative phase and not to our knowledge implemented in COTS devices.
- **Galvanic skin response** is a measure of the electrical conductivity of the skin, and has been used to estimate perspiration rates (Gerrett 2013), body hydration (Asogwa 2014) and stress (Perala and Sterling 2007). Measuring galvanic skin response requires that two proximate electrodes be in contact with the skin, perhaps beneath the faceplate of a wristwatch.
- **Foot strike impact** monitoring via foot-mounted accelerometers or force-sensing insoles permits the counting of steps, gait analysis (for injury detection), and load sensing (Hoyt 1994).

In addition to these basic physiological parameters, most of which are currently available from COTS devices, there are a number of measures which are more immature at the present time, but which might become more widely available in the future. These include:

- Electromyography (EMG) is monitoring of electrical/neurological muscle firing activity in the skeletal muscles, and may in the future be an effective measure of reduced force output due to muscular fatigue.
- An advanced form of physiological monitoring involves the “lab on a chip” concept, in which chemical analysis of biofluids such as blood, sweat, and saliva can be carried out on a small, portable platform that is either patched to the skin or carried by the user (Windmiller 2013, Bandodkar 2014, Matzeu 2015, Bandodkar 2015). The US Army, for instance, has experimented with continuous metabolic monitoring for diabetic soldiers (Hover 2005), but, as they noted, the concept could be generalized to other objectives and might be advantageous to soldiers operating in extreme environments.

Sweat biochemistry can be monitored noninvasively and in real-time using a variety of techniques. Devices to monitor pH, sodium, lactate, oxygen, and other chemicals have been implemented on a variety of platforms, including fabrics, elastic stamps, skin patches, and temporary tattoos (Bandodkar 2014, Soh 2015). Similar approaches could be used to monitor blood, but such devices would usually be somewhat invasive (Matzeu 2015).

The promise of this technology has also been demonstrated by fabrication and lab testing of epidermal patches containing microelectronics to measure more conventional physiological metrics, including ECG, EEG, EMG, and temperature (Kim 2011).

The "lab on a chip" is a platform that is finding more applications and is increasingly accurate, durable, and small. However, to a large extent this remains a research-grade technology at the present time, with a relatively small commercial presence.

2.2 Integration and Interpretation of Sensor Data

Physiological sensors provide detailed, low-level data about a body's activities and processes. This data must be further processed in order to produce higher-level indicators of interest. Algorithms to generate such indicators are in some cases integrated into COTS devices, and in other cases must be produced by additional, customized processing. The objective is to provide quantitative measures relevant to risk assessment for a variety of conditions, such as hyperthermia, hypoxia, low vigilance, poor sleep quality, and dehydration, for example. While investigation of the details of such algorithms is beyond the scope of this study, it is important to keep in mind that the mere ability to monitor physiological parameters is only part of the problem; reliable interpretation of the meaning of such data is also critical.

Turning physiological data into useful guidance is a challenging problem involving sensor noise management, design of algorithms to provide high-level health state indicators, and decision support based on high-level indicators (Buller 2010). The architecture of a wearable physiological monitoring system typically involves a set of individual sensors connected wirelessly to a central, body-worn processing hub which converts the low-level data into useful high-level indicators. The system then provides the indicators to the wearer, or, via the soldier's communication system, transmits them to another party, such as a commander or medic.

Management of health status data is a challenging problem. In some cases it would be advantageous to give the wearer access to the data, but too much data could result in excessive cognitive load. Likewise, commanders might have a legitimate interest in the health data collected from the soldiers under their command, but too much data would be an impediment to good decision-making.

The infantry soldiers with whom we consulted stressed that the only good reason to use physiological monitors would be to inform decision-making at some level; if a sensor system cannot help inform good decisions then there is no reason to use it. There was also general agreement among the soldiers that health data should be synthesized and reduced as it ascends to higher levels in the chain of command. A soldier may want to know his vital signs in detail, but a commander may want to know only a general indicator of the overall health of his unit. A sensor system should convey only what is essential.

An additional challenge to the integration and interpretation of data from COTS devices arises from the processing of data on the device by proprietary algorithms prior to transmission. Obtaining raw data from the devices is often impossible for independent engineers/researchers, and data manipulation is limited by the manufacturer's routines/protocols/tools integrated into the application program interface (API).

2.3 Sensor Design Objectives

Design of wearable physiological sensors is a complex technical challenge (USARIEM 2008, Tharion 2010, Chan 2012, Soh 2015). There are numerous competing performance requirements to balance, of which the most important are:

- **Low weight:** Soldier burden is an important issue that receives justified attention, since additional weight decreases performance and increases injury risk. As our CAF consultations made clear, soldiers are understandably reluctant to add additional weight unless they perceive a clear benefit. Even more than in civilian athletic contexts, physiological sensors for military use should be as small and light as possible. Commercial devices are trending in this direction: the popular UP fitness tracker from Jawbone weighs less than 25 g (Up Extended User Guide), and even the capable Equivital LifeMonitor, which measures heart rate, respiration rate, accelerometry, and skin temperature, weighs just 38 g (excluding batteries) (Equivital Reference Manual).

- **Low power:** For military use it is important that electronic devices have low power requirements so as to extend battery life for as long as possible. Soldiers typically carry numerous electronic devices, and the addition of integrated physiological monitors would be an additional drain on power. Advances in battery technologies have improved the time-between-charges for commercial physiology monitors: a simple activity monitor such as the FitBit Zip, which counts steps and tracks distance and calories, claims a battery life of 120 days, and the Jawbone Up Move, which tracks the same quantities but adds sleep tracking, claims a battery life of up to 180 days (https://jawbone.com/store/buy/upmove). More sophisticated monitors have shorter battery lives: the Equivital LifeMonitor claims a battery life of approximately one day. Some authors have argued that it might be possible to harness power from the soldier's body: for example, Torfs (2006) and Leonov (2007) describe a wrist-worn pulse oximeter powered by body heat. Some power might also be harnessed from the frictional motion of clothing made from advanced textiles (Seung 2015). In addition, the application of intelligent energy optimization strategies to an integrated soldier system can contribute significantly to extended battery life (Egbogah 2013). It might also be desirable, as was suggested during the CAF consultations, for devices to charge wirelessly.

- **Wireless:** It is highly desirable that physiological monitors positioned at various locations on the body be able to communicate wirelessly with the central processing hub so as to minimize interference with soldier mobility. Sensors not co-located with the hub and wired would almost certainly risk restricting or otherwise interfering with the wearer's physical range of motion and overall performance. The potential for such interference was identified by several of our CAF consultants as among the leading impediments to adoption of this technology.

- **High quality data:** A sometimes unstated but important requirement is that the data provided by a physiological sensor be accurate. Standards for data quality are high in military applications since those making decisions on the basis of the data must be able to trust it. There is evidence that the data provided by market-leading COTS devices is sometimes of low accuracy (Lee 2014, Case 2015, Segall 2016). Medical-grade physiological monitors are generally more expensive and less portable (Buller 2010). The challenges of designing small, wearable biosensors to rigorous engineering standards have been outlined (Gilbert 2015). Noise control is a central issue; many physiological monitors operate through a sensor in contact with the body, and motion artifacts are common if the sensor slides across the skin. Numerous strategies for noise reduction have been proposed, such as better sensor design, data filtering and signal processing, and redundancy (Chon 2014). Data quality of COTS devices is currently being assessed by various groups including the United States Air Force Research Laboratory (Richard Murdoch, AFRL, personal communication, 9/12/2015).

- **Robust:** A general requirement for military equipment for use in the field, including physiological monitors, is that they be ruggedized for the extreme environments and demanding conditions of military deployments (MIL-STD-810G). They should be waterproof and shock-resistant, for example. Although some COTS devices for athletic use are ruggedized to a limited extent, it is not evident that they would be adequate for military purposes. Physiological monitors for use in training exercises or employed as part of a physical fitness initiative would not need to be as robust and rugged as devices intended for operational use.
- **Integrated:** A physiological monitoring system will typically include more than one sensor or sensor type. For example, one sensor may measure accelerometry and another heart rate. It is desirable that all sensors be integrated into a single central processing unit so that high-level status indicators, which will in general depend on more than one measure, can be derived and reported. Integration of all sensor signals also allows for consistency checks and provides a centralized communication hub for conveying data and health indicators to other parties.
- **Networked:** The data provided by wearable physiological sensors may be of interest to the wearer, but it may also be of interest to his or her superior or to the unit medic. It is desirable, therefore, that a soldier's physiological monitoring system have access to the local tactical network so that information about health status can be conveyed to the appropriate parties. Bandwidth limitations impose constraints on the data that can be transmitted, which highlights the need for intelligent *in situ* processing of raw data to extract health indicators of high value.
- **Modular:** A physiological system consisting of several sensors should have a modular architecture so that sensors can be added or removed without disrupting the overall operation of the system. The importance of this requirement was stressed during our consultation with D-FIT. Sensors might be "removed" from the system because of damage. A well-designed system should be resilient under such changes. This applies particularly to the algorithms which process the underlying signals to produce health indicators: they should know what high-level indicators can be provided with a given set of sensors, and should respond gracefully if sensors fail.
- **Comfortable:** Comfort is an important consideration affecting the user acceptability of physiological monitors. Users are more likely to appreciate the monitors, and more likely to wear them voluntarily, if they are comfortable. Ideally the wearer should not be aware of them. This was one of the key requirements identified by our CAF respondents, and has been a priority in the commercial market as well.
- **Compatible with clothing and equipment:** Because military personnel are typically wearing heavy clothing and carrying equipment, such as firearms, radios, backpacks, and first aid

supplies, it is imperative that the placement and profile of physiological monitors be compatible with such gear (Menke 2015). Sensors must not impede mobility, and should not be placed at pressure points where they would cause pain.

- **Secure:** Data privacy has been a concern for wearable physiological monitors in the civilian world (Hilts 2016). Some COTS devices are vulnerable to data interception and tampering by a motivated eavesdropper. Devices which track location can provide a record of the user's movement which could be valuable to an attacker. These concerns are relevant in a military context as well, as when monitors are providing information about soldiers in theatre. Consequently it would be important that the information provided by a soldier systems physiological monitoring system be encrypted, both locally and in transit over tactical networks.
- **Intelligent decision support:** As was already mentioned, the raw information provided by physiological sensors is in itself of limited value. High level health indicators derived from the raw data are generally more intelligible and actionable. Therefore the algorithms which produce the indicators from the raw data are an essential part of any physiological monitoring system. Moreover, the information conveyed to the user, and the manner in which it is conveyed, are of great importance for maximizing value and minimizing cognitive load. For instance, some systems output a simple colour-coded indicator (Ma 2014) or specify merely whether vital signs are present or absent (Borsotto 2004, Savell 2004). Concerns about cognitive load, in the form of distraction or information overload, were common among the CAF members with whom we consulted. A physiological monitoring system integrated into a soldier system would need to clearly specify simple high-level indicators and include robust algorithms for generating them.

  Most COTS devices output one or more indicators (heart rate, distance travelled, body orientation, etc.) rather than raw data; for some devices it is possible to also access the raw data (as with the Equivital™ LifeMonitor, for example), but this is not guaranteed in general. From a research perspective, access to the raw data is highly desirable.
- **Easy maintenance:** For military use physiological monitors should be simple to manage and maintain. This includes, for instance, cleaning, changing batteries, charging, transferring data, and upgrading software and firmware.
- **Affordable:** Use of COTS devices is one strategy for reducing costs, since the growing adoption of such devices in the civilian world brings prices down. However, here as always, there are generally trade-offs between cost, technical capability, and quality (measured by all of the foregoing criteria) which would have to be taken into consideration.

In any wearable physiological monitoring system, the technical capabilities of the system are only part of the requirement. It is at least as important that the system be designed so as to be acceptable to users, and several of the above criteria, especially comfort, security, weight, and compatibility bear directly on this need. The development plan for a wearable physiological monitoring system should have a cyclical structure whereby designs are revised on the basis of technical performance and user feedback (Tharion 2013).

3 Use of Physiological Monitors by Other Nations

In this section we provide an overview of activities related to wearable physiological monitoring in a military context that has been undertaken by other nations. We consider both research activities and operational use of wearable technologies. This information was gathered partly by making inquiries in international forums such as The Technical Cooperation Panel (TTCP) and NATO Science and Technology Organization, and partly by a literature review.

3.1 United States

The United States is the world leader in this technology domain. Over many years they have invested funds and expertise to articulate a vision for military use of wearable physiological monitors and to develop the technologies to achieve their objectives. In this Section we survey a number of initiatives. However, due to the abundance of work from the United States in this area, we are not able to summarize all of their efforts. For a more comprehensive review, please see Friedl, 2016.

3.1.1 Warfighter Physiological Monitoring System (WPMS)

The Warfighter Physiological Monitoring System (WPMS) is the principal program under which work on this topic has taken place. The program, under the auspices of the US Army and led by USARIEM, started in the late 1990s and continued for over a decade.

The WPMS was envisioned to include an array of body-worn sensors integrated with a decision support system, and the initial objectives were medical: to improve outcomes for wounded soldiers and to prevent injuries due to environmental factors such as heat and altitude (Hoyt 2002). Over time the objectives broadened somewhat to include, for instance, fatigue monitoring, but overall the program focused on real-time monitoring of core indicators of soldier health.

The capability objectives of the WPMS included a basic alive/dead indicator, heat strain predictions, hydration monitoring, and fatigue prediction based on sleep and activity patterns (Friedl 2004). By 2008 this initial capability was largely achieved (USARIEM 2008). The system consisted of an actigraph wristwatch for assessing sleep quality, a fluid intake monitor, core temperature measurements via a radio pill, and vital signs measurements including heart rate, respiration rate, ambulation, body orientation, and skin temperature. The vital signs were measured by the Equivital™ monitor, which was developed, refined, and commercialized under the auspices of the WPMS program (Tharion 2010, Tharion 2013). The sensors were all coupled to a central, body-worn processing hub which ran a variety of algorithms and output health state metrics (Buller et al. 2015, Tatbul et al. 2004).

The information provided by the system was linked to a medic's display so that the health indicators could be remotely monitored (CAIPS et al. 2007). A study was conducted to ascertain the medical data and method of presentation that would be most advantageous to a medic in theatre (Kaushik 2009). A group of 26 Army medics provided input to an iterative design process of a graphical user interface, with the aim of promoting effective remote triage and early treatment of a battlefield casualty. As a result of this process, a medical monitoring system was designed which included continual updates of all soldiers' vital signs (heart rate, respiration rate, and core temperature), simple icons indicating status and, in the case of injury, easily interpreted images indicating the nature of the injury. The system included maps so that the relative positions of all soldiers and medics could be quickly consulted, and a variety of other features as well. This conceptual design of a graphical user interface has not been installed in a working software package.

Future capabilities of the WPMS were variously said to include energy flux estimates, comprehensive soldier databases, mental status monitoring, and energy expenditure estimates (Friedl 2004). The extent to which these more advanced capabilities have been realized is unclear, as indeed is the current status of the WPSM program itself. Nonetheless, it is fair to say that the WPMS is, at this time the premiere example of an integrated physiological monitoring system for military use.

3.1.2 Integrated Soldier Sensor System (ISSS)

In 2013 the United States Army published a Statement of Work for development of an Integrated Soldier Sensor System (ISSS) (ISSS 2012, ISSS 2013). The ISSS includes a helmet sensor, blast overpressure sensor, and physiological status monitor. The three components are integrated into a single system, and together form part of the larger Soldier Protection System (SPS), which also includes personal armour.[1]

The ISSS physiological status monitor will directly measure heart rate, skin temperature, and body motion (using a three-axis accelerometer), and it will also monitor core temperature and heat stress. The core temperature and heat stress will not be measured directly, but will be inferred based on heart rate data. It has recently been shown that core temperature can be predicted with good accuracy (bias: -0.03 ± 0.32°C) based only on sequential observations of heart rate (Buller 2013). On the basis of measured heart rate and inferred core temperature a Physiological Strain Index (PSI) can be computed (Moran 1998); the ISSS will compute and monitor this index, calibrated on a scale of 0–10. This indicator is a step up in sophistication from the initial Dead/Alive/Unknown indicator of the WPMS system described above.

The collected data, especially heart rate and PSI, will be shown to the wearer on a display (wireless, and perhaps wrist-mounted), and ISSS will also transmit data wirelessly to a base station or handheld reader when within range (< 50 m). This data will then be available to the chain of command.

According to the Statement of Work, the ISSS will be designed to permit the further integration of other wireless or wired sensors and displays. The system will be capable of onboard data storage for up to 72 hrs of recording time. It will have a target battery life of two weeks, and will be rechargeable via a standard micro-USB port. The physical size of the sensor will be less than 3 in.^{3} (~ 50 cm^3), with a weight of less than 2.5 oz (~70 g).

[1] We are indebted to Dr. Reed Hoyt, Division Chief of the Biophysics and Biomedical Modeling Division at USARIEM, for providing access to the ISSS documents.

Based on this overview of the architecture and capabilities of the proposed ISSS, we can make a few observations:

- The proposed ISSS, including the physiological status monitors, is intended to be part of the standard-issue equipment for in-theatre US Army soldiers.
- It is not clear how the data provided by the ISSS physiological status monitors would be used by the chain of command.
- A central aim of the ISSS is to prevent heat-related overstress. This is evident from the fact that the Physiological Stress Index, computed from heart rate and core temperature, is one of the principal physiological parameters reported by the system (along with heart rate). This emphasis on thermal monitoring makes sense in the context of recent and current environmental conditions during US Army deployment.
- Certain important design features of the physiological status monitors are not specified in the ISSS Statement of Work, but are left to the discretion of the contractor, including the design of the electrocardiograph components and the position of the physiological monitoring hardware on the body. The system is only required to be compatible with the standard-issue Improved Outer Tactical Vest (IOTV III).
- The value of the ISSS will depend critically on the quality of its heart rate data, which is an input to both the core temperature estimates and the calculation of the Physiological Strain Index. The ISSS Statement of Work does not specify the nature of the electrocardiograph components, nor does it set specific limits on motion-induced noise in the cardiac signal, only indicating that the electrodes be “well coupled to the wearer” (ISSS 2012). Managing motion-induced artifacts is likely to be a significant data processing challenge.

It may be possible to follow the development of the ISSS through the NATO HFM-260 Research Task Group on “Enhancing warfighter effectiveness with wearable biosensors and physiological models”.

3.1.3 Marine Expeditionary Rifle Squad Initial Capabilities

To support the Expeditionary Force 21 operating concept, the United States Marines will be developing a health and fitness monitoring capability for use by a squad leader to monitor troops during extended operations. Due to the increased number of crises of small to medium scales, the Marines are composing a Marine Air-Ground Task Force (MAGTF) that is scalable, expeditionary, rapidly-deployable, and task-oriented. A Marine Rifle Squad is the lowest unit of employment of a MAGTF during Contingency Operations, and may be employed as a battalion landing team, or may be the core of a rapidly deployable contingency MAGTF. The Marine Rifle Squad, as part of a Rifle Platoon, is the smallest team that executes mission essential tasks and must be capable of operating across a range of disaggregated/dispersed military operations. A health and fitness monitoring capability in this context will address the Materiel Gap that indicates that dismounted ground elements from a squad are currently unable to reliably effect/initiate MEDEVAC from an increased distance, which hinders the squad’s capacity to maneuver (McNulty 2015).

3.1.4 Battlefield Airmen Trauma Distributed Observation Kit (BATDOK)

The Battlefield Airmen Trauma Distributed Observation Kit, BATDOK, is a government-owned point-of-injury tool for dismounted medics. Its development was initiated to enhance the AF-Pararescuemen's (PJ) ability to wirelessly monitor multiple patients' vitals simultaneously at the point-of-injury and throughout the transportation to the forward operating base's medical facility. Although it strongly aligns with the AF's Personnel Recovery mission, BATDOK's capabilities synergizes with other DoD missions and Armed Service's needs. BATDOK leverages operator-centric, intuitive, easy-to-use mobile interfaces, designed through extensive collaboration with AF PJ and Combat Rescue Officers (CRO), to facilitate maximum awareness and documentation of in-field patient care. BATDOK hosts a variety of multimodal covert/overt notifications, conducive to SOF and CASEVAC missions, alerting the medic when a patient crosses predefined health thresholds set by the medic. BATDOK possesses the capability to reference, offline, current standard medical care procedures/guidelines through a drop and drag file structure that can be accessed with single-click actions. Moreover, BATDOK was designed as an open-architecture system to easily incorporate existing/emerging FDA wireless sensors allowing the dismounted medic to select their desire sensors for their unique mission sets (BATDOK is sensor and wireless protocol agnostic allowing it to scale as new sensor come online). BATDOK is 100% government-owned and can be shared with other government agencies' efforts for integration, collaboration, evaluation, and use. BATDOK has undergone several live mass-casualty military exercises and is currently being evaluated by ACC/SG and AFSOC Special Operations Wing (R. C. Murdock, USAF/711 HPW).

3.1.5 24/7 Combat Fitness System

The Air Force is currently developing a wearable sensor suite and sensor integration software, is known as the 24/7 Combat Fitness System (CFS). The CFS will provide Airmen with real-time physiological load data that reflects true energy expenditure during PT or operational training to enable up-to-the-minute physical readiness scores. Physical training leaders and trainers can use this technology to examine individual and team performance data to customize daily training regimens, allowing for proper recovery and avoidance of overtraining that can lead to injury. An Overall Fitness Index (OFI) can also be calculated with data from human subjects in Phase 2 of this project that will be personalized to the Airman and provide unit/squadron commanders with information regarding performance/mission readiness. It can also be used to provide additional insight for selection and training processes. Additionally, a Smartphone App will be developed containing this information for ease of use for the operators/customers. With respect to the sensor suite, the data streams necessary to feed the personalized algorithms contained in the CFS are: sleep metrics, daily activity, hydration/electrolyte levels, heart rate (HR), heart rate variability (HRV), and accelerometers. The Air Force is currently working with multiple athletics and sensor companies to produce integrated multi-sensor packaging in an advanced textile / intelligent clothing format that will be easier to use and more comfortable to the operator (R. C. Murdock, USAF/711 HPW).

3.1.6 Related Activities in the United States

A key challenge for a deployed soldier system is to develop a software platform for integration of the various components. General software architectures for sensor integration and information sharing between soldiers are being developed by the US Army Natick Soldier Research, Development and Engineering Center (NSRDEC) (Sisto 2015) and the Communications-Electronics Research, Development and Engineering Center (CERDEC) (Thompson 2015). This vision includes a role for physiological monitoring, but at present the focus appears to be on other environmental sensors. It is worth noting that the documentation for the ISSS described above (ISSS 2012, ISSS 2013) makes no reference to this larger framework. The horizon for this ambitious program is 2025.

A further important challenge to deployment of an integrated physiological monitoring system is to provide a feasible means by which to transmit relevant physiological data to commanders or medics. Depending on the specific communications protocols in use on the military network, a COTS device may not be able to interoperate. The United States Coast Guard has studied the use of tactical radio networks to communicate vital signs data (Coates 2015) provided by a COTS device, with the intention of improve pre-hospital data during medical evacuations and thereby improving outcomes. They used the Zephyr BioHarness 3 (BioHarness 3), which measures key vital signs (heart rate, respiration rate, and body temperature, among other metrics), and demonstrated that, despite several technical challenges, it could be successfully integrated into a military network.

The Tactical Assault Light Operator Suit (TALOS) project is a major initiative to develop a combat exoskeleton for military personnel, under the auspices of the United States Special Operations Command (SOCOM) and the Defense Advanced Research Projects Agency (DARPA). The vision for this project includes a physiological monitoring component, tracking heart rate, respiration rate, skin temperature, and hydration levels in order to provide a real-time assessment of physiological exertion (Ma et al. 2014, Miles 2014). This project appears to be in the relatively early stages, and will bear watching.

The United States is also exploring the use of advanced textiles and intelligent clothing in a soldier system, and some of the proposed applications relate to physiological monitoring, especially for medical purposes. For instance, the Defense Threat Reduction Agency issued a solicitation (DTRA 2012) in which requirements were outlined for clothing to improve injury awareness and medical treatment. The clothing will be designed to identify the location and severity of bullet or shrapnel penetration in order to inform remote triage decision-making. This is a research-grade initiative, and information about the program is scarce.

Use of physiological sensors could be situated within the wider context of tactical sensor deployment. The United States Army has an ambitious soldier-borne sensor development plan which includes a variety of different sensor types: electro-optical, infrared, and Chemical, Biological, Radiological, Nuclear, and Explosive (CBRNE) (McNally 2015); the broad intent is to improve soldier situational awareness, mobility, and target acquisition in order to maximize mission success and soldier safety (CERDEC).

3.2 Netherlands

Aside from the United States, the Netherlands have perhaps engaged the most in the domain of physiological monitoring devices for their armed forces. Fatigue (Van Wouwe 2011), injury prevention, and reducing course attrition rates are their primary interests and data quality of their physiological monitoring systems (Hidalgo and ARMOR systems) are the current focus. The

ARMOR system is based on a Garmin Fenix activity monitor paired with sensors integrated into a boot insole, and is being developed in a collaboration between the University of Twente and Evalan (a private company), with funding from the Department of Defence of the Netherlands. The ARMOR system will be used for real-time measurement of heat stress and to quantify workload during training. Improved algorithms for the ARMOR system are required for the calculation of energy expenditure, the calculation of sleep duration and quality, and the prediction of core temperature. The Hidalgo analysis software that was developed by the Netherlands can be made available to DRDC and the CAF.

3.3 Switzerland

Switzerland's interest in physiological monitoring is also focused on injury prevention, and Dr. Thomas Wyss has engaged a monitoring the physical activity of Swiss Army Recruits (Wyss 2012). He has used body-worn sensors, including accelerometers and heart rate monitors, to characterize the physical requirements of typical military tasks (Wyss 2010) and, in an interesting example of deriving high-level output from low-level sensor data, to estimate the energy expenditure associated with various military activities (Wyss 2011). Such data could be used to develop a profile of military trades based on actual physical activity requirements, or to objectively characterize the physical demands of military training exercises. Because increased injury rates during training have been shown to be related to increased physical demands (Jordaan 1994, Knapik 2007, Knapik 2011), a clearer understanding of those physical demands may lead to better strategies for injury prevention.

3.4 France

France's interest in physiological monitoring devices is focused on the fatigue of their personnel during operations, particularly in the French Navy (Marine nationale), and the French Air Force (Armée de l'air). Dr. Mounir Chennaoui leads a team of scientists, students, post-docs and research technicians at the French Armed Forces Biomedical Research Institute and the University of Paris Descartes that focus on sleep and fatigue monitoring. A particularly notable development from their lab is the automatic in-flight detection of vigilance states using a COTS single-lead EEG monitor (Sauvet 2014). The group has also performed similar work under the ocean on the French nuclear submarines to look at sleep and wake patterns during a 70-day sail (Trousselard 2015).

3.5 United Kingdom

Dr Simon Delves from the Institute of Naval Medicine (INM) is the project lead for Surgeon General's Armed Forces Thermal Burden Project (SGAFTBP). One element of the SGAFTBP is the development of the UK/US Thermal Work Strain Project (TWSP), which is a collaboration between the INM and the United States Army Research Institute of Environmental Medicine (USARIEM). The INM is collaborating with USARIEM to validate the US Army core temperature prediction algorithm (ECTemp™) for a UK military population to mitigate the risk of heat illness. The INM is also collaborating with the United States, Switzerland and the Netherlands as part of the INM Biosensor Programme to improve the measurement and estimation of energy expenditure and training load.

Personnel at DSTL have been working on a report assessing wearable sensors for the exploitation of data collected during military training exercises, including both physiological and other sensor types (Waldron, Private Communication), and have also been conducting interviews with stakeholders. However, we have been unable to determine the current status of this report. Promotional materials for the UK Future Soldier Vision allude to a wearable communications element which includes “real-time reporting of soldier health” (DSTL). However, it is not clear if any research program is associated with the Future Soldier Vision at this time.

3.6 New Zealand

In New Zealand, concerns about moral, ethical, and legal issues related to access and use of physiological data have tended to predominate. There is therefore at present no active research programme on this topic (Fordy 2014).

3.7 Australia

In 2008 some work on physiological monitoring was done for the Australian Special Forces. However documentation of that work is designated For Official Use Only (FUOU), and is not generally available. A key outcome was that Army leadership were unsure how to make effective use of the physiological data to support tactical decision-making. As a result, there has been little subsequent activity on this topic by Australian defence researchers (Mark Patterson, member of TTCP Technical Panel 19).

One recent study, a collaboration between DSTO and AFRL, investigated user acceptance of physiological monitoring in the Australian Air Force (Menke 2015). In this study, command and control operators took part in simulated scenarios during which their physiological data was monitored remotely in real-time, and they were subsequently asked about their acceptance of the technology. Each participant wore a Zephyr BioHarness 3 device to monitor physiological metrics. The research group anticipated that participants would express reservations about having their data continually monitored. Interestingly, these expectations were not generally supported by the study. Instead, they found a relatively high acceptance of physiological monitoring, with relatively low levels of concern about data privacy among the study participants. Participants also generally reported that they did not find the device a distraction or a discomfort.

3.8 Singapore

Singapore’s interest in physiological monitoring devices is focused on heat strain injury prevention. Similar to the Buller algorithm to predict core temperature from heart rate (Buller 2013), DSO National Laboratories is developing a predictive algorithm to estimate core temperature from heart rate and surface skin (Seng et al. 2016a, Seng et al. 2016b). Dr. Jason Lee from Singapore will be working on a “dashboard” as the end goal for monitoring of military personnel during training scenarios. Thermal monitoring and injury prevention (through workload monitoring) will remain as key areas of interest for Singapore.

Singapore also has a long-standing soldier modernization project called the Advanced Combat Man System (ACMS). Dating to 1998 and still ongoing, this project aims to provide state-of-the-art personal armour, communications capabilities, and situational awareness to soldiers (Ministry of Defence, Singapore 2012). There has been some work on physiological monitoring under the auspices of ACMS. For instance, a system has been described for monitoring heart rate, brain activity, oxygen saturation, and accelerometry via an instrumented helmet (Lim 2010). However, this work appears to be in early stages, and a recent press release positioned physiological monitoring within the ACMS as one among several possible future directions (Qiang 2015).

3.9 Spain

The Spanish Ministry of Defense has funded the ATREC (Analisis en Tiempo Real del Estrés del Combatiente) project as part of its Future Combatant Program. ATREC aims to assess the mental stress levels of soldiers in real-time by monitoring several physiological metrics.

The ATREC system prototype uses custom-built sensors and electronics instead of COTS technologies (Seoane 2014). The sensor modules include an instrumented glove which monitors both skin temperature and galvanic skin response, an upper arm strap which monitors the same variables, and a chest strap which measures heart rate and respiration rate. The system also includes a smartphone which records the user's voice for analysis. Preliminary laboratory studies to predict levels of stress based on physiological data were carried out; ECG and respiratory data were found to be the best correlates of stress. This work is in an exploratory phase, and appears to be ongoing. The authors report that in future iterations of the system they intend to move to an instrumented garment model, rather than using arm and chest straps.

3.10 Russia

There is evidence that Russia also has begun to explore physiological monitoring within their military forces (Tiurin, 2014). Information is limited because only the abstract of the report has been translated from the Russian. It would appear that their work is an early, exploratory phase, and that one of their principal objectives is to use physiological data to improve combat casualty care, as well as to study the potential operational benefits to commanding officers in the field.

4 Integrated Physiological Monitoring in the CAF

4.1 Canadian Army (CA)

4.1.1 Expanding the Operational Envelope

The "Operational Envelope" is roughly defined as the limits that confine a task within an acceptable range of risk. An operational envelope may be related to speed, distance, weight/cargo requirements, duration of operations, and physiological measures such as core body temperature, fatigue and sleep requirements, and caloric/fluid requirements. A speed limit for motor vehicles on a roadway is an obvious example of an operational envelope. However, there are a significant number of operational envelopes related to human physiology and cognition. The human need for sleep and propensity to fatigue is the reason for implementing an operational envelope on work hours, and similarly, there exists an operational envelope for core body temperature—if the body becomes too hot or too cold, physiological functions are degraded.

Physiological monitoring could increase the operational envelope of individual soldiers by allowing them to push to their physiological limits, during training and operations. As a collective, physiological monitoring of a whole platoon/company would enable more data-based decision-making; for example, deciding which section is most fit for a given task.

4.1.2 Injury Prevention

4.1.2.1 Musculoskeletal Injury Prevention

Musculoskeletal injuries from strain and overuse are a common and ongoing problem in both civilian endurance athletics as well as in modern armies. Such injuries to dismounted soldiers are related to heavy loads, and often have a gradual onset that may incapacitate the soldiers, sometimes for long periods of time (Roy et al. 2012). Knee injury, for instance, is the leading cause of medical military discharge in the British Army (Sinclair 2015), and musculoskeletal injuries are the predominant non-combat medical issue among the United States National Guard (Warr 2012). Although detailed data on non-combat injuries within the Canadian Army was not available, the combat medics with whom we consulted agreed that knees and ankles are common injury sites.

Risk factors for musculoskeletal injuries in US soldiers deployed to Afghanistan include length of deployment, time spent standing, and weight of load carriage (Roy 2012). Recent studies in the Israeli Defense Force found that walking distance was positively correlated with incidence of lower extremity stress fractures (Moran et al. 2013) and also that there was high variability in distance walked among soldiers assigned to the same training program (Epstein 2015), which suggests that changes to the structure or requirements of training programs might not be an effective way to reduce overuse injuries.

However, it may be possible to mitigate such injuries through the use of wearable physiological monitors, which can provide individualized feedback on distance walked, load carried, and also detect gait abnormalities which forecast the onset of lower extremity injuries. The Swiss Army has used wearable sensor data to better understand the pattern of injuries that occur during Basic Training (Wyss 2014). It has been shown that load carriage can be estimated on the basis of a body-worn accelerometer (Williamson 2015a), and a considerable amount of work has been done exploring the identification of gait abnormalities in real-time using either body-worn accelerometers (Williamson 2015b) or force-sensing insoles (Bamberg 2010, Redd 2012). The challenge is to develop signal processing algorithms to allow for a reliable tracking of changes in an individual's gait patterns and correlation of these changes to musculoskeletal injuries.

Body-worn accelerometers have also been used to characterize the physical workload requirements of various military jobs in an effort to better match specific personnel with specific positions (Wyss 2010). Increased workloads are known to be associated with increased risk of strain injury, so it may be possible to reduce injuries by more carefully selecting soldiers for high workload positions.

4.1.2.2 Heat-Strain Injury Prevention

The use of wearable physiological monitors to prevent heat-strain injuries is an interesting possible application of the technology. Core body temperature, whether measured directly or inferred indirectly, serves as an indicator of risk of heat-strain. As mentioned in Section 3.1.2 above, the United States Army appears to have a particular interest in this application.

A soldier equipped with sensors to monitor core temperature could be alerted when his or her temperature rose above a threshold, signaling the wearer to hydrate, reduce physical exertion, or take some other mitigating action. Such a warning system might contribute to a reduction in heat-strain casualties.

Although monitoring core temperature has traditionally been a somewhat invasive process, recent studies have suggested that core temperature can be reliably inferred from less invasive measures. (Buller et al. 2013) have developed a Kalman filter model which establishes a correlation between heart rate and core temperature, thereby permitting core temperature to be predicted on the basis of sequential heart rate measurements with accuracy comparable to direct esophageal or rectal measurements. This method has been validated on a number of data sets over a range of ambient temperatures, humidities, and levels of exertion. It warrants further investigation because if it could be shown to be reliable and robust it would make heat-strain injury prevention more technically feasible and acceptable to users.

During our Infantry Focus Group we received mixed feedback on the value of using technology to prevent heat-strain injuries. The participants stated that heat strain is usually diagnosed by visual inspection (splotchy skin, lack of perspiration), and conceded that the affected individual is usually already a heat casualty by the time this diagnosis is made. While some participants stated that an early warning of heat-strain risk would therefore be very advantageous, others regarded physiological monitors as an overly complex solution to the problem, questioning whether technology was really necessary to remind soldiers to drink water. Interestingly, most participants agreed that in their experience incidence of heat-strain casualties was generally low.

4.1.2.3 Cold Weather Injury Prevention

Although Canada's most recent deployments have been to hot climates, the Army maintains a strong interest in cold weather operations, both for training (during Arctic Ops, for instance) and as a means to asserting national sovereignty in the north.

Many of the same physiological considerations apply in cold weather conditions as in hot: hydration remains important (and, as we were told at an infantry focus group, dehydration is surprisingly common in cold conditions due to the low relative humidity), and stabilization of core temperature is still critical. Naturally the risk is of hypothermia rather than hyperthermia, and the remedy is not so much to do with maintenance of hydration, but ensuring adequate clothing and exercise to increase peripheral blood flow. The innovative method for tracking core temperature non-invasively described in the previous section (Buller 2010) has not been validated in cold weather conditions.

A leading cold weather injury is frostbite (DeGroot et al. 2003), in which skin tissues freeze, and especially occurs in extremities such as hands, feet, ears, and nose (Heil et al. 2016). Risk of frostbite increases when cold weather exposure is accompanied by sustained physical exertion (Castellani et al. 2001). It would be possible to mitigate frostbite injuries through real-time monitoring of peripheral skin temperature, although we have not found this mitigation strategy documented in the literature.

4.1.3 Medical Monitoring

Physiological monitoring for medical purposes is among the leading motivations for development of wearable biosensing technology. The primary objectives of battlefield medicine are reduction of mortality and morbidity, reduction of non-battle injuries (heat, load, etc.), and improvement of casualty care. Wearable physiological monitors could contribute to the achievement of all of these objectives (Borsotto 2004). In our consultations with CAF members, members indicated that in their view medical applications of this technology were highly relevant to the Canadian Forces.

Medical applications of this technology on the battlefield can be considered under three interrelated principal headings: remote health monitoring, remote triage, and casualty management.

Physiological monitors which are integrated into a soldier system and have access to the soldier's communications network can in principle transmit physiological data for consideration by medics and commanders, which makes possible remote health monitoring. Medics typically want to know vital signs such as heart rate, respiration rate, and body temperature. If soldiers wore devices which monitored these indicators it would have clear benefits to a medic, and in our conversations with DLR-5 this was identified as a principal potential benefit of this technology. As was described in Section 2.2, the raw physiological data would ideally be processed locally on the soldier in order to extract high-level health metrics prior to transmission, although possibly with the option to pull lower-level data if desired. Decision support algorithms which translate physiological data into simple high-level metrics, such as a basic Alive/Dead/Unknown indicator, have been published (Savell 2004), and the information requirements for medics have also been assessed (Kaushik 2009).

Even in the absence of battlefield injuries, remote health monitoring could prove advantageous. In our consultation with the Directorate of Fitness (D-FIT), the potential benefits of remote monitoring for personnel on ramp duty or security duty were explored. These personnel are sometimes required to stand for long periods, even in intense heat, and fainting sometimes occurs. If the individual's health status were being monitored, it might be possible for either the wearer or a medic to be alerted if the vital signs begin to weaken. Another possible operational benefit, suggested during our consultation with DLR-5, is that a commander's ability to monitor the hydration status of his troops could pre-emptively flag the need for an emergency water resupply.

In a battle scenario, the ability to remotely monitor health makes possible technology-enabled remote triage of casualties. This could represent a significant advance over the current practice. "The call of 'MEDIC' is the most common way to remotely triage the wounded" (Blackbourne 2010). However if medics could monitor vital signs remotely, then it could be possible to identify and prioritize casualties efficiently, with a corresponding improvement in casualty management during multiple casualty scenarios. Indeed, DLR-5 identified improved mass casualty response as a key benefit of wearable biosensors.

Remote monitoring poses some challenges as well, because vital signs alone can sometimes be ambiguous. An interesting recent study attempted to use physiological data to remotely distinguish subjects undergoing physical exercise from those undergoing early stage (simulated) blood loss (Rickards 2014). Without visual access to the individual, hypovolemia (early stage) can look surprisingly similar to physical exercise: both result in elevated heart rate and respiration rate and in reduced heart rate variability (HRV). They can be distinguished on the basis of blood volume, to the extent that this can be assessed remotely. In this study, the authors relied on a machine-learning algorithm that considered ECG, heat flux, skin temperature, galvanic skin response, and 2-axis accelerometry inputs, all obtained from a SenseWear Pro 2 armband. On these bases the authors found that they were able to distinguish the two diagnostic groups with high accuracy, sensitivity, and specificity (>90% in each case). Given that 80% of potentially survivable battlefield fatalities in recent conflicts have been cases of hemorrhage (Eastridge 2012), the finding that hemorrhage can be detected via remote monitoring is highly relevant.

Wearable physiological monitors could also contribute to improved casualty care, especially by improving the availability and accuracy of pre-hospital data (Coates 2015). Soldiers who are injured and require medical evacuation are typically triaged by a medic and then transported in stages to a hospital facility. However the medical data about the soldiers' status en route is not reliably available to the hospital staff responsible for initial treatment, and this is because the pre-hospital data is usually recorded with pen and paper, and is often not transferred to the hospital chart or electronic medical record in a timely manner. The lack of pre-hospital data has been identified as a major gap in modern combat casualty care (Eastridge 2011). In fact, a recent study of the Joint Theater Trauma Registry found that fewer than 10% of patients had any recorded pre-hospital data (Blackbourne 2010), yet it is known that pre-hospital data improves outcomes. For example, a large civilian study of trauma patients found that absent or incomplete pre-hospital information/data on vital signs were associated with a two-fold increase in mortality, even after controlling for injury severity (Laudermilch 2010). Vital signs data collected with wearable physiological monitors could, with the right network infrastructure, be automatically transferred to the hospital system and made available to the medical team receiving the patient.

Vital signs collected manually in theatre and during evacuation are also likely prone to errors and omissions. Although the accuracy of pre-hospital military medical records has not, to our knowledge, been studied, in civilian contexts vital signs recorded on a paper chart have been shown to have error rates of 10% (Smith 2009) or even 20% (Fieler 2013), often due to transcription errors. In contrast, automated measurement and upload of the vital signs reduced the error rate to less than 1% in both studies.

It is worth noting that comparable improvements to the availability and accuracy of vital signs data collected during medical evacuation might be achievable even without the use of *wearable* physiological monitors. A wireless vital signs monitor that is sufficiently small and portable could be used by medics to electronically gather and transmit vital signs data during medical evacuation from a combat zone, and several such systems have been described in the literature (Salinas 2011).

4.1.4 Training

Outside of an operational deployment, a physiological sensor suite used during training exercises could improve individualized evaluations and after-action review, helping soldiers to better understand their own performance and commanders to better appreciate the relative strengths and weaknesses of the soldiers under their command. A fieldable testbed of wearable physiological sensors could also be used to evaluate the effects of, for instance, new equipment on soldier performance under simulated operational conditions. In this section we will discuss the use of physiological monitoring to enhance training effectiveness, especially fitness training, in analogy with use in athletic contexts. In our consultations with CAF stakeholders, all respondents indicated that training is a domain in which physiological monitoring technology could confer a significant benefit. In fact, this was the only domain for which all were in agreement.

4.1.4.1 Personal Fitness Training

The physical fitness of its members is important to the CAF, and it encourages better physical fitness through a number of programs and initiatives: the Canadian Forces Health and Fitness Strategy, Canadian Armed Forces Sports Programs, the Weight Wellness Lifestyle Program, and the Canadian Armed Forces Health and Wellness Challenge, to name a few.

In November 2015 the Canadian Army launched the Canadian Army Integrated Performance Strategy (CAIPS 2015), the mission of which is to “adopt a performance-oriented, health, and fitness-based culture” within the Army (CAIPS 2015b).

Physiological monitoring devices have a valuable role to play in helping individual CAF members monitor their own fitness levels and improve their physical health. In early 2016 the Army announced that it plans to acquire approximately 20,000 personal fitness tracking devices and distribute them to all Canadian Army personnel, as a means of promoting better physical fitness within the ranks. This is a reasonable strategy, as the commercial success of physiological monitors in the civilian world has been driven to a great extent by fitness-related applications, with a large industry arising around the devices and platforms that allow users to quantify their performance and fitness levels, and to track those metrics over time.

Our consultation with D-FIT identified physiological monitors as playing an important role in addressing two significant fitness-related problems within the CAF: exercise motivation and exercise safety. The massive success of the physiological monitoring industry for personal athletic and fitness trackers suggests that many people do find the data provided by the devices motivates them to exercise. The ability to set benchmarks and to compare performance against one's personal history and those of others provides an incentive to improve (Bravata 2007).

It should be noted, however, that physiological monitors are not a silver bullet solution to problems of exercise motivation. A recent study of United States National Guard personnel compared the physical fitness results achieved by those enrolled in a traditional high-intensity fitness program with those achieved by those enrolled in a less structured, pedometer-based exercise program (Talbot 2011). The study focused on personnel who had failed the National Guard's physical fitness test, and who can be presumed to have low exercise motivation or other impediments to regular exercise. The study found that over a 12-week period both groups achieved comparable gains in physical fitness levels, but also that both groups suffered comparable relapses over the subsequent 12 weeks after the program had ended. It would be naïve to assume that the mere ability to monitor and measure one's physical activity is enough to provide motivation to those who lack it.

A thorough overview of pedometer-based fitness programs for civilian populations found that participants who did not have a daily step-goal or a requirement to record the number of daily steps showed no significant improvement over baseline (Bravata 2007). Pedometer-based programs which did impose such requirements saw daily activity increase by approximately 25% on average. The fact that the participants in these studies were mainly older (mean age: 49 years) and that 85% were women limits the applicability of these findings in a military context, but does suggest that pedometer use coupled with programs to encourage daily targets or record-keeping is a more effective strategy for increasing physical fitness than pedometer use alone.

However, a more recent study focused on a group of United States Army personnel judged to be overweight, and found that simply providing pedometers to the group increased the level of physical activity, with a corresponding decrease in weight and body fat (Staudter 2011). The benefits were comparable to those obtained with a similar group who also received fitness education and were encouraged to meet a daily step target. This suggests that the pedometer alone may have been the main motivating factor for this group.

As to exercise safety, the devices provide feedback to the wearer that can warn against, for example, overexertion, as indicated by elevated heart rate or respiration rate. The devices also have a role to play in increasing exercise effectiveness. For instance, optimal fitness training often involves exercising in certain target heart rate zones, and heart rate monitors have an obvious role to play in helping the user hit that target consistently. A program which made fitness-related physiological monitors available in garrison gyms, for instance, could provide beneficial feedback to those using the facilities.

Even if physiological monitors are not used strictly for personal reasons—as, for instance, if the data were being monitored in a training or operational scenario—there is evidence that endorsement and use is more likely if users are also permitted to access the data for their own purposes (Heron 2010). Therefore it would be prudent to accommodate the personal interest which users have in their own physiological data when considering any use of physiological monitors in the CAF.

4.1.4.2 Physiological Awareness Training

The data provided by physiological monitors can help soldiers to better learn to associate their subjective sensations with objective physiological measures. The feedback provided by a wearable physiological monitor establishes an objective correlate to the way the user feels, teaching him/her what the feeling means physiologically. This is a process that every soldier goes through, but physiological monitors could accelerate the learning by providing continual feedback.

During our Infantry Focus Group, several participants agreed that such feedback would be advantageous not only in a formal “training” context, but also in-theatre, when soldiers are adjusting to types of terrain and climatic conditions different from what they experienced during their training at home. Most also agreed that such feedback would be valuable initially but would gradually become less important as the soldier’s knowledge improved, eventually rendering the monitors unnecessary.

For example, during training it might be quite beneficial for a soldier to see how tactical breathing helps control heart rate and reduce stress, but once the technique is mastered the biofeedback is no longer essential. Or, to take another example, it might be helpful to soldiers to see how carrying certain amounts of weight affect their performance and physiological status, helping them learn their personal limits more efficiently. Or, thermal feedback can teach soldiers what heat-strain feels like, especially in the early stages, so that they can learn more effectively how to hydrate and control core temperature.

Monitoring might also help soldiers to identify and mitigate unconscious behaviours which affect performance. For example, consider the case of the Dufour-Lapointe sisters, Canadian Olympic medalists, who reported that only after they began wearing wireless physiological monitors did they realize that one of them had been holding her breath at high-stress moments. Once this unconscious behaviour was corrected, performance improved even further (National 2014). In a military context the awareness-raising function of physiological monitors might have similar benefits.

4.1.5 Fatigue and Stress

Accelerometry has been used by sleep scientists for over two decades to objectively collect data about sleep quality and quantity in a non-invasive way (Ancoli-Israel et al. 2003, De Souza et al. 2003, Sadeh 2011). Several algorithms for reducing accelerometry data have been published in the open scientific literature, and have passed the test of peer scrutiny over the past several years (Cole et al. 1992, Jean-Louis et al. 2001, Sadeh et al. 1989). This is convenient for the discussion of physiological monitoring devices as actigraphy is the most common feature of physiological monitoring units today due to its small size and low weight. Therefore, every smart watch and fitness watch on the market has the potential to capture research-level sleep data from its users as long as the accelerometer is of a sufficiently high quality (measurable by quality and consistency of data).

The greatest benefit of distilling actigraphy data for the analysis of sleep quality and quantity in a military context is the subsequent capability of monitoring fatigue and cognitive performance of the user over the span of several days. During a course/exercise/operation, in which nighttime activity is a prerequisite to success, rest periods can be monitored and optimized to maintain a suitable level of cognitive functioning despite the restriction of rest periods. This is achievable with cognitive performance models that are widely used in the transportation industry (primarily air and rail, but also for land and occasionally sea transport).

In our consultations, CALWC identified one of the greatest benefits of physiological monitoring as the ability to monitor physical correlates of stress. In recent years there has been an effort, both within military organizations and outside them, to identify reliable physiological indicators of stress, so as to promote effective mitigation strategies.

For example, the Army has emphasized the value of tactical breathing as a technique to control stress arousal. This technique involves controlled breathing as a means of lowering heart rate and maintaining presence of mind in high stress situations. Physiological monitoring of respiration rate or heart rate could provide positive feedback in real-time to someone learning tactical breathing techniques, enabling a soldier to see the effects of the technique on his or her physiological state.

In addition to training soldiers in techniques to moderate and mitigate stress, there has been interest in actually monitoring the mental status of soldiers in order to ascertain fatigue, stress, or cognitive overload. This is a daunting objective which faces a number of challenges (Friedl 2007). First it would be necessary to determine what psychological metrics are the best indicators of the conditions of interest, and then to investigate whether these can be reliably identified on the basis of physiological data. For instance, if fatigue has a negative impact on working memory and is associated with lower blood glucose, than it may be possible to draw inferences about fatigue status from wearable glucose monitors. Similarly, it might be possible to draw conclusions about cognitive status based on data from a wearable EEG monitor or from eye movements (Matthews 2007). However, this is a subject that is not mature and we are not aware of reliable and robust correlations between psychological metrics and physiological measurements. Research at the DRDC Toronto Research Centre is currently being conducted to explore this.

4.1.6 Capability Development

An intriguing role for physiological monitors that emerged in the course of our consultations with the CAF was as a tool in the service of capability development. The potential of this application was especially stressed during conversations with CALWC, but it was a theme common to a majority of our respondents.

Physiological monitors could assist with the evaluation of new equipment, processes, or tactics because they could provide quantitative evidence as to whether a proposed change has a positive, negative, or neutral impact on soldier performance. Such evidence could inform acquisition planning or future soldier system development. For example, if the Army is considering new equipment for dismounted soldiers, its effects on soldier performance could be evaluated by conducting an experiment in which the old and new configurations are compared, with at least part of the data for comparison coming from soldier-worn physiological monitors. A model for this sort of evaluation is the Load Effects Assessment Program (LEAP) programme (Bossi et al. 2014).

4.1.7 Niche Areas

4.1.7.1 Chemical Biological Radiological and Nuclear (CBRN) Operators

Chemical Biological Radiological and Nuclear (CBRN) Operators wear personal protective equipment which establishes a microenvironment for the user to protect him/her from exposure to an unknown chemical or biological hazard. If deployed in a warm environment for an extended period of time, a CBRN operator is at a greater risk of heat illness due to the inability to readily dissipate heat (Petruzzello et al. 2009). In this context, physiological monitoring devices with real-time core temperature monitoring would provide vital information about the individual's vital signs and core temperature so as to limit the risk of injury during an emergency response.

4.1.7.2 Sniper Training

The relevance of physiological monitoring to the training and performance of marksmen was suggested during our consultation with D-FIT. Effective marksmanship requires focused attention, sensitive motor control, and emotional regulation. A substantial literature exists exploring the physiological correlates of expert marksmanship.

Numerous studies have used EEG monitors to investigate the patterns of brain activity associated with effective marksmanship, with both pistols and rifles (Konttinen 1992, Hillman 2000, Kerick 2001, Loze 2001, Deeny 2003, Janelle 2008). These studies indicate that effective marksmen exhibit several consistent patterns of cortical activation in the moments leading up to a shot, especially in areas of the brain associated with attention, and that they exhibit a relatively low correlation between cognition and motor processes, suggesting that long practice has made the process of shooting "second nature" to experts. Significant differences have been observed between brain activity preceding accurate shots and that preceding inaccurate shots (Konttinen 1992, Loze 2001). Differences between the brain activity of expert and novice marksmen have also been studied, with interesting results. Experts, for instance, exhibit lower overall levels of cortical activation than novices (Haufler 2000), but higher attention immediately prior to a shot (Doppelmayr 2008), and experts are also associated with more effective visuospatial processing (Pojman 2009). In general the findings support the view that marksmen undergo changes in cerebral cortex activity with greater practice.

Other physiological indicators have also been studied within the context of marksmanship, with heart rate being among the most important. Deceleration of heart rate prior to a shot is one of the simplest and most robust patterns associated with effective marksmanship; after the shot the heart rate rebounds to normal levels (Konttinen 1992, Daniels 1994, Konttinen 1998, Robazza 1998). Lower heart rate levels are associated with greater experience and higher accuracy shooting (Tremayne 2001, Borsotto 2012). Similar patterns have been observed in measurements of skin conductivity in the context of marksmanship (Tremayne 2001). Respiration patterns of expert marksmen have received modest attention, with the basic finding being that the timing of a shot usually correlates with slow exhalation (Konttinen 1992).

The existence of these fairly reliable associations between physiological indicators and superior marksmanship suggests that there could be role for the use of physiological monitors in the training of marksmen. Monitoring could help to identify, for instance, particular weaknesses in those undergoing training, flagging them for focused development (Pojman 2009). Biofeedback of heart rate and respiration rate have been associated with improved shooting performance (Daniels 1981), so simply equipping marksmen with physiological monitors might help them to better understand their bodies and improve their performance. In this connection, one company has developed the Adaptive Peak Performance Trainer which monitors EEG and heart rate and provides biofeedback to in-training marksmen. They report that the feedback is indeed correlated with improved shot accuracy (Berka 2010, Behneman 2012).

4.1.8 Enhancement of Soldier System Technology with Physiological Sensors

The Canadian Army is currently in the process of upgrading its soldier system under the auspices of the Integrated Soldier System Project (ISSP). The ISSP is intended to enhance the soldier's capability to fight effectively and efficiently by increasing situational awareness and improving battlefield communication. The planned system will include a GPS receiver, a smartphone-like computing hub with, among other things, a mapping capability, as well as an improved radio and enhanced communications headset, all of which allow the soldiers to communicate over a field-deployed network. This will be a significant step toward providing Canadian soldiers with a tactical advantage on the battlefield (ISSS 2013).

Future enhancements to a soldier system platform might include a suite of physiological monitors. Consider a deployed force in which soldiers were equipped with sensors that provided biofeedback about their health status. Each soldier would be able to monitor their own status, taking measures to mitigate overstress and injury when necessary, and suitably filtered collective status updates could be communicated up the chain of command in real-time over the tactical network, providing commanders with a bird's eye view of the health status of their personnel. Medics, too, would have access to status updates on each of the soldiers, with the ability to drill into details if desired. In a battle scenario, physiological data coupled with GPS location data would help commanders to better appreciate battlefield dynamics, and the same data would help medics to remotely triage the wounded and organize a more effective medical response. In the event of a casualty, the physiological data recorded by such a system might serve as a "black box" to help better understand the nature of the casualty and the conditions under which it occurred, on analogy with the data recording devices used in vehicles.

4.2 Royal Canadian Navy (RCN)

4.2.1 Expanding the Operational Envelope with Physiological Monitoring Devices

Human physiology constrains the operational envelope aboard RCN vessels, just as it constrains operations on a battlefield. A speed limit for vessels in a narrow canal is an obvious example of an operational envelope. However, there are a significant number of operational envelopes related to human physiology and cognition. The human need for sleep and propensity to fatigue are the reasons for operational envelopes on workhours. However, in a situation of high operational tempo, what would be the risks of working the tactical (1-in-2) crew 18 hrs per day? The risks would certainly be vastly different if sleep quality for the 6-hrs off-watch period was very high, as opposed to being very low. What would happen if the boat or ship in question was involved in an international anti-piracy effort such as Operation Ocean Shield, or similar? As an example, a sonar operator who was intensely drowsy because of limited off-duty rest opportunity and low quality of sleep could miss cues and thereby jeopardise the safety of the entire crew. These are situations in the RCN where real-time physiological monitoring could offer benefits. With a physiological monitoring device that tracks sleep effectively, the sonar operator from our previous example could visit the MIR on the ship prior to going on duty, for a short-term fatigue countermeasure, such as caffeinated gum, and a prescribed time course for its use. It should be stressed that this would be a short-term solution—an Op Tempo that demands 18-hr workdays from the crew is not sustainable for more than a few days; however, the risks of degraded cognitive functioning, and reduced vigilance specifically, can be managed with the use of physiological monitoring devices and appropriate fatigue countermeasures.

4.3 Royal Canadian Air Force (RCAF)

4.3.1 Expanding the Operational Envelope with Physiological Monitoring Devices

The RCAF generally have well-defined Operational Envelopes when it comes to pilot hours, maximal speed and flight durations, payload constraints, airframe service requirements, and financial constraints. For example, the RCAF has operational limits on how many hours a person can fly, length of rest periods, and similarly, how many hours an air asset can operate before it must be serviced. Technology can be used to expand the operational envelope in many cases, and one example may be payload maximization with logistics software or flight planning tools, which similarly act to ease the financial constraints on the transport Wings, and the RCAF as a whole. When it comes to the human element, operational constraints are put in place by Transport Canada or the FAA; however, these are generally conservative numbers that the regulatory agencies have put in place to protect the safety of the public. In an operational context, these limits may simply not be practical, and going beyond these limits does not necessarily cause an increased flight safety risk if physiological monitoring tools are being used, because of their ability to quantitatively track crew rest intervals.

5 Conclusions and Recommendations

We have given an overview of possible applications of wearable physiological monitors within the CAF. After providing an overview of the current and future capabilities of wearable biosensors, and of the main design objectives of an effective physiological monitoring system, we gave an overview of international military activities involving wearable devices. Informed by consultations with stakeholders and subject matter experts within the CAF, we then described and discussed numerous ways in which physiological monitors could contribute significantly to the effectiveness of the Canadian Army. In this Section we summarize our principal conclusions and make several recommendations to guide future work in this area.

There is widespread international interest in using wearable physiological monitoring technologies to improve the safety and performance of soldiers, and many nations have undertaken efforts to employ this technology for military benefit. The United States has invested the greatest effort and resources to date, and is, to our knowledge, the only nation with an active program to develop a physiological monitoring system for operational use in the relatively near future. Other nations have focused their efforts on using wearable biosensors for research purposes, in order to better understand the scope of application of these technologies and to advance the quantitative study of soldier performance. Some nations have announced their intentions to employ wearable biosensors for operational use at a future date.

– **Recommendation 1:** Canada should continue to participate in international military research forums related to wearable physiological monitors in order to offer expertise, report on Canadian activities, and stay informed about the activities and intentions of our allies with respect to this technology.

A principal application of wearable physiological monitors is to provide biofeedback for injury prevention. As described in this report, biofeedback could mitigate heat strain injuries by providing measures of core body temperature, reduce cold-weather injuries such as frostbite by monitoring peripheral skin temperature, reduce fatigue-related injuries by providing objective measures of sleep quality as input to fatigue prediction models currently used by the Air Force and Navy, to limit lower extremity repetitive strain injuries by monitoring foot impact forces and gait abnormalities, and by promoting more effective tactical breathing techniques for arousal control in high-stress environments, among other applications.

Several specific applications which combine scientific interest with significant potential to positively impact CAF performance have been identified.

– **Recommendation 2:** If the Canadian Army chooses to endorse further scientific research to develop and exploit the capabilities of wearable physiological monitors, topics deserving consideration include:

  – Further development and validation of a proposed method (Buller 2013, Seng 2016) to predict core body temperature on the basis of heart rate observations. If proven reliable, this method is likely to mitigate incidence of heat strain injuries. (See Section 4.1.2.2.)

  – Adapting existing models of fatigue developed for the Air Force and Navy for use in the Army. The models are reliant on sleep quality metrics derived from a body-worn accelerometer. (See Section 4.1.5.)

- Given the Army's commitment to tactical breathing training to help soldiers in high-stress situations, a study investigating the efficacy of biofeedback, especially of respiratory rates and heart rates, in promoting and enhancing such training might be warranted. (See Section 4.1.4.2.)
- In support of the Canadian Army Integrated Performance Strategy (CAIPS) the Army will provide personal fitness tracking devices to Army personnel as a means of encouraging greater physical fitness within the Forces. Studies suggest that fitness trackers yield better results when accompanied by specific activity targets. To better realize its objectives, therefore, the Army should consider combining the acquisition of fitness tracking devices with a fitness program to encourage their use. (See Section 4.1.4.1.)

A physiological monitoring system consists of sensors, which provide raw and usually noisy data, and a set of user interfaces presenting high-level health indicators that are tailored to the needs of specific users (whether an individual soldier, a medic, or a commander). Between the raw data and the high-level health status indicators are a set of data processing algorithms which, among other things, filter noise, monitor data quality, reduce data quantity, extract important features, and construct health status indicators that are robust and informative. Sensors are being continually improved by the competitive commercial market, but the algorithms to produce high-level indicators of military relevance and meeting military-grade standards of reliability are lacking. Therefore, a gap has emerged between the data that is provided from the COTS devices, and the information that is required by commanders or medics.

Furthermore, information display systems must be generated so as to limit the cognitive burden on the user; in fact, the information display systems should be designed in such a way that they do not need to be continuously monitored, but simply checked or referenced when warning thresholds are exceeded. Information provided by physiological monitoring systems is relevant to commanders and medics, but without an advanced information display system, the data from these devices is unusable during training courses or operations.

- **Recommendation 3:** Future research should focus on development of data processing algorithms to produce informative and reliable high-level health status indicators, relying on commercially available sensors to supply raw data.
- **Recommendation 4:** Information display systems for targeted user groups must be developed and put through a rigorous regime of testing and revision for the unique user groups that exist within the Canadian Army (e.g., soldiers, medics, and the various levels of Commanders).
- **Recommendation 5:** Given the rapid pace of development of wearable biosensing technology in the civilian commercial sector, a technology watch on this topic should be maintained by Defence Research & Development Canada.

A consistent message received through our consultations with CAF stakeholders is that this technology is likely to be more readily accepted for training purposes than in an operational context. There is some skepticism within the Forces about the reliability of the technology and about the value of the information it provides, and this skepticism is not without warrant. Use in a training context would be a good opportunity to improve the design of a physiological monitoring system and to increase user confidence in it. If the technology can prove its value in training, it might then be transitioned to an operational role.

- **Recommendation 6:** Future work with physiological monitors should focus first on using the technology in a training context with sufficient research support, in order to mature the technology and educate users, prior to any attempts to use it operationally.
- **Recommendation 7:** To support capability development and further research on quantitative measures of soldier performance, a portable testbed of physiological sensor systems should be developed by DRDC, for use in scientific research or by commanders of the various training courses. This would increase the data available to the course officers, and the data generated would support capability development and research on soldier performance.

There is considerable scope for wearable biosensors to improve medical monitoring and casualty care. A body-worn physiological monitoring system integrated into a tactical network could promote more effective injury mitigation and greater efficiency by enabling remote monitoring of soldiers' health status and remote triage in the event of casualties. Moreover, the availability of continuous physiological data would provide a more complete and consistent record of a casualty's status during evacuations and reduce errors and data loss during transfer of care. The technology would need to meet high standards of reliability in order to be used in these ways.

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Appendix A Integrated Physiological Monitoring Sensors Questions

Integrated Physiological Monitoring Sensors
Questions

1. How informed do you feel you are about the capabilities of wearable physiological monitors?

   Very Somewhat Slightly Not at all

2. Have you had any practical experience with wearable physiological monitors? If so, please briefly describe.

3. Assuming that reliable wearable physiological monitoring technologies were available, in what contexts to you think they would provide a significant benefit? (All that apply.)

   a. Operational (in-theatre);
   b. Training;
   c. Medical;
   d. Assessment of soldier systems and equipment;
   e. Other.

   Comment:

4. In your judgment, what principal benefits could result from the use of wearable physiological monitors?

5. In your judgment, what principal challenges or difficulties could result from the use of wearable physiological monitors?

6. Who would benefit most from the data produced by wearable physiological monitors?

   a. Unit commanders;
   b. Individual soldiers;
   c. Other.

   Comment:

7. A. Can you describe a significant problem or deficiency that you think could be addressed by the use of wearable physiological monitors?

B. On a scale of 1 to 10 (with 1 being mild and 10 being critical), how would you rank the severity of this problem or deficiency?

8. What do you consider the principal impediments to the use of wearable physiological monitors?

   a. Technological;
   b. Programmatic;
   c. Financial;
   d. Ethical;
   e. Legal;
   f. Other.

9. In your judgment, to what degree is such technology likely to provide a more reliable indicator of health status / readiness / fitness level than the methods currently used?

   Greatly   Substantially   Moderately   Marginally   None

   Comment:

10. Are you aware of any activities to develop, investigate, or deploy physiological monitoring technologies among Canada's allies (NATO, TTCP, other?)? If so, are you able to provide any details or contact information that would allow us to learn more? (If details are sensitive or classified, we can obtain contact information through appropriate channels.)

11. Please indicate the service with which you are most closely affiliated? (All that apply.)

    a. Army;
    b. Navy;
    c. Air Force;
    d. Other.

12. Please indicate the sphere of activity with which you have the greatest knowledge and experience?

    a. Operational;
    b. Training;
    c. Medical;
    d. Other.

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Background: Wearable physiological monitors provide real-time information about many aspects of a person's physical state. They can provide biofeedback to assist tactical breathing and arousal control, core/skin temperature, breathing rate, heart rate, oxygen saturation, or quantification of sleep/fatigue, along with a range of other measurable physiological parameters. These measures can be useful to improve the effectiveness of training, or to prevent injury in the training area or on the battlefield.

Methods: Several data collection approaches were used in the writing of this report. In order to better understand the attitudes and outlook within the Canadian Armed Forces (CAF) with respect to our topic, we consulted numerous individual stakeholders within the CAF through questionnaires and focus groups, including members of the Infantry, combat medics, the Directorate Land Requirements (DLR), the Canadian Army Land Warfare Centre (CALWC), Canadian Forces Health Services (CFHS), and the Directorate of Fitness (DFIT). Furthermore, we attempted to learn as much as possible about the activities and interests of other nations in this technology domain by soliciting feedback through The Technical Cooperation Program (TTCP) Technical Panel 19 (Human Systems Performance (Land)) and North Atlantic Treaty Organization (NATO) RTO HFM-260 (Enhancing Warfighter Effectiveness with Wearable Biosensors and Physiological Models).

Results: We have found there to be widespread interest in physiological monitoring devices internationally. However, the United States military (Army) is currently the only nation that is moving forward with operationalizing the technology; other nations are using the technology primarily as a research tool at this time. Our CAF consultations revealed that there is interest and a high degree of comfort with using physiological monitoring devices as a training aid in the near future, and potentially during operations once significant confidence and experience with the technology is obtained. We have also found that there is currently a significant gap between data output from Commercial Off-the-Shelf (COTS) devices and the information required by commanders and/or medical staff. A substantial R&D effort is required to reduce the data from the physiological monitoring devices and present it to commanders and/or medical staff in the form of a dashboard containing only the most vital information.

Conclusions: This report explores potential applications of this technology within the CAF, with a focus on the Army, and reviews the recent activities of other nations in this technology domain.

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Physiological Monitoring; Biosensors.