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Military applications of soldier physiological monitoring☆

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ABSTRACT

Wearable physiological status monitoring is part of modern precision medicine that permits predictions about an individual's health and performance from their real-time physiological status (RT-PSM) instead of relying on population-based predictions informed by estimated human, mission, and environmental/ambient conditions. RT-PSM systems have useful military applications if they are soldier-acceptable and provide important actionable information. Most commercially available systems do not address relevant military needs, typically lack the validated algorithms that make real time computed information useful, and are not open architected to be integrated with the soldier technological ecology. Military RT-PSM development requires committed investments in iterative efforts involving physiologists, biomedical engineers, and the soldier users. Military operational applications include: (1) technological enhancement of performance by providing individual status information to optimize self-regulation, workload distribution, and enhanced team sensing/situational awareness; (2) detection of impending soldier failure from stress load (physical, psychological, and environmental); (3) earliest possible detection of threat agent exposure that includes the "human sensor"; (4) casualty detection, triage, and early clinical management; (5) optimization of individual health and fitness readiness habits; and (6) long term health risk-associated exposure monitoring and dosimetry. This paper is focused on the performance-related applications and considers near term predictions such as thermal-work limits, alertness and fitness for duty status, musculoskeletal fatigue limits, neuropsychological status, and mission-specific physiological status. Each new measurement capability has provided insights into soldier physiology and advances the cycle of invention, lab and field testing, new discovery and redesign.

> "Unless the void that exists between the scientist or engineer and the war fighter is recognized, a hiatus will exist between the inventor who knows what they could invent, if they only knew what was wanted, and the soldiers who know, or ought to know, what they want and would ask for it if they only knew how much science could do for them. You have never really bridged that gap yet."
>
> Winston Churchill, World Crisis, v. 2, 19271

1. Introduction

Wearable physiological monitoring can provide predictions about an individual's health and performance from their real-time physiological state. This precision medicine approach offers major improvements over population-based predictions derived from ambient conditions and the general context of a mission. Advances in computing power and microelectronics make possible this improvement in human performance assessment, with real time physiological measurement capabilities and data processing that can provide actionable and important information about the individual. This review summarizes current progress in the development of these systems for military applications.

Previously, predicting soldier work-rest cycles and training limits could only be addressed using generalized models based on estimated inputs about individuals and ambient conditions.[2] In this example of thermal-workload limits, real time physiological status monitoring (RT-PSM) now provides new military capability with individual assessment of soldier performance limits.[3,4] The technological advance has come about by turning the focus inward, to consider the actual state of an individual, instead of extrapolating from external conditions and assuming typical responses. Thermal-work strain monitoring is one of the first military PSM applications to be used outside of the research community but provides only one example of near term uses (Table 1).

Currently available commercial systems generally do not satisfy the requirements for military use. Even when the systems offer

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Table 1
Some military applications of wearable physiological monitoring technologies.

Soldier performance and readiness applications (to be used by soldiers) and leaders)

Specific outcome assessments in near term system development
- Thermal-work strain limits
- Alertness and fitness for duty
- Impending musculoskeletal injury & physical fatigue limits
- Neuropsychological status (mood and cognitive status)
- Pulmonary exposures limiting performance
- Specialized environmental exposures (e.g., hypoxia, peripheral cold monitoring)

Some likely use cases
- Training to personalized safe limits of performance
- Mission decision support tool (e.g., optimized route, pacing, soldier status)
- Physiological controller for performance augmentation systems (e.g., agile microclimate cooling, exoskeleton activation/proprioception)
- Man-machine interface to distribute workload (i.e., stress management)
- Biofeedback to train self-regulated performance
- Situational awareness in networked squad (i.e., shared sensing)
- Materiel testing and acquisition/product selection decision tools

Health and medical management applications (to be used by medical) providers)
- Casualty detection, remote triage, and medical management (e.g., hemorrhage)
- Chemical/biological threat agent exposure – early detection and management
- Environmental/military occupational exposure dosimetry (e.g., blast exposure)
- Health readiness behavioral management tool (e.g., Army Triad initiative)

something more than raw physiological data, computed information such as recent sleep history or caloric expenditure, is usually based on proprietary algorithms that cannot be properly reviewed and validated, making the output unusable. Unsecure and power-demanding Bluetooth connections and proprietary architectures cannot be easily integrated into tactically secure systems and military communications networks. The systems should not add significant weight to the soldier and they cannot require daily recharge or battery replacement. Thus, reduced size, weight and power (SWaP) is critical to soldier acceptability and tactical usability and relevant applications are best developed iteratively with the intended users. These are some of the considerations to making a RT-PSM system fit into the technological ecosystem of the soldier (Fig. 1).

The critical component of a RT-PSM system is the algorithm that turns data into useful and actionable knowledge for a soldier or a small unit leader. Useful information from a RT-PSM system is defined as vitally important alerts that can be acted on to affect the outcome of a mission or, in a training environment, to improve safety and effectiveness of the training. Physiological telemetry has been an important research tool to investigate the full range of normal human responses outside of the laboratory; however, reams of raw physiological data are not particularly useful in military applications. Even to a trained medic, a parameter such as elevated heart rate could mean variously that an individual is: properly activated for peak performance, hemorrhaging and needs urgent care, or experiencing psychological distress. The validated algorithms that turn data into useful information are fundamental to RT-PSM, and these algorithms should then guide the minimal sensor set that is required. A technology "push" from new and interesting sensors must be at least matched by an informed "pull" strategy driven by Army problems and leader information needs. This represents the coordination gap that Churchill identified: "what the inventor could invent" and "what the soldier wants".[1]

2. Field measurement of energy metabolism and workload demands

Energy expenditure is a metabolic parameter that is fundamental to many models and applications involving thermal, workload, and injury risk predictions. For example, cold injury risks can be significantly reduced during high energy expenditure with metabolic heat production, while high physical activity levels are increasingly limited in hot environments. Activity energy expenditure (AEE) has been used to assess workload; fatigue limits for commander foot march planning have been expressed in terms of energy expenditure rates (although endurance time for operational missions and overuse injury risk in training would be more practical translations of the workload information). Total daily energy expenditure (TDEE) estimates are also used for fitness and weight management programs. Generalized predictions of AEE and TDEE are not good enough. For example, population-based predictions of energy expenditure such as the original Goldman–Givoni model and subsequent modifications provide general planning estimates for walking speed and load carriage but are inaccurate, with underprediction of metabolic costs by as much as one third.[5] The recently reported Ludlow–Weyand model simplifies assumptions to walking speed, grade, and total mass and may prove to be more generalizable, but this needs to be fully evaluated.[6]

Wearable systems have typically estimated individual TDEE from heart rate or accelerometry.[7,8] Triaxial accelerometry on the trunk improves TDEE estimates over that predicted simply from age, body mass, and height, with estimates within 1 MJ/d.[9] The location of the sensors on the body is an important factor in capturing the desired information. Wrist-worn heart rate measurements are less reliable than chest or trunk, even after correction for motion artifacts during intense exercise.[10] If only one sensored site is available, trunk is also more reliable than wrist for accelerometry-based TDEE.[11] This is unfortunate as wear compliance is generally better with a wrist-watch like system than other typical body sites. Boot-worn systems can accurately estimation activity-based energy expenditure (AEE) and classify types of activity.[12] Simple foot contact time from a boot-worn device provides AEE.[13] Measures of foot contact time and heart rate over a period of time also track changes in aerobic fitness of an individual.[14] Measuring distance traveled, including inertial navigation and global positioning systems, combined with barometric measures to measure movement up and down, further increase opportunities to improve AEE estimates.[15]

Monitoring workload associated with physical training injury risk is an important target for wearable technologies as musculoskeletal injuries continue to be a major modifiable component affecting military readiness.[16] Energy expenditure is only one component of these predictions. Patterns of movement and ground reaction forces may predict impending injury, permitting preventive "prehabilitation" such as gait retraining or other interventions. Sophisticated but intrusive wearable systems have been used experimentally for field biomechanical assessments. Simpler "smart shoe" devices with sensors on each shoe have provided useful performance data based on pattern analyses.[17] It has been rather more difficult to develop suitable footwear inserts to measure ground reaction forces without causing foot irritation and without rapidly breaking down from use; a notable line of inquiry led by Reed Hoyt has explored a succession of strategies ranging from sensors in form-fitted insoles to acoustic ground sensors to piezoelectric foam technologies. Development efforts in the Netherlands and the U.S. have produced prototypes for field studies on training workload and load carriage.[18,19] Parallel efforts have demonstrated the feasibility of estimating ground reaction forces using only inertial sensors worn around each ankle, suggesting other options outside the boot.[20]

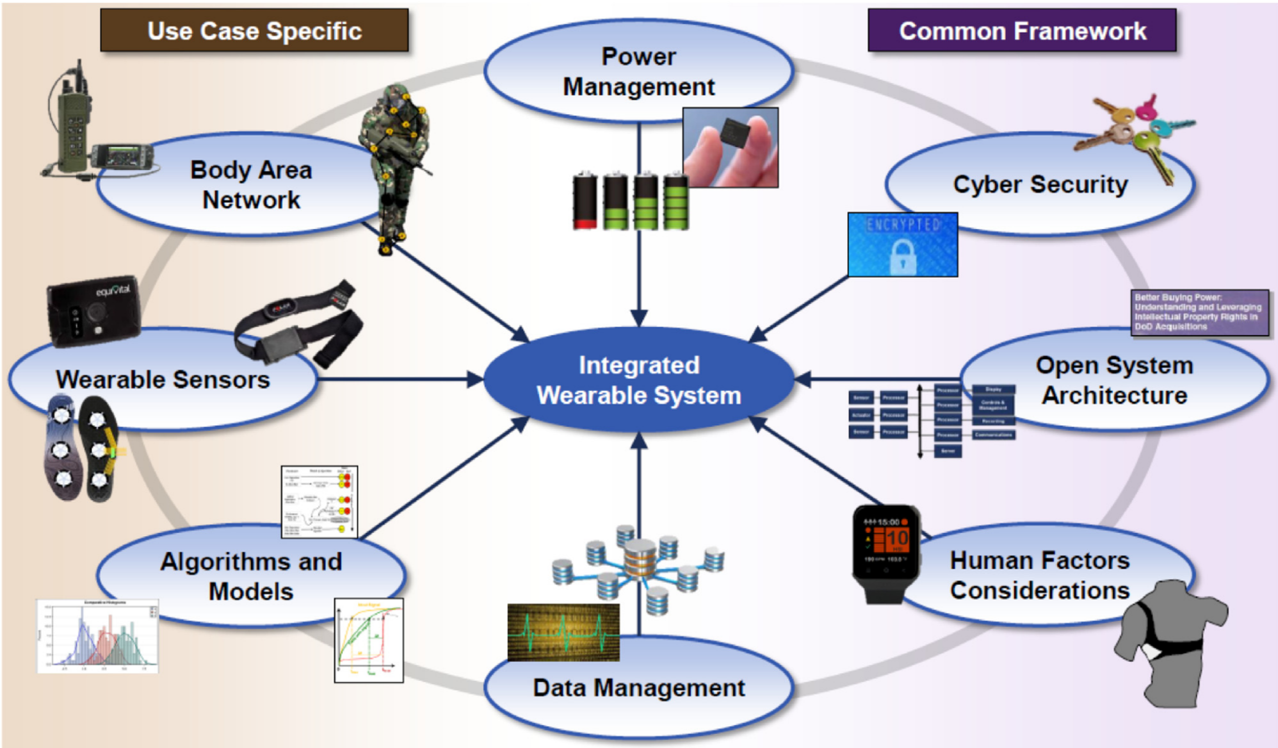

Fig. 1. The range of technical considerations for a real time physiological status monitoring system includes much more than the algorithms and physiological measurements discussed in this paper. Close partnerships with the developer and user communities are necessary to the actual implementation of a soldier useable system.
Source: Reed Hoyt (USARIEM) and Jeffrey Palmer (MIT Lincoln Labs), unpublished.

More direct TDEE measurements may be obtainable with new portable metabolic monitors that measure expired O_2 and CO_2, represent technology advances that make century-old concepts feasible.[21,22] The advantage of more portable metabolic monitoring systems is the access to more detailed aspects of energy metabolism such as macronutrient nutrition. Knowledge about shifts between lipid and carbohydrate metabolism provide insights about physiological posture in extreme conditions as well as more routine uses such as progress in weight management.[23] New technologies to measure water turnover/flux will provide future sensing of water balance related to performance for more precise and optimal hydration.[24,25] Advances in metabolic monitoring are opening the door to assessment of key circulating components of energy metabolism such as glucose and lactate, associated with fatigue limits affecting physical, cognitive, and behavioral performance. Minimally invasive continuous glucose monitoring systems have greatly improved individual management for diabetics; however, these systems still require some form of analyte sampling through the skin.[26] Improved transcutaneous spectroscopic methods, sweat sampling systems, and even breath analyses currently under investigation may soon reduce metabolic assessments to noninvasive wear-and-forget systems.

3. A wearable monitoring application success: thermal-work strain

In clinical medicine, hyperthermia is confirmed by temperature measurement in the context of an individual exhibiting neurological symptoms. But simply measuring core temperature to detect hyperthermia without this context belies the physiological adaptation to persistence hunting. Humans are uniquely suited for endurance running at high temperature, and core temperature sustained at over 40 °C for several hours in marathon runners is associated with peak performance rather than indicating a medical emergency (of course, soldiers have additional thermal and workload burdens, including personal protective equipment).[27] Thus, the core temperature monitoring with the ingestible temperature pill has provided a useful field research tool, but simple core temperature monitoring or prediction does not solve the problem of detecting individuals approaching their limits of work in the heat.

Safe work limits have been addressed with thermal-work strain (TWS) indices, using inputs such as core temperature combined with heart rate,[28] and several other developments have made this a practical solution. One was the development of a core temperature predictive algorithm based on analysis of time series heart rates to replace the need to swallow temperature pills.[29] Another was the development of a sufficiently accurate and reliable physiological measurement system. The U.S. Army invested heavily in the testing, integration, and validation of monitoring technologies which resulted in a commercially available chest worn system.[4] Recent efforts have further reduced RT-PSM size, weight and power requirements, improved comfort, and provide tactically acceptable communications. A third aspect of improving practical but reliable individual estimates of TWS limits has been the development of an adaptive TWS index.[3] The Army National Guard Bureau is an early adopter of this enhanced capability, using RT-PSM technology to closely monitor limits of individuals performing critical tasks while encapsulated in protective suits in specialized operations by their Weapons of Mass Destruction Civil Support Teams (WMD-CST).[4] Personalized monitoring in hot training environments is also being investigated, where it could improve training effectiveness by permitting higher training workloads than might be predicted by group-based predictive heat strain models.

Simple core temperature also does not provide actionable information regarding hypothermia. Large drops in core temperatures have been observed without medical consequences in

Ranger students and Marine Infantry school officers during high risk field training, while hypothermia deaths have previously occurred unexpectedly in moderate temperature conditions. Productive monitoring approaches will likely center on indicators of thermoregulatory failure such as cessation of intense shivering thermogenesis.[30] This area of research is still immature although the effects of cold on hands and feet is being intensively investigated with skin, boot, and glove temperature sensing to prevent peripheral freezing cold injury and to sustain critical performance capabilities, especially involving hands.[31]

4. Early models of alertness and fitness for duty assessment

Situational awareness is a critical component of soldier readiness and this is an important target for alertness monitoring. Sustained alertness applies to the point man on patrol, sentries, or even military technicians monitoring computer displays. Even well rested individuals concentrating on threat detection and friend–foe identification begin to increase errors after two hours of sustained effort. Vehicle drivers face alertness challenges in tactical settings, especially driving in low light conditions at night. Soldier effectiveness is reduced during night operations when performance circadian rhythms are lowest and sleep drive is highest and attentional lapses and micro sleeps increase markedly with inadequate sleep.

Early concepts for fatigue and acute alertness monitoring were as simple as a mercury switch on the back of the helmet to detect head bobbing. A more sensitive measure of attentional lapse uses infrared reflectance to detect slow eyelid closure (PERCLOSE), tracking retinas from a dashboard mounted system. This is more reliable if built into a helmet or glasses that move with the head to maintain alignment with the eyes. Eye movements ("oculometrics") such as eye blinks, eye saccades, and pupillometry have long attracted fatigue researchers as performance assessment predictors but are still only promising possibilities.[32,33] Despite a large Army investment in oculometrics evaluation systems intended for assessment of fitness for duty, the technology has not matured. More complex EEG monitoring of alertness has been demonstrated by computational neurophysiologists[34] but has always been hampered by limitations on computing power and speed as well as the intrusiveness of the EEG scalp electrodes. When power is not a limiter, such as in a vehicle or aircraft, EEG monitoring of soldier fatigue is feasible and has been used in performance research, but a full array of scalp electrodes is overly intrusive for routine use.[35] Simpler single channel EEG systems have been developed that might eventually be positioned in a cap or in a helmet headband.[36] The French military is now using a system developed by military researchers to optimize rest and flight schedules and to modify tactics, techniques and procedures for more effective performance.[37] This represents an important near term military PSM application. The value of near infrared spectroscopy forehead measurements, perhaps in conjunction with single channel EEG, may add to alertness predictions.[38]

Measurement of sleep history has been used to predict alertness status, especially when combined with the variation in alertness expected through the circadian cycle in a two process sleep and performance model.[39] General conclusions can be drawn about decreased performance and attention at various levels of sleep restriction or hours of sleep deprivation but many moderating factors from genetics of sleep resilience to the effect of naps and caffeine confound reliable performance predictions.[40] Sleep history is obtained from total sleep time estimated by triaxial accelerometry. The commonly used algorithms predict sleep duration with >90% reliability but are poor at correctly classifying wake state (~60%).[41] Nevertheless, sleep monitoring appears to help improve sleep behaviors in soldiers, providing benefit to health readiness initiatives.[42] Reliable measurement of sleep quality (e.g., sleep stages) outside of a laboratory will be important to development and evaluation of attempts to compress restorative sleep in the field for soldiers; feasibility of correctly measuring deep sleep and REM sleep stages with a wrist-worn system has been demonstrated.[43] More studies are also needed on the translation between the psychomotor vigilance task, the performance outcome measure often used in sleep laboratories, and militarily-relevant performance outcomes.[44]

5. Neurophysiological assessments of performance readiness

Military leaders would like to have some assurance that individuals are competent to make critical decisions and to know if someone is about to fail due to overwhelming psychological stress. Early research efforts during the Korean War investigated predictive stress markers, and neuroendocrinologists further clarified stress mechanisms in combat studies during the Vietnam War.[45] The markers that are useful in measuring acute stress, including appropriate stress responses to a novel threat, do not appear to be useful predictors of imminent failure. Measureable physiological responses such as changes in skin conductance, heart rate and heart rate variability, and components of voice are consistent markers of acutely stressful events such as parachute training and confidence courses.[45] Voice stress analysis detects an emotionally stressful event and this response diminishes with increasing confidence in subsequent trials, while elevated heart rate is a persistent feature of appropriate stress activation in preparation for a dangerous task.[45] Similarly, landing on a pitching aircraft carrier deck in a storm at night provokes appropriate and measurable physiological responses that are interesting in characterizing an emotionally significant event and stress activation but do not provide actionable information.[45]

New approaches from the growing field of affective computing, based on other aspects of voice and behavior, show predictive value in important outcomes such as depression and cognitive impairment. A DARPA initiative, Detection and Computational Analysis of Psychological Signals (DCAPS), was organized to target "honest signals" in human behavior that signal psychological status. This led to advances in voice stress analysis, assessments of social interactions through modern media, and the development of physiologically aware virtual agents (PAVA) such as the Institute of Creative Technologies' "SimSensei," incorporating mental status monitoring technologies such as eye gaze, body posture, voice analysis, and even speech content analysis.[46,47] Components of speech have been further dissected by providing a differential assessment of involved brain domains.[48] Combined with facial unit activation, voice analysis can successfully distinguished depressed patients from nondepressed.[49] Patterns of movement have been used to detect changes in cognitive status. Meandering patterns of movement, reflected in a high fractal "D" score, identify cognitive impairment and separate demented from normal veterans.[50] This may also identify individuals with persistent symptoms following traumatic brain injury.[51] Combined with information from embedded neuropsychological testing, these technologies will provide additional insights into neurocognitive status.[52] In combination with the thermal-work strain index, this neurocognitive assessment based on changes in movement patterns might provide reliable prediction of both impending heat stroke and hypothermia. These neurophysiological efforts significantly leverage current research on wearable systems to improve the quality of life for patients with chronic diseases such as Parkinson's.[53]

Future monitoring will include other modes of sensing such as volatile odor production. We know that humans produce unique stress signals detectable by dogs, based on the emerging empirical value of diabetic alert dogs to Type 1 diabetics and psychiatric dogs to veterans.[54,55] At some point those distinguishing patterns of movement, physiological response, or secretion of volatile organic compounds may be useful in machine detection of what dogs already can detect. Human odors are a potentially rich source of information with specific volatile organic compounds produced during infection and possibly following head injury, and new olfactory receptor-lined nanotube sensing technologies make detection feasible.[56,57]

Moderating soldier "stress load" will be an important application of a neurophysiological monitoring capability. This application is an essential component of future man-machine interfacing. This was recognized in another DARPA research initiative on "Augmented Cognition," where redistribution of mental workload within teams, the amount and form of information displays, and various types of performance augmentation were all based on an assumption of a real time neurocognitive status monitoring capability.[58] Another application is to detect and help reduce maladaptive psychological stress responses in soldiers. Continued physiological activation in the hours following an intense psychologically traumatic exposure has been postulated to contribute to later trauma disorders, and psychological first aid involving pharmacological interventions has been proposed. An effective self-management calming alternative has been demonstrated using biofeedback from cardiovascular measures combined with gaming technology on a smart phone.[59]

6. Monitoring to overcome mission-specific physiological limitations

Soldier performance may be enhanced by real time behavioral guidance based on RT-PSM ("technological doping"). One of the thematic session at the 4th International Congress on Soldier Physical Performance (ICSPP) provided examples of workload pacing and accelerated acclimation that might be accomplished using PSM tools.[60] Many more such applications can be envisioned. For example, voluntary control of metabolic rate and heat production in certain extreme conditions could provide soldiers with a performance and survival advantage. PSM-informed biofeedback might provide soldiers with a capability that currently takes years of disciplined training, where Buddhist monks can increase and decrease basal metabolism by 60% in either direction and increase finger and toe temperatures.[61,62] An increase or decrease of core body temperature by only 1 °C is associated with a ~15% change in metabolic rate.

RT-PSM opens the door to many other solder performance applications, including needs for specialized missions and environments. This calls for a plug-and-play design of the soldier system so that it can be configured for specific mission needs, ranging from respiratory monitoring in subterranean and dense urban environments to thermal threats from directed energy systems. Prediction of hypoxic impairment of performance during ascent to altitude is also tactically relevant, as many national borders and potential sites of military conflict are formed by high terrestrial environments. Performance predictions based on RT-PSM monitoring of cardiovascular parameters such as blood oxygen saturation can guide staging to altitude and identify individual performance risk. Military pilots are also at potential risk for "physiological events," unexplained episodes of hypoxia in the cockpit, that may compromise health and critical performance. Many closed environments, including submarines and diving systems to vehicles sealed to protect against environmental threats to expeditionary suits for astronauts would benefit from RT-PSM metabolic sensing.

7. Practical considerations

Military leaders have well-founded concerns about adding more information to an already overcrowded attentional space. Earlier concepts of a "soldier dashboard" were derived from clinical practice where a patient's vital signs are displayed with an impressive range of data. The information needs of an intensive care unit specialist caring for a patient are not the same as the information needs of a small unit leader orchestrating the performance of a team of soldiers. Equating soldiers to vehicles is even less appropriate. Humans are not cars and a "dashboard" displaying human analogs of temperature, fuel, and maintenance requirements is a rather simplistic view of useful monitoring for humans that can sense and communicate about their own systems. Leaders may actually want to receive higher level computed information about things like gaps in security due to real time attentional lapses of sentries; who is about to fail due to cognitive or physical burdens that can be redistributed; or identify a soldier who should not be making critical decisions because their head is not in the game (e.g., due to stress, depression, or recent head impact). RT-PSM offers new capabilities to leaders for alerts about soldier readiness status that they may not otherwise readily detect, but these alerts must roll up into simple stoplight displays (i.e., red/yellow/green) that can be further queried only if more information is required. Many applications of RT-PSM may be reserved for training environments to better prepare for the operational environment, providing a technology assist to teach individual and team performance limits and ensure safer training.

8. Medical applications

There are logical extensions of the current RT-PSM efforts that serve the needs of medical specialists. This information is derived from many of the same sensors already used for performance predictions and the same platform and data management architectures would support these additional capabilities (Table 1). However, these medical capabilities generally must follow behind the performance capabilities. The adoption of wearable systems only to support remote medical triage, especially for live-dead detection, has not garnered widespread interest from soldiers, even though these were some of the first capabilities developed by direction of the Army medical department.[63] Soldiers might be more agreeable to wearing a performance-based RT-PSM that could *also* detect a casualty event, support a "911" alert, and support medical management (Fig. 2).

Casualty detection, triage, and early clinical management would likely involve many of the same physiological measures and primarily requires a set of "casualty algorithms" that detect and track hemorrhage and other critical problems. Hemorrhage is the major preventable cause of death on the battlefield and systems to detect hemorrhage and predict hemorrhage severity would be of immediate importance in conserving the fighting strength.[65] This might be possible with algorithms that are currently in development, such as the Compensatory Reserve Index (CRI) that quantifies a failing hemodynamic response due to intravascular volume depletion based on photoplethysmography (PPG) measurements.[66] At present, the medic brings a sophisticated suite of medical monitoring tools to the casualty and lacks the initial wounding detection capability.[67]

Optimization of individual health and fitness readiness habits is already supported with commercially available fitness systems that serve as behavioral prompts as much as providing meaningful

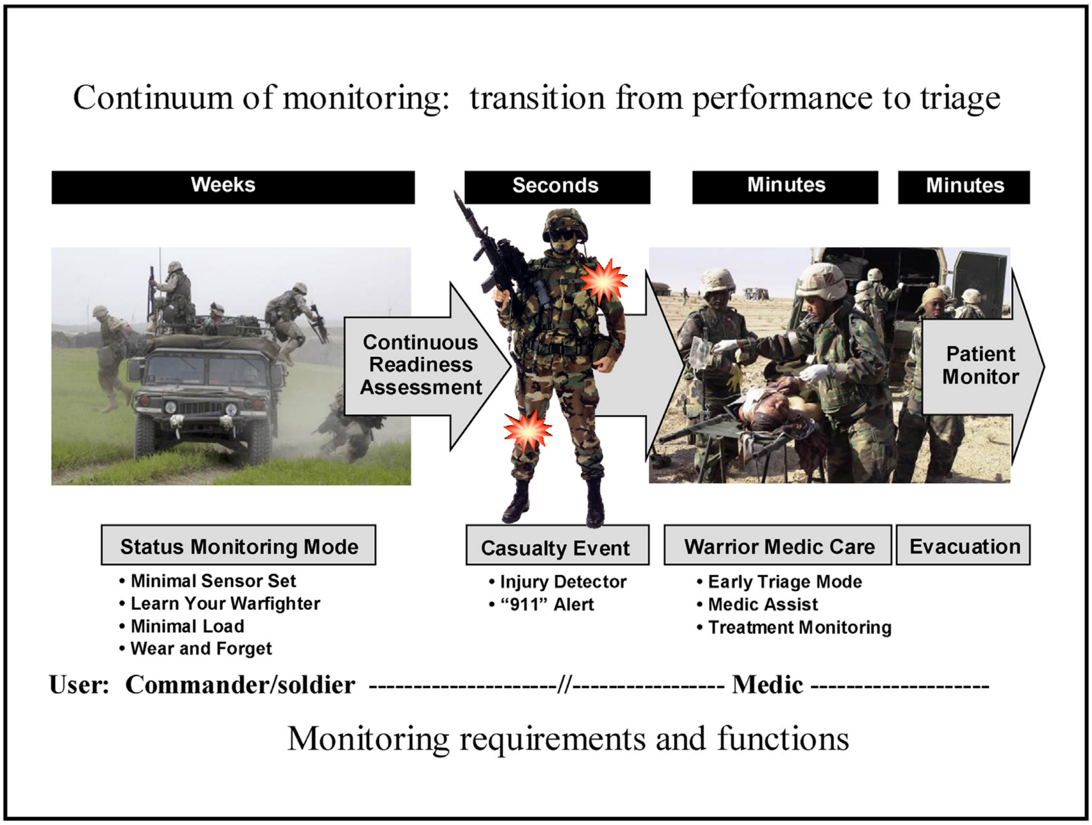

Fig. 2. Concepts for real time physiological status monitoring (RT-PSM) include a common sensors and communications architecture for a system that supports soldier readiness status and performance, and will also be able to support medical needs.
Source: Friedl.[64]

data about total sleep time or daily activity in the U.S. Army Triad Initiative.[42] RT-PSM, combined with outward looking environmental sensors, may also become important for individual exposure monitoring and dosimetry, tying deployment and occupational exposures to longer term health risks (this may not require real time information). At present, this involves extraordinarily complex issues of what to measure in the environment and in the individual (e.g., acute responses, exposomic markers, etc.) and how to relate these measurements to actual health outcomes. Recent efforts with wearable blast sensors and mild traumatic brain injury illustrate the practical challenges of linking measurable exposures to health risks. Current work by programs exploring critical air quality triggers and related respiratory distress signals in asthmatics may provide a new model approach to environmental exposure and RT-PSM.[68] Other RT-PSM efforts will also provide rapid warning of immediate risks from chemical and biological threat agents, especially from inhalation threats. These other applications are beyond the scope of this review but would likely build on the common PSM strategies and architecture.

9. Conclusions

Physiological sensors will have useful military applications if they are soldier-acceptable and provide important actionable information. This paper has focused on operational medicine priorities, considering the components of a "soldier readiness score" comprised of thermal-work limits, alertness and fitness for duty status, musculoskeletal fatigue limits, neuropsychological status, and mission-specific physiological status (e.g., hypoxia, pulmonary threats, freezing cold). One of the most promising and still least developed part of performance monitoring is to use measurements of human physiological and behavioral signals to detect neurophysiological status, particularly in predicting individuals reaching stress limits and with impending degraded performance.

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