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ASSESSMENT OF WEARABLE TECHNOLOGY FOR INTEGRATED DECISION SUPPORT

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Over the past five years, research and development of commercial wearable sensors have grown exponentially. Wearable sensor technology will allow future operational forces to identify and increase early warnings of chemical and biological (CB) threat exposures well before the onset of mission disruptive symptoms, providing for faster recovery, better incident management, and restored mission capabilities after agent exposures or attacks. Currently, army forces at all levels cannot monitor CB exposures of individual soldiers in real time over wide areas of operation. Wearable technology has the potential to make each soldier a chemical, biological, radiological, nuclear, and high-yield explosives point sensor, giving commanders an unprecedented ability to conduct continuous surveillance in real time over wide areas of operation with little to no interference by equipment. Unfortunately, today, most commercial-off-the-shelf wearable sensor technologies fall short of Department of Defense mission needs. This report is intended to guide CB defense program stakeholders forward in wearable science and technology, drive future investment strategies, and characterize the benefits and limitations of near-term wearable technology against CB threats.

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EXCECUTIVE SUMMARY

The Department of Defense (DoD) has an opportunity to leverage the substantial investment by the commercial sector in wearable technologies to improve the readiness of the deployed and training Warfighter and to support decisions and actions in response to operating in a threat environment. Building from the synergy between commercial investment and adoption by the general public, today's COTS technologies already support physiological monitoring, fitness and health, physical performance optimization, and heat stress monitoring. However, the current technology does not expressly derive and report the information products needed by the Chemical and Biological Defense Program (CBDP). Specifically, a focused technology development effort that leverages the community of interest and intensive investment in assessing and exploiting this technology is mandated. Based on the research described in this report, several critical needs were identified to build a suite of systems which meet CBDP requirements.

- **Define a Common Architecture for DoD Development:** A common architecture is required for rapid, integrated development. It will be impossible to leverage across multiple organizations if developers are not all working with the same communication protocols, software architecture, and rough integration strategy such as an 'open architecture' for data integration. Sensors can improve in fidelity when they are combined; therefore independent development must not preclude future sensor modeling and analytics development.
- **Implement a Systems Engineering Approach.** JPEO CBD has invested in the development of an analytical framework that combines portfolio analytics, system-of-systems modeling, force-on-force modeling, and business analytics. These tools, along with other capabilities, should be leveraged to iteratively layer a wearable sensor design concept for chemical and biological response.
- **Validate Using Animal Models:** To capture the integrated picture of response to a chemical exposure, animal models represent the only solution for the evaluation of chemical warfare agents. Through animal models, biomarkers of response may be discovered, sensor suites can be combinatorically evaluated, and predictive algorithms can be developed and tested. ECBC is uniquely positioned to execute the animal exposure, data collection, biomarker discovery, and COTS/GOTS sensor evaluation through *in vivo* models to chemical response.
- **Institute a Collaborative Approach to Leverage Existing DoD Investments.** Physiological monitoring and modeling are not unique DoD needs and the applicable partners in this space are varied and experienced. To harvest the strengths of the leading contributors in his field, a collaborative approach is required.

Data from an ensemble of wearable technologies must be consumed in a systematic way so as to inform decision-making for force protection. Population-level analysis of these data may be more likely to provide decision support value than individual-level data points. However, individual-level data products may motivate users to consistently utilize the ensemble. By further integrating with environmental data products and equipment inventory and status reporting, the force protection benefit will be increased. This holistic approach will provide a significant improvement in situational awareness at multiple levels of decision authority.

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PREFACE

The work described in this report was started in February 2016 and completed in March 2016.

The use of either trade or manufacturers' names in this report does not constitute an official endorsement of any commercial products. This report may not be cited for purposes of advertisement.

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I. INTRODUCTION

Wearable sensor technology will allow future operational forces to both identify and increase early warning of chemical and biological threat exposure well prior to the onset of mission disruptive symptoms, providing for faster recovery, better incident management, and restored mission capabilities after agent exposure or attack. Currently, Army forces at all levels cannot monitor the chemical or biological exposure of individual soldiers in real time over wide areas of operation. Wearable technology has the potential to make each soldier a CBRNE point sensor, giving commanders an unprecedented ability to conduct continuous surveillance in real time over wide areas of operation with little to no interference by equipment. Unfortunately, today, most commercial-off-the-shelf (COTS) wearable sensor technologies fall short of DoD mission needs.

In the summer of 2014, the Edgewood Chemical Biological Center (ECBC) conducted a technology survey of the minimally invasive wearable sensor technology market for the Defense Threat Reduction Agency/Joint Science and Technology Office (DTRA/JSTO). **The survey determined that the development of wearable technologies for the DoD will not be accomplished by a single commercial, academic or government entity, but will require the coordinated efforts of many different organizations having long-standing expertise** engineering, chemical and biological agent science, analysis, testing, chemistry, and the multiparametric testing of sensors, among many others. The 2014 survey also recommended focused investment in a small number of relevant common or commercial platforms that could be adapted by the DoD for surveillance in the field. Selected platforms should be tested using unbiased test beds sensitive enough to differentiate between responses to expected physiological battlefield stresses and responses to chemical or biological exposure. As most wearable sensor measurements will likely be displayed and transmitted simultaneously on a real-time situational map, the software packages must ensure the security, fidelity, and analytical value of data collected.

Over the past five years, research and development of commercial wearable sensors have grown exponentially. There is an immediate need to recognize which wearable technologies are in late development or are commercially available, as well as what the limitations and utility of their data measurements are. It is also imperative to continuously test and evaluate these late development or commercial devices for accuracy of the physiological signals. For non-Federal Drug Administration (FDA) approved devices, where many commercial devices currently sit, there is no standards testing. Current testing in the DoD Air Force Research Laboratory (AFRL) has shown a large variance in accuracy of many commercial devices. As many of these devices will likely contain more than one sensor, developers must anticipate large quantities of multiparametric data being collected and analyzed in real-time. These data can include things such as temperature, location, heart rate, atmospheric pressure, ambient light, oxygen saturation, the relative position of groups of people, environmental compounds, and the direct measurements of individual biomarkers, to name only a few.

As sensor technologies continue to miniaturize and integrate, they will progress from devices mounted on drones, vehicles, and handhelds, to wearable devices that wirelessly communicate with wearable computers, and eventually to implantable and/or microscopic devices. Technologies and applications once relegated to desk top computers and telephone landlines are now available on devices smaller than a deck of cards.

II. SCOPE

Today's commercial-off-the-shelf (COTS) wearable sensor technologies fall short of DoD mission needs. To better shape the future Concept of Employment (CONEMP) for wearable technologies, the role of Wearable Sensor technology as a part of an integrated early warning system is discussed. Invasiveness, cost, and the fidelity, utility and reliability of data are considered, as well as existing gaps between current wearable technologies and current operational needs.

This report is intended to guide CBDP stakeholders forward in wearable science and technology, to drive future investment strategies, and to characterize the benefits and limitations of near-term wearable technology against chemical and biological threats. In this report, a small, and by no means exhaustive, set of available near-term COTS sensors are assessed for a variety of monitoring categories that may provide both physiological and environmental metrics that may or may not correlate to chemical or biological exposure. A cost/benefit analysis for these COTS sensors is provided, along with an overall utility rating for each sensor listed. Recommendations for evaluating, testing and comparing new and improved wearable components as they become available are also discussed.

III. TRENDS IN THE WEARABLE CONSUMER-OFF-THE-SHELF (COTS) MARKET

Wearable technology, which consists of something that is worn, or directly integrated into things we wear, carry with us or implant into our bodies, has undergone tremendous innovation in the past decades and continues to revolutionize the ways in which we interact and understand the modern world. So ubiquitous is this technology, that the daily use of devices such as smart phones and sports watches, each with ever-increasing sensors capabilities incorporated into them, have become the norm, rather than the exception. Advances in communication standards, power management, and general understanding of how to manipulate and process information have led to new, unanticipated applications far beyond the capabilities envisioned by early developers or manufacturers.

A better understanding of wearable technologies that are on the market now, that are currently under development, and that can be expected in the next few years, will help guide the military and CBD stakeholders in making solid investments in the future. Wearable technology portfolios should be invested in widely, with the understanding that many early products will fail upon more rigorous evaluation. These “failures,” should be viewed as necessary as they will guide and inform more expensive and riskier investment decisions in the future. The military is poised to be a principal leader by supporting the development of collaborative open standards, assuming a level of risk early in the developmental process, and focusing on solid commercialization strategies.

To understand the possibilities of wearable technology, it is useful to categorically segment the products of interest so that individual applications can be evaluated in their contextual use. For example, a hotel key in the form of a temporary tattoo would fall under the business operations sector and would need to address access control applications and uses. While the tattoo may give secure key function initially, additional functionality might be added to incorporate more personalized services to the user, such as granting access to the private lounge, meal plans, or transportation. Additional functions to the tattoo could also integrate applications from other sectors, such as security and safety, medical, communications and sports fitness. This interoperability will break down walls so that companies that once cornered a particular product market will be obliged to sell various iterations of their product to a wider base of consumers. This trend was clearly demonstrated with the phone, internet and cable service providers, and to an even greater degree with companies like Amazon and Apple.

A. Technological advances are increasing the efficiency of integrated circuits

Integrated circuits are becoming increasingly efficient, as measured by almost any metric, whether cost, power consumption, processing ability or size. As a result, the smart phones carried by most people go far beyond simple telephone communications, and serve as central processors loaded with personal sensors capable of interacting with a variety of other networked sensors and applications. The smart phone serves as an excellent model of what can be accomplished in terms of measuring surrounding environments and activities, and communicating that information with other groups and sensors. **Figure 1** shows the growth in smart phone sensors

between 2010 and 2015. The number and types of sensors being incorporated will continue to grow as innovation continues to change the general idea of what a phone is. Far from their wall-tethered predecessors, today's phones are integrated into items such as cars, wrist watches and glasses, to name only a few, and phones of the future will likely be further incorporated into articles such as clothing, jewelry, smart textiles and "heads-up" displays in smart contact lenses. Furthermore, sensors will be incorporated into the skin, cannulas, micro needles and wearable patches for various health applications. New processors available by Intel® are the size of a fingertip, yet have the processing power of an internet web server complete with network connectivity, all costing less than a dollar. These processors will help to make up the new "internet of things" (IoT), a massive network estimated at about 2 billion members and growing, where machines talk to other machines. For example, the new Internet Protocol version 6 (IPv6) addressing system, which replaces IPv4, allows for 2^{128} IP addresses or 3.4×10^{34} - enough addresses for every atom found on the surface of the planet. The potential for interconnectivity and increased efficiency will continue to drive the application of new wearable technologies, so that soon there will be little distinction between what we see as non-wearable and wearable. In fact, many autonomous actions, such as switching on a light or downloading a detailed map of an environment, will be done with a gesture or unconscious movement captured by a wearable, rather than by a dedicated command given from what we recognize as a desktop or cell phone.



Figure 1. Increasing numbers of sensors added into phones from 2010-2015. [Source: <https://www.qualcomm.com/news/snapdragon/2014/04/24/behind-sixth-sense-smartphones-snapdragon-processor-sensor-engine>].

These same technologies will also drive future markets through the sensing and reporting of consumer needs, purchases and trends, and individuals users will be provided the opportunity to develop their own personal use cases when consumer trends are carefully tracked by manufacturers. It is critical that CBD stakeholders understand and participate early-on in this development cycle, as the cost of influencing this rapidly developing market is minor relative to the return in capability that will benefit both the soldier and DoD mission needs.

B. Segmenting the market to make sense of the chaos

The lines between the large sectors of the industry are becoming increasingly blurred, as is seen currently by the financial and security fields. However, by segmenting these sectors, the significance of each sensor capability and utility based on both initial function and maturity can be determined.

Sports & Fitness:

Measuring, collecting and tracking personal performance is now done using a variety of platforms that push collected data to phones and social media, allowing athletes to benefit from vital data before, during, and after workouts. Without impeding the performance they are measuring. Wearable technologies are central to making these measurements in real-time. Global positioning system (GPS) watches, heart rate monitors and motion detectors give information on distance, gait, work-out intensity and duration, and are widely accepted and used. In the near future, information on things such as equipment life span (i.e., shoe wear) body posture and position, and analysis of gait, can provide actionable information on fatigue levels, rest requirements, and potential for injury.

Healthcare & Wellness:

Increased awareness of the benefits of a healthier life continue to drive new markets for health care products that not only track quasi-clinical data, but can also measure and modify behaviors to improve overall well-being. Remote patient monitoring is reducing costs by allowing patients to keep track of their health while avoiding unnecessary visits to the doctor. This is not only a market with an extremely high growth potential, but also a very diverse market with basically endless opportunities for new technology solutions. Wearable medical devices allow patients more independence and the freedom to move around as they like. Rehabilitative health services, as well as invasive monitoring and treatments such as catheters and medical ports, currently require direct medical supervision and hospitalization. Wearable sensors and nanoneedle technologies may allow patients to become ambulatory during treatment and monitoring, allowing them to stay at home, reducing the costs and hospital stays.

Security & Prevention:

Wearable technologies are essential in countless industries in ensuring the highest up-to-date safety and security standards. Whether it be special lighting for better visibility, home security systems, protective clothing and special gear for extreme sports, rescue teams, workers, or tracking devices for children or the elderly, wearable technologies will play an increasingly significant role. Devices that can track, sense sudden changes in acceleration, detect unauthorized or nefarious activity, and facilitate biometric identification and forensic sample collection will become more and more available in wearable platforms.

Smart Clothing:

Smart clothing that measures fitness and performance is already commercially available. Examples include running shoes such as Under Armour's SpeedForm® Gemini 2, which measure details such as distance, pace, speed and calories burned; or MC10's CheckLight™, a wearable

skull cap designed to gauge the severity of an impact. Hexoskin's body metric shirts combine several sensors to measure steps, pace, heart rate and calories burned. Technical clothing will incorporate components seen in our laptops and smart phones. From the simplest undergarment to Kevlar exoskeletons this convergence will see incredible innovation in the next 10 years.

Exoskeletons:

An exoskeleton device, like the one pictured in **Figure 2**, is a harness or frame worn on the outside of the body that does physical work for the person wearing it. There are currently over a hundred companies commercializing this kind of product, with the military making large investments in this area for several decades. Exoskeletons could provide a focal point for wearable technology integration through the incorporation of new components, such as additional powerful processors, batteries and electric motors that power joints. For example, electric servomotors have been adapted and redesigned from fixed robots on vehicle assembly lines. The motor of an exoskeleton today weighs about 400 grams, but can deliver about 700 N of force – something a human joint could not



Figure 2. Lockheed Martin Fortis Human Powered Exoskeleton

achieve. Exoskeletons are currently being developed to assist in labor-intensive jobs that require human decision making and/or working in confined spaces. These devices help to better distribute heavy equipment weight so that a worker can perform a task for longer periods of time without risk of fatigue or injury. These devices are currently available for anywhere from \$2000 to \$30,000 and are being evaluated by the agriculture, manufacturing, shipping and construction industries. In the medical rehabilitation industry, exoskeleton frames compliment prosthetic limb replacement and assist motor skills to maintain muscle tone in patients with spinal cord and brain injuries. Exoskeletons have processing units devoted to sensors that can detect everything from the intent of motion to the surrounding environment and manufacturers are just beginning to assess the utility of health and environmental sensors in improving the utility of their devices. Exoskeletons could serve as test beds for the military to test new sensor components that can measure both soldier and environmental health and have the ability to incorporate a variety sensors and improvements, much as the way the phone or car aggregates technology. They represent a convergence of technology, physiology and apparel design.

C. An integration of wearable sensors example

IBM jStart and Jabil Circuit Inc. recently developed a system that pairs sensors with IBM Bluemix Internet of Things (IoT) and Analytics Services, including Spark steaming and predictive analytics. The result was a waterproof wearable “widget” that can be used during resort stays and could replace a traveler’s traditional room key and credit card. The system also allows for real-time data analytics, allowing the resort staff to know everything from how the wearer likes her martini, to when she prefers to swim or dine. Moreover, combining profile preferences with other databases, such as weather information, local events and social customs, can allow the staff to anticipate the user’s every need, whether it be a product question in the resort gift shop or the ingredients list of a menu item. The wearable for this system incorporates an “attention”

button that summons assistance and can even track the wearer’s children at the pool. The resort demonstration for this technology required outfitting an entire floor of one of Jabil’s St. Petersburg locations with iBeacon technology and then building a small hand-held device to simulate a wearable capable of capturing location, temperature and humidity. The floor selected at Jabil mapped very closely to the lobby level of the Jabil’s Hotel Resort targeted customer.

iBeacons combined with a few capture devices and the IBM® Bluemix Platform allowed Jabil to create a real-time dashboard that demonstrated the ability to track locations while instantaneously calculating the dwell time of individuals as they walked around the representative lobby level of the resort (see **figure 3**). A Node-Red application orchestrated a series of events: 1) the storing of data to a Cloudant Service for retrospective analysis, 2) the sending of data to the Predictive Modeling services to be scored (resulting in the identification of the zone location of the individual), and 3) publishing temperature/humidity data by zone to a Softlayer hosted Kafka service.

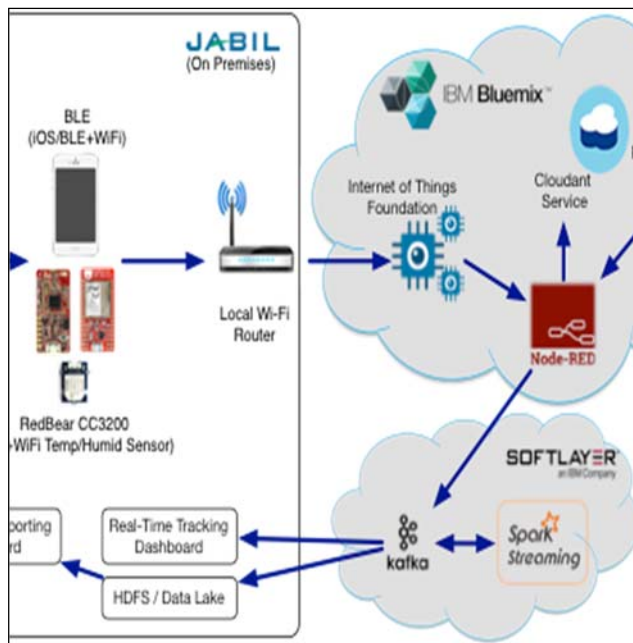


Figure 3. Jabil's on-premises application <http://www.jabil.com>.

gave unexpected data that could be used to provide additional services and develop additional products. This kind of exercise could easily be developed for a military advanced technology demonstration (ATD).

First, the topic was subscribed to by a Jabil on-premises application that stored the data to a Hadoop File System (HDFS). Second, a Softlayer-hosted Spark Streaming service processed the data calculating both individual average zone dwell time and aggregated zone average dwell times. Results were then published to a real-time dashboard web socket application for proof of concept to demonstrate the real-time tracking and analytics of the system. The dashboard was part of a demonstration project leveraging COTS services and was developed in under 6 weeks by students. The resulting integration

IV. TECHNOLOGY CONSIDERATIONS

A. Invasiveness

The invasiveness and potential of a wearable device to disrupt normal operational duties must be considered when developing wearable sensors for the assessment of chemical or biological threat exposure. While non-invasive devices, such as smart watches and eyewear, have seen a boon in commercial production and utilization, there remains the question of whether the quality of data collected from these devices is on-par with that of the more cumbersome analytical instruments traditionally used by the health-care sector. Recent improvements in piezoelectric, electrochemical transducers and optical sensor technology have opened the door for more diverse, minimally invasive wearable sensor applications, however, the trade-off for these less-invasive sensors may be a reduction in sensitivity and therefore data value.

While non-invasive sensors are generally met with less user apprehension, these passive wearable sensors may not providing sufficient quality of physiological data relevant to biosurveillance missions. Minimally invasive devices (such as smart tattoos or smart contact lenses) that measure glucose levels or ocular pressure may provide better continuous monitoring of analytes in fluids like sweat, tears or saliva, but require more active wearer participation which may be met with less acceptance than more non-invasive devices. Additionally, minimally invasive devices may be intrusive as well as hindered by low sample volume requirements. Despite the encouraging fact that many of these kinds of minimally invasive sensors have been in development for several years, at present few, if any, of these sensors are commercially available.

Finally, implantable sensors represent the most invasive of wearable sensors, requiring intervention and monitoring by healthcare professionals. While these indwelling sensors promise the most accurate data, the technology also has several pitfalls, such as implantation trauma and infection, sensor fouling, long-term calibration issues¹, the need for periodic *in situ* calibration, and discrepancies between sensor reading and traditional *in vitro* test results.

The most recent innovations in this sensor field are the continuous glucose monitors (CGM). These are wearable sensors with an implanted component that makes continuous observations of blood glucose levels in order to provide better diabetes control. There are currently three CGM systems available (Abbot Laboratories, Medtronic, and Dexcom). All three require at least one calibration per 12 hours (via conventional 'finger-stick' blood assay) and 3-4 calibrations per day are recommended. Due to this, only partial automatic control of insulin pumps is FDA approved (the most recent Medtronic integrated pump/sensor system can temporarily pause scheduled insulin delivery if blood glucose is below a certain threshold)².

While these products can be considered the 'gold standard' for wearable biomarker-tracking systems, they still have limitations. For example, these implants last between 3 and 7 days, require frequent calibration, and must continuously sample interstitial fluid making them more invasive than traditional glucose monitoring systems. These sensors demonstrate that near-real-

time tracking of biomarkers is possible; this development benefits from two main advantages: a multi-billion dollar diabetes management industry, and an extremely well known and characterized enzymatic sensor (glucose oxidase) modality. A multi-billion dollar industry lends to very large industrial internal R&D investments specific to glucose monitoring. This likely will not be the case for biomarkers specific to chemical and biological exposure. Additional focused S&T investment will be required to leverage the current knowledge in this field into devices specific to military needs.

B. Data fidelity

There are two aspects of data fidelity that must be considered when expanding the available technologies into the CBDP mission space: the innate variation between individuals and the precision/accuracy of the data product.

Variation between individuals:

Across multiple individuals, biological responses to an insult or challenge can vary significantly: this type of variability is in fact an evolutionary feature which permits long-term survival of species. Even if a sensor produces entirely ‘true’ data, at an individual level we may not be able to determine if a deviation in the data is significant in a decision-making context. This will be particularly true for biological exposures due to the complexity of the immune system and host: pathogen interactions. In contrast, chemical exposures produce far more well-understood and predictable sequelae, albeit some low-level exposure effects are still being elucidated. As the investment in wearables is prioritized, these inherent differences should be taken into account. Specifically, COTS / near-COTS wearable technologies could be evaluated in a chemical exposure context, producing potentially valuable data and tools, without facing the complexity (and risk) inherent in biological challenges that may not yet be tractable.

Fidelity of data products:

Wearable sensors can vary considerably in how precisely their data products represent the physiological property being measured. Differences can arise either from the accuracy of the specific sensor, or in the case that a sensor measurement is a proxy for a physiological property, how well correlated that measurement is with the property. As an example of the latter, highly accurate temperature sensors are widely available and easily positioned to measure skin temperature, but this is typically a poor proxy for the more-relevant measure of core body temperature. For some properties like this, either better measurement techniques are needed, or devices should only be used where the lower correlation is acceptable. In other cases, multiple sensor readings can be combined with a suitable algorithm or model to increase the quality of the measurement. The following charts illustrate how much variability can exist between sensors and techniques in current COTS wearable platforms.

It is important to point out the critical importance of interplay between data fidelity, invasiveness, and use case. Intuitively, it would seem obvious that the more accurate measure would be correlated with a more invasive or less comfortable (e.g. chest strap versus wrist band for heart rate) measurement. However, until the concept of employment for wearables is

defined, the required fidelity of the measurement is unknown and the exchange space between comfort/adoptability and accuracy can only be estimated.

V. INDIVIDUAL COTS SENSOR UTILITY RANKINGS FOR VARIOUS EXPOSURES

In the following section, variables such as cost, invasiveness and data fidelity of wearable sensors are considered. General “stoplight” metrics are used to provide an approximate assessment of a sensor’s ranking in each area, with an overall score given at the end (see **figure 4**). For sensor cost, a price of \$5 or below is considered “green”, \$5-\$50 “yellow”, and over \$50 “red.” For invasiveness, sensors that are “wear and forget” (such as in a watch keychain) are considered “green”; sensors with minor encumbrances (such as peel and stick patches or straps) are considered “yellow”, and invasive sensors (such as implantables or ingestibles) are considered “red.” Data fidelity is mostly determined by the relative performance of the sensor compared to clinical standards, with some consideration of the fidelity of the clinical standard itself.

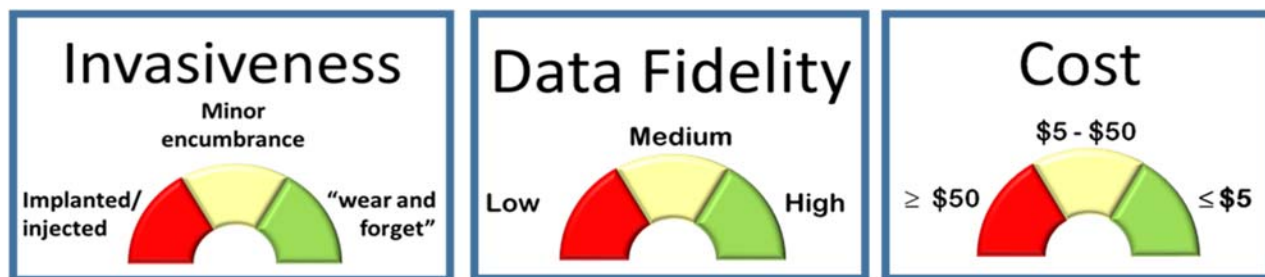


Figure 4. Stoplight for sensor rankings.

Each sensor type is given a qualitative utility rating (1-10) based on cost, invasiveness, and data fidelity, with example products provided for each sensor type. Also included are a representative market scan of available sensors (Appendix A) and COTS and near-COTS integrated sensor products (Appendix B). Assessments are comprehensively integrated into vignettes that represent potential chemical or biological events that utilize wearable technologies to assist in command situational awareness and mission planning.

A. Kinds of data gathered:

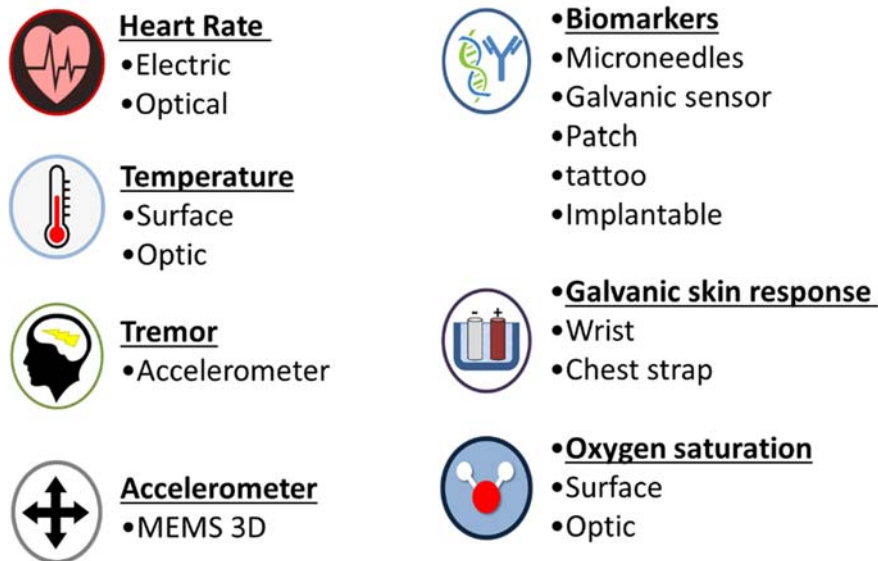
Data gathered by wearables can be collected from a variety of sensor types. These data and measurements presented below in **table 1** represent a sample of the available capabilities.

Table 1. Current Wearables Measurement Capabilities

	Biological	Affective & Social	Cognitive	Behavioral	Environment
Data	Heart rate, amylase activity, blood pressure, respiration rate, tidal volume,	Facial expressions, Team dynamics, Relationships, Cohesion	Alpha-activity, brain network activity, Subjective data	Movement patterns, gesture recognition	Temperature, humidity CO ₂ level, pressure
Measurement	PPG, ECG, chest expansion, sphygmomanometer, salivary amylase	Visible/IR spectrum camera, time/frequency voice analysis, proximity via bluetooth	EEG, MEG, Survey data	GPS, accelerometry	Thermometer, barometer, gas detector

B. “QUASI CLINICAL” measurements of wearable sensors

Data gathered by wearables can be collected from a variety of sensor types (figure 5) to be used individually or in combination. These types of sensors and data include:




Heart Rate Figure 5. Quasi clinical measurements of wearable sensors.

Wearable heart rate sensors fall generally into two categories; Photoplethysmographs (PPG) and Electrocardiogram (ECG) devices (see figure 6). PPG sensors work by optically capturing changes in blood volume in the microvascular bed of tissue under the outer layers of the skin. PPGs are often found in healthcare settings (such as integration into pulse oximeters) and have typically low invasiveness with sensors placed on the fingers, wrists, or ears. While invasiveness

for PPG is low in healthcare, there is little to no mobility in patients which allows this to be measured accurately. Motion artifacts in PPG based heart rate sensors is considerable. ECG devices monitor electrical signals on the skin derived from the depolarization of the heart during heartbeat. Similarly to PPGs, ECGs are also commonly used in healthcare settings, often in the form of adhesive patches (worn for prolonged periods of time) that are wired to vital sign monitoring or ECG equipment. Because of the patch mechanism, the wearable technologies for ECG monitoring also tend to be minimally invasive.

PPGs are widely deployed because of their cost, size, and relatively good fidelity when compared to clinical grade measurements for heart rate³. Most of the wearable components utilizing PPGs, however, have major deficiencies when it comes to capturing heart rate during motion^{11,20}. This deficiency is critical regarding the utility of wearable technologies including PPGs during operational conditions²¹. There are efforts to use controlled experiments to generate “motion and noise artifacts” in order to computationally dampen these undesired outside influences^{8,18,19}. In their current state as sensors for heart rate, PPGs have utility only in static or low-movement situations.

In contrast to PPGs, ECG devices have much greater fidelity when deployed in ambulatory conditions for heart rate monitoring¹². Traditionally a 12-lead monitoring system, commercial products now exist that reduce the burden of customary Holter monitors and power sources for continuous observation while also determining if fewer leads are viable for accurate measurements^{12,16}. Studies are ongoing to determine if wireless systems can help provide valid, continuous data¹⁴ and if these types of systems can work in austere environments^{5,6,9,22,23}. The monitoring of electric heart signals at the sensor-skin interface provides more valid data with a minimal amount of invasiveness, but the need for a broader sensor-collector interface and the issue of greater power consumption remain.



Sensor Type	Metrics			Example Product	Overall Utility Rating
	Cost	Invasiveness	Fidelity		
PPG (Optical)				<i>Osram SFH7051</i>	7
ECG (Electrical)				<i>Plessey PS25205B</i>	7

Figure 6. Wearable heart rate sensors.

Body Temperature

Measurement of body temperature is challenging, as core body temperature can vary drastically from that of skin temperature. Unfortunately, core temperature is the most relevant measurement for medical monitoring applications, yet it is also the most challenging. Wireless, ingestible temperature sensors are one commercially available solution, but these “pills” are expensive and not convenient to swallow given their large size. Others approaches have estimated core temperature using heart rate measurements, achieving accuracies that, while not replacing direct core temperature measurements, can be used as early warning indicators of acute heat stress²¹ or other conditions. It is therefore likely that integrating algorithms that consider other data sources (e.g. skin temperature, ambient temperature, respiration, etc.) could further improve core temperature estimates without the need for more invasive technologies. Technologies that measure skin temperature are more readily available (see **figure 7**). Thermal infrared monitors are commonly available as ‘temperature guns’ that rely on tiny, cheap, low-power infrared detectors that could be readily integrated into most wearable devices. “Peel and stick” patches that measure skin temperature are also commercially available, but are expensive and tend to last only about 24 hours before needing to be replaced.

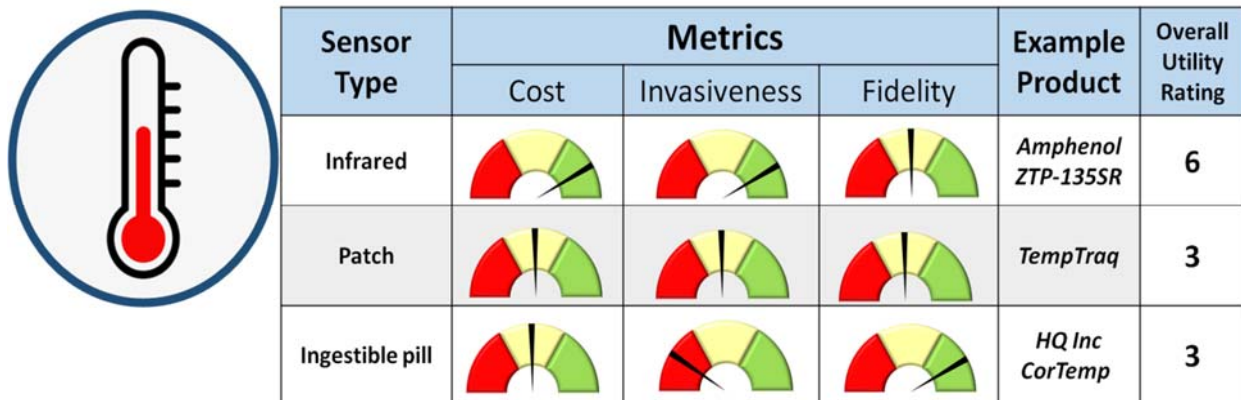


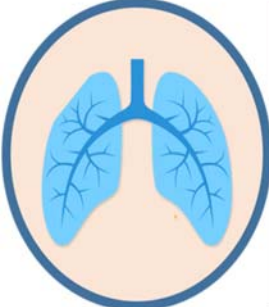
Figure 7. Wearable body temperature sensors.

Respiration

Numerous metrics of respiratory function are generally lumped under the umbrella term of pulmonary function testing. In the clinic, one such test is spirometry which uses a tabletop device that measures how much and how fast air is inhaled and exhaled into a mouthpiece. Similar systems have been integrated into a mask format for assessing athletic performance, to include portable versions. While wearable spirometers do exist (**figure 8**), they are at best moderately invasive as they must measure respired air through active participation, making them realistic for the field only in situations where full masks are required.

An alternative approach to estimating respiration is the use of a band or accelerometer to measure chest movement during respiration (**figure 8**). Such measurements could be used as breathing-related indicators of stress, tension, or other states. However, these sensors tend to be highly sensitive to placement and motion of the subject, making them impractical for measurement in anything other than short term clinical monitoring or sleep studies.

Blood Oxygen Saturation



Sensor Type	Metrics			Example Product	Overall Utility Rating
	Cost	Invasiveness	Fidelity		
Spirometry				<i>Spiropalm 6MWT</i>	4
Chest Motion				<i>Spire</i>	4

Figure 8. Wearable respiration sensors.

Pulse oximetry determines blood oxygen saturation levels by measuring the difference in the absorption of red light by oxygen-bound (or unbound) hemoglobin in the blood (see **figure 9**). The measurement is achieved by shining both red light and infrared light through tissue and assessing the relative absorbance intensities. Transmissive pulse oximeters place an light-emitting diode (LED) illuminator and light sensor on opposite sides of a body part (mainly finger or ear) and rely on light that is transmitted through the body, while reflective pulse oximeters



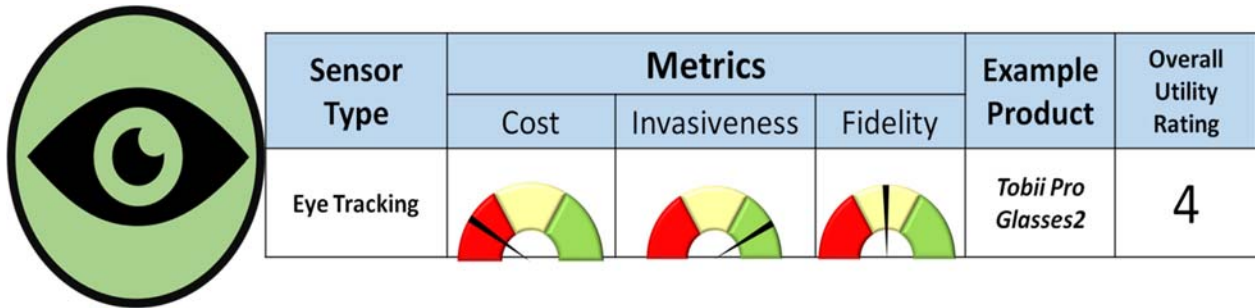
Sensor Type	Metrics			Example Product	Overall Utility Rating
	Cost	Invasiveness	Fidelity		
Pulse Oximeter (reflective)				<i>Maxim MAX30102</i>	9
Pulse Oximeter (transmissive)				<i>ChoiceMMed</i>	7
Muscle Oximetry				<i>BSXInsight</i>	4

Figure 9. Wearable blood oxygen saturation sensors.

place the illuminator and detector near each other and are reliant on reflected light. Apart from minor body placement considerations, there is no significant difference in performance between either approach in general²³. While both types are based on essentially the same technology, transmissive pulse oximeters have been used clinically for many years and are more common. COTS transmissive devices are common and typically incorporate displays and some form of data connectivity. These devices must be clipped on a fingertip or ear, making them inconvenient when moving. Reflective pulse oximeters, on the other hand, are available as integrated circuit (IC) devices that are easily integrated into wearables. Oximetry is further used to assess oxygen saturation in other tissues, particularly muscles. While the underlying measurement technique is the same, monitoring other tissues like muscles require much more sophisticated technologies that incorporate more intense light for deeper penetration and more complex data analysis to take into account more complex tissue. For wearable applications, the most relevant products are placed on the calf and can be used as a proxy for lactate to assess muscle fatigue.

Eye Movement

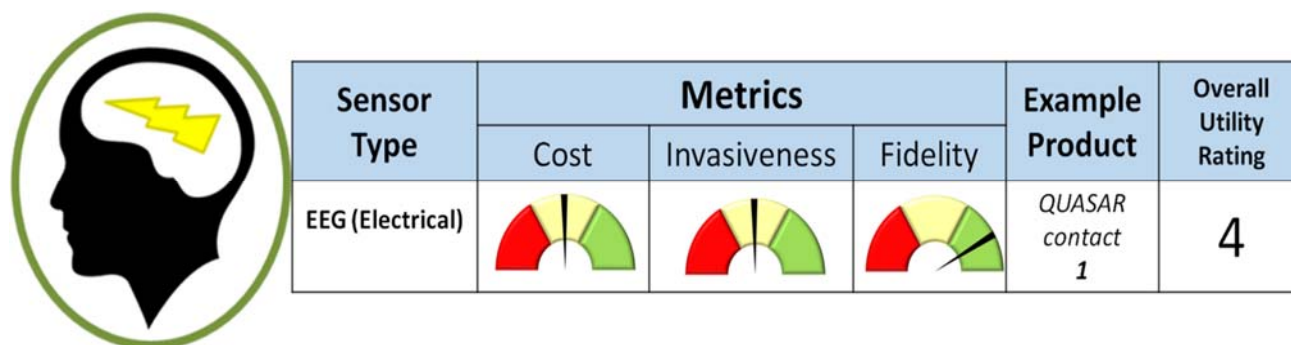
While the science of eye tracking has been around since the 1800’s, the invention of digital gaming, virtual reality, and immersive media have taken this technology to a new level. The technology is currently being evaluated for several applications, such as novel human-computer interfaces or assessment of alertness. Cameras integrated into glasses, helmets, or mounted on fixed displays track eye movement and can, in some wearable applications, be paired with external facing cameras to assess what the user is looking at. Similar assessment can be done using cameras mounted on fixed displays. In other applications, cameras assess the speed of blinking or other eye movement as an indicator of alertness. Several companies are developing products in this space, though only a few are currently commercially available (see **figure 10**).



Brain Activity (EEG)

Brain activity is frequently measured by electroencephalogram (EEG), which uses electrodes placed on the scalp to measure electrical activity in the brain. The measured electrical potentials represent the summation of pools of regional neural activity generated by hundreds to thousands of interconnected neuronal circuits. The resulting potentials at the scalp are extremely small, 1/10th-1/50th the amplitude of electrocardiogram (EKG or ECG), resulting in a relatively low signal-to-noise ratio (SNR) and easy susceptibility to contamination from other electrical sources, such as electromagnetic interference (EMI) or other physiological sources such as EKG and Electromyography (EMG). As a result, signal fidelity can vary substantially depending on the equipment and environment. Conventional medical electrodes and amplifiers are fairly bulky, require gel application, and often some degree of skin abrasion. However in recent years, many smaller, wireless, easy-application commercial (non-medical) products have become available, and the evidence is that the signal qualities are about as good as conventional systems²¹. There have also been many recent development in “dry” electrodes, which do not require gel, which have a much higher potential for use in everyday, real-world applications¹⁸. Efforts to use several less-invasive electrodes in a wearable hat or helmet have working on various approaches to dry EEG sensors (see figure 11), and within the near future it is likely to become a commonly available standard. Meanwhile low-power IC-design and built-in artifact rejection are becoming more common, suggesting that while there are some limitations to overcome before EEG is usable for every day, long-term monitoring applications, however the promise is very high for the near future.

Figure 11. Wearable brain activity sensor.



Biomarkers

The field of biomarker discovery is being spurred by investment in the “omics” technologies and is booming into a large field within infectious disease and chemical exposure. As identified biomarkers are translated into clinically validated indicators of biological agent infection, wearable technologies will look to integrate small molecule, metabolite, nucleic acid, and protein biomarkers into sensor arrays. This is captured by the chart below (see **figure 12**) that details some developmental and near-COTS sensors for customizable biomarker identification. A majority of the biomarker sensors utilize a patch deployment that relies on microneedles for sampling of bodily fluids accessible directly under the outer layers of the skin (blood, interstitial fluid). Other similar patches deploy more non-invasive techniques for detection of biomarkers from secretions on the surface of the skin.



Sensor	Type	Data Product	Type	Body Position	Cost	Invasiveness
FibroTx Transdermal Analysis Patch	Antibody capture array	Protein Biomarker	Biomarker	Any (patch)	Future product	Minimal
Gentag NFC Skin Patches	Metabolite Biomarker/ Multifunction	Glucose	Biomarker	Any (patch)	Future product	Minimal
Kenzen ECHO Smart Patch	Sweat Biomarker		Biomarker	Any (patch)	Future product	Minimal
Eccrine Systems Sweatronics	Sweat Biomarker		Biomarker	Any (patch)	Future product	Minimal
Profusa lumee	Long term injectable	Oxygen	Biometric	Any (fixed site injectable)	Future product	Moderate

Figure 12. Wearable biomarker indicators.

Experimental microneedle patches have been used for a variety of marker capture applications, such as sampling the dermal interstitial fluid⁴ and for detecting viral antigens during early immune responses¹⁰ and circulating malarial antigens¹⁵. These patches are at various stages of commercial development and can sample fluids that are relevant for chemical and biological agent exposure. The patches themselves are minimally invasive, with little pain recorded from

the insertion⁷. However, it remains to be seen how effective passive fluid sampling through microneedles will be in a motion-intensive operational environment.


While microneedles are minimally invasive, there is a thrust to use non-invasive sampling (sweat, oral samples, etc.) to capture biomarkers. Sweat has been a major area of development with high-profile studies being performed with multiple-analyte capture systems and sensors^{13,17}. These systems work by integrating multiplexed sensor arrays into flexible patches for the analysis of sweat metabolites and electrolytes. Collecting multiple inputs and doing remote analysis within a wearable, non-invasive patch creates the opportunity for differential biomarker detection in one platform. These technologies are still in the experimental and development stages, but represent the cutting-edge possibilities for the complicated problem of bodily fluid biomarker sampling using minimally invasive techniques.

C. ENVIRONMENTAL SENSORS

Small integrated circuit components are now available to detect a range of environmental conditions, such as temperature, pressure, etc. The demand for these devices in smart phones has driven development of sensors that are generally robust, accurate, tiny, and very cheap. Notably, temperature, pressure, ambient light, humidity, and position (compass, accelerometer, gyroscope) are all available for roughly \$1 each in small, easily integrated packages. In addition, GPS and some measures of air quality are available for around \$20.

Ambient Temperature

Ambient temperature measurement is available via small, cheap COTS chips (see **figure 13**). The chips are available for any practical temperature range and use minimal power. Accuracy is to a fraction of a degree. The chips are easily integrated into wearable devices and are often found in smart phones.






Sensor Type	Metrics			Example Product	Overall Utility Rating
	Cost	Invasiveness	Fidelity		
Temperature				TE TSYS02D	9
Combined (temperature, pressure, humidity)				SEN-09403 MQ-7	9

Figure 13. Wearable ambient temperature sensors.

Pressure

COTS IC chips are readily available for pressure measurement (**figure 14**). These devices are frequently used to assess altitude, and are present in many smartphones and wearables (e.g., FitBit Surge). Costs and power consumption are low, but can climb for higher accuracy models. Chips are small and readily integrated into devices.




Sensor Type	Metrics			Example Product	Overall Utility Rating
	Cost	Invasiveness	Fidelity		
Pressure				Measurement Specialties MS5805-02BA01	9
Pressure				Measurement Specialties MS5805-02BA01	9
Pressure, Temp, Humidity				TE MS860702BA01-50	9

Figure 14. Wearable pressure sensors.

Air Quality

The availability of air quality sensors for wearable applications varies widely for different objectives. This variability derives from a variety of methodologies implemented and relative demand for COTS solutions (**figure 15**). For example, carbon monoxide home monitoring has driven the development of relatively small, low cost monitoring devices that are integrated into numerous COTS products for home use. The technology to make this measurement, namely a change in resistance of a metal oxide, is readily implemented in an integrated chip. These sensors are roughly a few dollars. Carbon dioxide sensors, too, have recently been implemented as MEMS integrated circuits but are more costly. Other COTS sensors measure Total Volatile Organic Compounds, which provides an indication of general air quality but no information about what specific compounds are present. In general, detection of a few specific gases on small integrated chips is available, but detecting others may require development effort. For air particles, small devices (~1"x2") are available, primarily driven by the market for smoke detectors. These devices use an LED and photodetector such that reflected light from air particles are detected. While cheap and small, these sensors only provide an indication of the amount of particles present. Devices that provide information about particle size or other characteristics are not yet available in a wearable format.












Sensor Type	Metrics			Example Product	Overall Utility Rating
	Cost	Invasiveness	Fidelity		
Carbon Monoxide				SEN-09403 MQ-7	8
Carbon Dioxide				K-30 SE-0018	7
TVOC				ams iAQ-Core	6

Figure 15. Wearable air quality sensors.

Light

Sensors to detect ambient or UV-specific light are available as cheap COTS integrated chips driven by the smart phone market. These devices are readily integrated into wearable applications (**figure 16**). Additionally, a wearable patch with UV sensitive dyes has been announced but is not yet available. Though it requires active imaging of the patch for a readout, it represents an alternative approach to the integration of sensors into wearable devices.




Sensor Type	Metrics			Example Product	Overall Utility Rating
	Cost	Invasiveness	Fidelity		
Light (UV and Ambient)				<i>Silicon Labs Si1133 UV</i>	9
Light (Ambient)				<i>Maxim MAX44009</i>	9
UV-sensitive Dye				<i>L'Oreal My UV Patch</i>	4




Figure 16. Wearable light sensors.

Humidity

Due to demand from the smart phone market, COTS humidity sensors are available as cheap integrated chips (**figure 17**). They are further available in multifunctional COTS integrated chips capable of measuring multiple environmental quantities (e.g. temperature, pressure, etc.).

Figure 17. Wearable humidity sensors.



Sensor Type	Metrics			Example Product	Overall Utility Rating
	Cost	Invasiveness	Fidelity		
Multifunction (pressure, temp, humidity)				<i>TE MS860702BA 01-50</i>	9

Position

The demand for positional information from both military and civilian markets has driven the availability of cheap, small, integrated circuits sensors of multiple measures of position or motion. These measurement technologies are accelerometers, gyroscopes, magnetometers, and GPS devices (**figure 18**). Accelerometers provide a measure of linear acceleration, while gyroscopes provide rotational acceleration. Combined, these measures give 6-degrees-of-freedom and enable dead reckoning of position, though only measure changes in position or orientation as opposed to absolute measures. Magnetometers measure gravitational fields to provide an absolute measure of orientation as a compass does. GPS devices also provide absolute location information. It is important to point out that in addition to providing positional information, accelerometers in particular have been used to estimate a variety of other measures, including physiological variables. Some examples include respiration by sensing chest movements and sleep quality by assessing restlessness during sleep.




Sensor Type	Metrics			Example Product	Overall Utility Rating
	Cost	Invasiveness	Fidelity		
Accelerometer				<i>STMicroelectronics LIS2DH</i>	9
Gyroscope				<i>ITG-3200</i>	9
Magnetometer (compass)				<i>ST LIS3MDL</i>	9
GPS				<i>MediaTek MT3339</i>	8

Figure 18. Wearable position sensors.

Sleep and Fatigue

Unlike the physiological measures described here, such as heart rate, there is no direct variable to measure for assessment of sleep quality or fatigue; yet, fatigue and its corresponding correlation with sleep quality is one of the most important factors for predicting an individual's performance. Evidence of this importance is reflected in the decades of research both within the DoD and elsewhere. In clinical settings, many different monitoring technologies are combined in order to assess quality of sleep. Some of these monitors include EEG to monitor brain activity, ECG to assess heart rate, mask-based spirometers to measure respiration, and various tools such as cameras or accelerometers to monitor movement and respiration. Each of these technologies exist in wearable format to varying degrees. In particular, wearable ECG and accelerometer sensors are highly developed and are available in many COTS devices marketed to the public explicitly for sleep monitoring. Products that take EEG measurements for assessing phase of sleep are under development but not yet available commercially.

VI. INTEGRATION AND DATA MANAGEMENT

There are evolving standards for the integration of sensor data that have applicability to the implementation of a physiological monitoring component. It is important to couch the physiological monitoring systems in the context of a decision support tool vis-à-vis a medical monitoring device that reports on soldier health and wellness. A prominent rationale for this distinction is the fact that the development and fielding of medical monitoring devices will invoke Food and Drug Administration (FDA) vetting and approval processes that would mandate an extensive testing regimen and many years of additional development time for the technology. In Addition, the implementation of a real time medical reporting system can be interpreted as a means of intervening on mission readiness.

As has been alluded to in the previous discussion, and captured in operator feedback (See LIMITATIONS and CONCERNS), the use of any physiological monitoring data in isolation is unlikely to yield acceptance and confidence among capability developers and the services. The best case scenario for the use of wearable device data will be that of an aggregated data product consisting of both a plurality of physiological data streams and correlated environmental monitoring that corroborates the potential for a problem. Additionally, it is anticipated that the analysis of isolated individual data would be unreliable, in that the ability for any one individual data value to present signs deviating from the norm could easily be manifold. A more likely use case would be the holistic analysis of population-level data.

The standardization of data models within the Army's Common Operational Environment (COE) exemplifies the mechanism by which sensor data, including physiological monitoring, can be published and discovered in an interoperable environment. The COE framework is depicted in **Figure 19**.

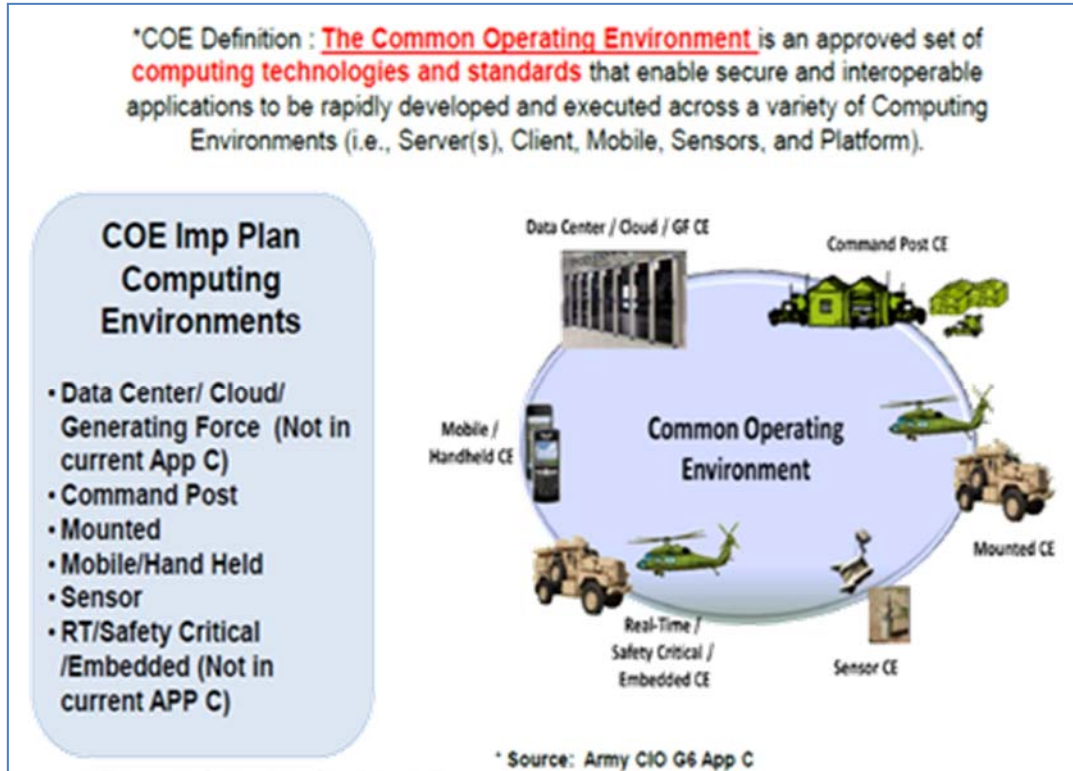


Figure 19. Sensor Computing Environment (SensorCE). A common interoperability layer that implements standards and technology for data services, network awareness, and security for specialized, human-controlled or unattended sensors and sensor systems. The Sensor CE does not specify hardware and software for the core functions of the sensor or sensor system devices (I.e. Sensor is treated as a “Black Box”).

VII. LIMITATIONS AND CONCERNS

During the development of this report, limitations were identified by both the report authors as well as those interviewed for their subject matter expertise (SME). At presents, there is a large knowledge gap concerning non-specific metrics (i.e., heart rate, sleep, temperature, etc.) in the context of a combat, deployment, or training environment. The importance of combining multiple data sources from a plurality of independent measures and, in particular, in conjunction with an environmental threat monitor that correlates the presence of a hazard with the suspected physiological response data should be emphasized. Developing wearable sensors capable of tracking low-level exposures to things such as alkylating or nerve agents along with the development of an environmental monitor that reports the presence of threats in real time would be of great value to service members in deployed environments (**figure 20**). In the future, a more direct linkage between a given measure and a particular decision (i.e., an implanted sensor that monitors acetylcholinesterase activity semi-continuously could be an easily understood metric to support decision-makers). From an operator’s perspective, ‘threat specific’ metrics will likely trump ‘threat agnostic’ metrics, making the direct linkage between a given measure and a particular decision particularly important. The importance of combining multiple data sources from a plurality of independent measures, and in particular in conjunction with an

environmental threat monitor that correlates the presence of a hazard with the suspected physiological response data, should be emphasized.

In addition to the technical challenges presented by any new technology, there are always social aspects and implications that should be considered. Of interest to decision makers could be a non-invasive device to assess combat readiness when presenting data that may result in a service member's removal from combat. While acclimating to a deployed environment, soldiers encounter multiple stressors such as minor infections, sleep deprivation, heat exhaustion and dehydration, to name only a few. The reliability and "actionability" of a wearable physiological data source indicating a possible exposure to an etiologic agent may be met with a fair amount of skepticism, particularly in the absence of concurrent environmental detection or identification of a threat agent. Defining wearable systems as a data source to be taken more as a holistic decision support tool (vis-à-vis an individual health monitoring device) may improve perception and acceptance of wearable systems, reinforcing the idea that the technology can be used more to support and augment, rather than hinder or encumber operations.



Figure 20. Wearable sensors and the Soldier.

Furthermore, relegating personnel to the level of commodities with health monitoring data directly feeding unit status reporting could be met with a significant degree of reticence. Furthermore, in the field, wearables would need to be compatible with personal protective equipment (PPE) and again, help - not hinder operations. The wearable's ability to monitor the state of PPE (breakthrough of permeable garments, failures in fit or function, the correct combination of appropriate equipment for the assigned mission or situation, etc.) could also be of tremendous benefit and should also be considered.

As wearables have the capacity to collect tremendous amounts of an individual wearer's information, the 'psycho-political' invasiveness of data collected must also be considered. The level at which such data should be protected (i.e., Health Insurance Portability and Accountability Act's (HIPPA) privacy rules) or consumed (i.e., tactical vs. operational) should be considered. Tactical and operational data collection will need intense analysis by the requirements and capability integration communities in a full Doctrine, Organization, Training, Materiel, Leadership & Education, Personnel, and Facilities (DOTMLPF) assessment. There may, however, be a clear value in keeping these decision support tools closer to tactical operators (i.e., at the battalion level) to prevent tactical units from becoming distracted or their mission disrupted by calls from higher headquarters voicing concerns about data readings. By essentially creating a "personal area network", wearables could also prove of great utility in terms of equipment tracking.

Currently, military vehicles are fitted with ‘gear tracking’ systems in order to prevent theft and loss. A wearable system capable of tracking weapons and gear, or validating the presence and functional state of PPE would be of particular value and could increase the overall palatability and acceptance of these systems.

VIII. DEVELOPMENT OF AN IMPARTIAL, MULTIFACETED TEST BEDS FOR THE EVALUATION OF WEARABLE TECHNOLOGIES AND ALGORITHM DEVELOPMENT FOR THE DOD.

Sensor platforms with promising attributes identified as being of interest should be thoroughly tested at an unbiased test bed site. The test bed site should be established with an ability to continually test and evaluate new components for these platforms as they improve and become available. An ideal test bed should have long-standing expertise in the science of emerging threats and core technical competencies in areas such as chemical and biological agent testing as well as the computational expertise required for device integration. Integration and data fusion is of substantial importance as the data products of wearable platforms will rarely be considered as isolates in a vacuum. Multiparametric testing of diagnostic wearable sensors should aim to differentiate between the typical physical battlefield stresses experienced in the field, and the physiological responses indicative of chemical or biological exposure. Multiple analytical outputs should be integrated into the Joint Program Executive Office for Chemical and Biological Defense (JPEO-CBD) Biosurveillance Portal so as to rapidly transition these capabilities to the Warfighter (**Figure 21**). In short the ideal test bed will not simply evaluate a wearable as a standalone device but as a useful factor in decision making.

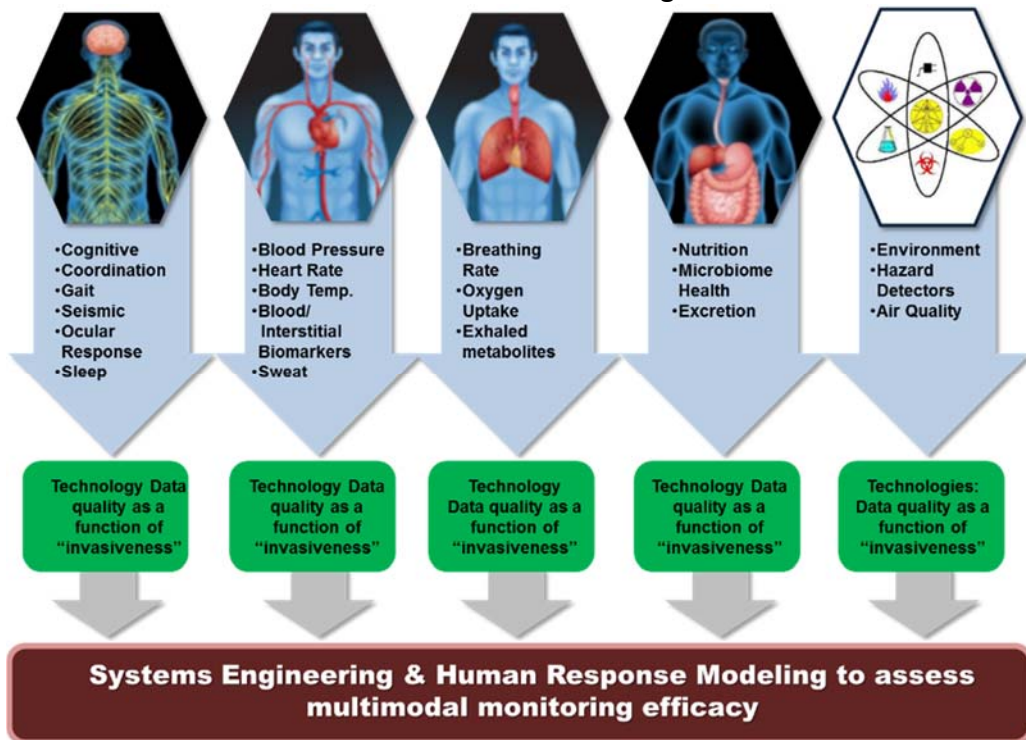


Figure 21. Monitoring Categories for Wearable Sensors

Common architecture should be defined and enforced for DoD co-development: Improved decision support will be provided by an interoperable architecture defined and implemented to incorporate physiological, defensive ensemble (e.g., individual body armor, personal protective equipment), and environmental data. It will become increasingly impossible to leverage capabilities across multiple organizations if developers are not all working with the same communication protocols, software architecture, and a rough integration strategy, such as an 'open architecture', for data integration. Sensors can improve in fidelity when their data are combined. Therefore, independent development should not preclude future sensor modeling and analytics development.

Animal Model Validation: An opportunity exists to use animal models to explore quantifiable physiological effects of chemical exposure which may be accessible with COTS technology. In addition to optical heart rate monitoring, such as that found in watches and wrist-wearables, inexpensive technology to measure muscle activation (transcutaneous electromyography) is currently available. There is precedent in the literature that exposure to and recovery from nerve agents has an effect on electrically measured muscle and sensory neuron activation, thus there may be 'low hanging fruit' available to leverage existing technology to a specific Combating Weapons of Mass Destruction (CWMD) use case.

Test beds will embrace collaboration. DoD labs have substantial investment in this area, and the ability for efforts to leverage expertise and work together is critically dependent on unbiased coordination and teaming etiquette. The Innovation Commons at the Army Research Laboratory (ARL) is a facility that is currently being instrumented that will provide a unique environment for the development of robust algorithms that will enable the distinction between signal and noise in human assessment. This space will be pervasively sensed and will be able to continuously monitor high resolution information from its users and therefore develop unique, accurate multi-dimensional assessments of humans working in the real-world. These data coupled with the computational capabilities at ARL provide an ideal space to develop targeted advanced analytics to disambiguate signals related to human assessment. This facility in conjunction with ARL's new research program in Continuous Multi-Faceted Soldier Assessment for Adaptive Technologies (CMSCFAT) will combine the expertise of 3 directorates and enable simultaneous, comprehensive analysis of multi-aspect data including behavior, physiology, subjective, networked, environmental, and task-dependent considerations to generate near real-time, accurate human assessment. The US Army Research Institute of Environmental Medicine's (USARIEM) Biophysics and Biomedical Monitoring Division has established an extensive body of expertise and an analytical framework for capturing and interpreting a host of metrics that can be captured by wearable devices in the context of Soldier mission sets. The "Signature TrRacking for Optimized Nutrition and training" (STRONG) Lab at Air Force Research Labs at Wright Patterson Air Force Base (AFB), OH has recently finished an initial controlled test of 10 COTS wearable devices, and is currently moving on to a second test as new devices have already emerged. The STRONG Lab has a controlled physiology lab setting, as well as access to numerous operational training sites where more advanced field testing is done.

IX. WEARABLE SCENARIOS

The following are hypothetical use cases that illustrate how wearable BSV sensor technology could revolutionize the way that decision-makers might gain situational understanding during CBRN operations.

Wearable Scenario 1: Chemical

Wearable monitors with sensors designed to detect biomarkers of nerve-agent exposure are available, but are mildly invasive and therefore issued only to trained Chemical, biological, radiological and nuclear (CBRNE) teams whose mission places them in a higher than normal risk for exposure. A sensitive site exploitation (SSE) team surveys and clears a suspected small-scale Sarin production facility, where a storage container containing a quantity of the Sarin product has a small leak and is emitting a low level of Sarin gas. The concentration of gas remains below the detection limit of the CBRNE capability, however, a follow-on team's wearable sensors detect physiological metrics consistent with low-level nerve agent exposure, despite a lack of symptoms from the operators. Mission leaders are now presented with considerably more options than before. They can: 1) ignore the sensor altogether, 2) increase the team's Mission Oriented Protective Posture (MOPP), 3) request additional testing of the environment, or 4) halt the operation outright. In the absence of this wearable data, the operation would likely have continued either oblivious to any exposure risk, or until sufficient symptoms were observed and reported to raise an alarm.

Decision making, such as to continue, increase MOPP, survey or test for threat agent concentration, or evacuate the site, would likely be influenced by the specificity of the information received along with the decision maker's confidence in that data. Here, specific metrics such as direct monitoring of acetylcholinesterase activity levels would be much less likely to be ignored than a model-based alert driven by more general physiological measures such as heart and breathing rates, or strength and coordination of muscle activation impulses. In this scenario, more general wearable metrics, such as heart rate (available through current COTS devices), could be ignored altogether.

S&T recommendations:

- Evaluate the use of currently-available sensors to detect physiological changes correlating to chemical agent exposures'
- Research chemical weapon agent (CWA)-specific biomarkers and validate their utility in determining extent and timeline of exposure'
- Develop connectivity and data reduction and handling algorithms for wearable technology
- Develop personal protective equipment inventory management Radio-frequency identification (RFID) technology
- Characterize device performance and reliability
- Develop concepts of operation and employment

Wearable Scenario 2: Biological

COTS wearable health monitors with motion, heart rate, and skin temperature sensors are issued to a large number of personnel at a supply and logistics location. The sensors, issued as part of a readiness initiative and to specifically track sleep quality for individuals with high-risk occupational specialties, are largely noninvasive and similar to a wristwatch. The program requires that the devices to be worn to bed, and the population being evaluated is well-acclimated to the location where the study is being conducted. A stationary particle sensor positioned outside of the logistics and supply area alarms on an aerosol plume. The areas fixed-site, automated biological detection and identification system registers positive for an etiological agent known to be naturally-occurring in the area, however, by the time this actionable information becomes known, many hours have passed. Even with this information in hand, the question remains if this was a deliberate attack or if an innocuous phenomenon caused the plume and a naturally-occurring pathogen was incidentally captured by the filters.

While cultures prepared from the automated detection system incubate, the wearable monitors worn by the logistics and supply personnel during their sleep indicate elevated heart rates for personnel residing in the area where CBRN models have shown the plume to have likely traversed. Based on this information, the medical officer is presented with the option of issuing prophylactic treatment to individuals working in the area in question, well in advance of laboratory culture results. In the absence of this information, precious hours could be lost waiting for cultured test results and prophylaxis may be issued far more broadly. Current available COTS technology could provide data that, when properly collected and analyzed, could be of genuine utility in CB-relevant decision making.

S&T Recommendations:

- Validate noninvasive technology as a means for early detection of exposure
 - Research the reliability of simple physiological metrics (sleeping heart rate, body temperatures) in cases of acclimation or stress"
- Validate symptomatic response using toxic agent and toxin animal exposure testing
- Integrate and correlate physiological data with environmental measurements
- Characterize device performance and reliability
- Develop concepts of operation and employment

X. THE NEED FOR SYSTEMS ENGINEERING

Stakeholder meetings have been planned to further define user requirements. Based on these requirements, a capability set will be designed to reduce operational risk to the Warfighter. Existing approaches can be implemented to immediately recommend available wearable sensor sets by merging existing COTS capabilities and evaluating modeled activity during a chemical exposure. For example, by combining combat simulation with physiological monitoring, multiple, layered evaluations could be used to optimize and refine capability sets (**figure 22**). Currently, there is a CDBP investment directed toward development of an analytical framework that combines portfolio analytics, system-of-systems modeling, force-on-force modeling, and business analytics.

These tools, along with other capabilities, can be leveraged to iteratively layer a wearable sensor design concept for chemical response. Once validated using the less-variable physiological responses of chemical exposure, design concepts could then be focused on pathogen response and validation.

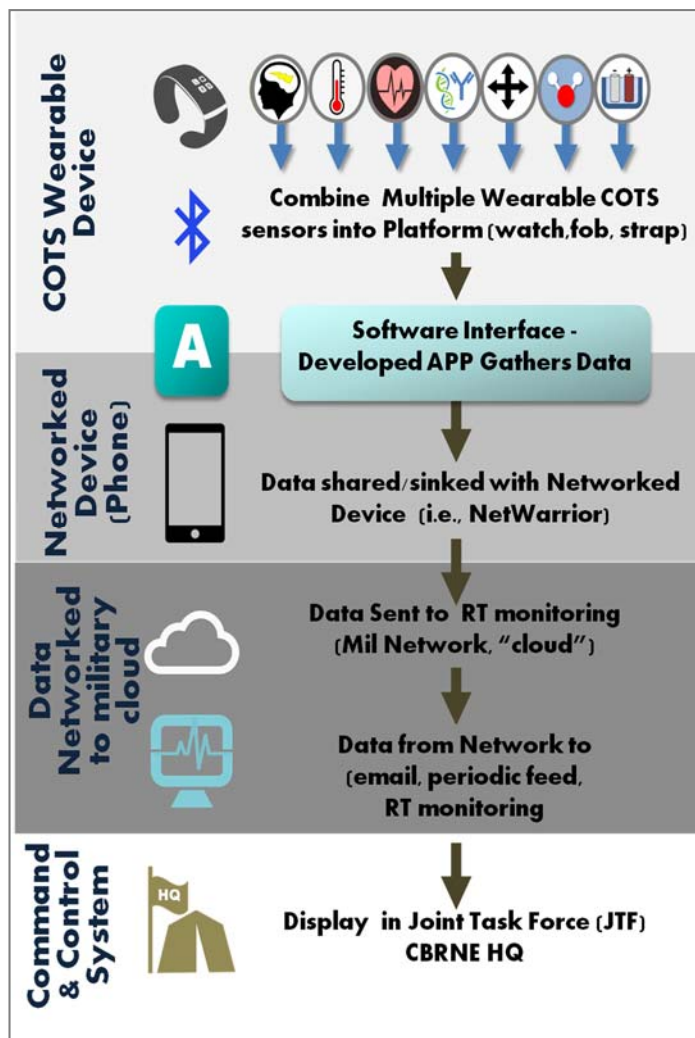


Figure 22. Concept of wearable sensor integration.

XI. RECOMMENDATIONS AND OTHER CONSIDERATIONS

In this report, we have analyzed the utility of wearable sensor data in developing decision support data products. Based on the information detailed in this report, recommendations or considerations include:

1. **Sensor platforms should be thoroughly tested at an unbiased test bed site.** Common sensor platforms should be selected by DTRA/JSTO and then tested by an unbiased test bed site established to test and evaluate these available wearable sensor technologies. Test beds should evaluate and compare new components as they improve and become available and should have long-standing expertise in the science of emerging threats and core technical competencies in areas such as chemical and biological agent testing as well as the computational expertise required for device integration.
2. **A common architecture should be defined and enforced for DoD co-development.** Improved decision support will be provided by an interoperable architecture defined and implemented to incorporate physiological, defensive ensemble, and environmental data. Leveraging across multiple organizations will be accomplished through the harmonization of communication protocols, software architecture, and rough integration strategies such as an 'open architecture' for data integration. As sensor combinations will likely improve data fidelity, independent sensor development should not preclude future sensor modeling or analytics development. Mobile sensor will require efficient and economical methods of data transmission that are compliant with the DoD information assurance policies, particularly if these sensors transmit personal or sensitive information. As the amount of data generated by these devices will likely be unprecedented, considerable effort will be required to ensure that the data collected is analyzed effectively and efficiently.
3. **Identify measurable physiological responses to chemical exposure can be derived from animal models.** An opportunity exists to use animal models to explore quantifiable physiological effects of chemical exposure which may be accessible with COTS technology. In addition to optical heart rate monitoring such as that found in watches and wrist-wearables, inexpensive technology to measure muscle activation (transcutaneous electromyography) is currently available. There is precedent in the literature that exposure to and recovery from nerve agents has an effect on electrically measured muscle and sensory neuron activation, thus there may be 'low hanging fruit' available to leverage existing technology to a specific CWMD use case.
- 4.
5. **Implement a systems engineering approach to define the optimal approach toward technology development.** JPEO-CBD has invested in the development of an analytical framework that combines portfolio analytics, system-of-systems modeling, force-on-force modeling, and business analytics. These tools, along with other capabilities, can be leveraged to iteratively layer a wearable sensor design concept for chemical and biological response.

- 6. Institute a collaborative approach to leverage the existing DoD investment.** Physiological monitoring and modeling are not unique DoD needs and the applicable partners in this space are varied and experienced. To harvest the strengths of the leading contributors in his field, a collaborative approach is required.

As an illustration of the consumption of data from an ensemble of wearable technologies, consider the case in which a team is deployed on a chemical reconnaissance mission following an insurgent attack suspected to involve a nerve agent. The team is equipped with a PPE monitoring system that indicates the mission oriented protective posture and any specialty PPE employed by the team and whether it is stowed or donned. As the team closes on the recon mission site, it increases its protective posture. Wearable data from the breathing and heart rate component confirms the change in equipment in collaboration with the PPE status monitoring system. As the team completes its mission, an electromyography signal from individuals who would not have expected to be exposed to a low level cholinergic agent informs their team leader of the possible exposure, who may make the decision to monitor them for further symptoms or send them to a clinic for acetylcholine esterase monitoring and further health screening.

XII. CONCLUSIONS

We report on the current utility and future potential of wearable physiological monitoring technology and wearable environmental sensing technology to provide value in decision support to reduce the risk of chemical and biological exposure on mission accomplishment. Risk reduction will be achieved by providing information that can alert leaders earlier than is currently possible through a host of wearable data products. These products include:

- Population level physiological well-being assessments vice individual level assessment of subordinate units.
- The type and current status of protective equipment being used by the units.
- Certain specific indicators measurable by current wearable technologies that correlate to possible chemical or biological exposure.

The DoD is positioned to further reduce the risk of exposure on mission accomplishment, and reduce casualties from exposure to chemical and biological threats by investing in the development of advanced capabilities for biomarker assays and other focused metrics and data points that correlate to exposure. The application of an integrated approach in a systems engineering framework along with animal testing to validate the correlation to exposure is advised to minimize programmatic and technical risk in the needed research.

The recommendations detailed in this document were based on the assessments of the current state of the art technologies for wearable sensor technologies and on how these technologies are both maturing and evolving.

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ACRONYMS AND ABBREVIATIONS

AFB	Air Force Base
AFRL	Air Force Research Labs
APP	mobile application
ARL	Army Research Laboratory
ATD	advanced technology demonstration
CBDP	Chemical and Biological Defense Program
CBRN	Chemical, biological, radiological and nuclear
CGM	continuous glucose monitors
CMSCFAT	Continuous Multi-Faceted Soldier Assessment for Adaptive Technologies
COE	Common Operational Environment
COTS	commercial-off-the-shelf
CWA	chemical weapon agent
DoD	Department of Defense
ECBC	Edgewood Chemical Biological Center
ECG (or EKG)	Electrocardiogram
EEG	electroencephalogram
DOTMLPF	Doctrine, Organization, Training, Materiel, Leadership & Education, Personnel, and Facilities
FDA	Food and Drug Administration
GOTS	Government off the shelf
GPS	Global positioning system
HDFS	Hadoop File System
HIPPA	Health Insurance Portability and Accountability Act
HQ	Headquarters
IoT	Internet of things
IP	Internet Protocol
IPv6	Internet Protocol version 6
JPEO	Joint Program Executive Office
JTF	Joint Task Force
LED	Light-emitting diode
MOPP	Mission Oriented Protective Posture
PPE	personal protective equipment
PPG	Photoplethysmographs
R&D	Research and Development
RFID	Radio-frequency identification
SME	subject matter expertise
SNR	signal-to-noise ratio
SSE	sensitive site exploitation
S&T	Science and Technology
STRONG	Signature TrRacking for Optimized Nutrition and training”
USARIEM	US Army Research Institute of Environmental Medicine
UV	Ultra violet

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