Open Body Area Network Physiological Status Monitor

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Lincoln Laboratory has developed and successfully transitioned to industry a prototype wearable sensor that monitors the thermal-work strain of an individual. Heart-rate data are processed on the device to estimate core body temperature; skin temperature and motion data are also collected. This information is used to produce a simple real-time actionable alert on the individual's physiological status that is then sent to an Android smartphone, allowing one person to assess the physical well-being of all members in a group. Designed for use by small military units during operational or training exercises, the networked monitors allow unit leaders and medics to make informed data-driven decisions that assure service members' health and performance are not compromised.

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Dismounted warfighters in austere environments face numerous physical, cognitive, and psychological stressors that reduce performance and lead to injury. Real-time physiological status monitors (RT-PSMs) can provide actionable information to small-unit leaders and medics to enable data-driven decisions that help them to maintain and improve warfighter performance and safety. The U.S. Army Medical Research and Materiel Command and its subordinate laboratory, the U.S. Army Research Institute of Environmental Medicine (USARIEM), have researched RT-PSMs through numerous technology iterations for the past two decades [1]. MIT Lincoln Laboratory first supported this effort in the early 2000s by conducting a study for USARIEM to develop an RT-PSM concept based on technology at that time [2].

Since about 2009, the year of the first Fitbit, decreases in the size, weight, and power (SWaP) of commercial electronics have led to a wave of consumer wearable sensors sold by hundreds of companies with billions of dollars in sales. It would be desirable if the military could simply purchase these low-cost commercial devices. However, with few exceptions, these commercial devices do not provide the information that small-unit leaders can act on. For example, heart rate, which is of high interest for consumers, does not in itself provide actionable information to a leader and is more likely to result in distraction. Integrating heart rate and other sensor measurements, such as skin temperature, into an individualized physiological model can provide clear actionable information, such as an alert that specific team members need to cool off. However, consumer-grade

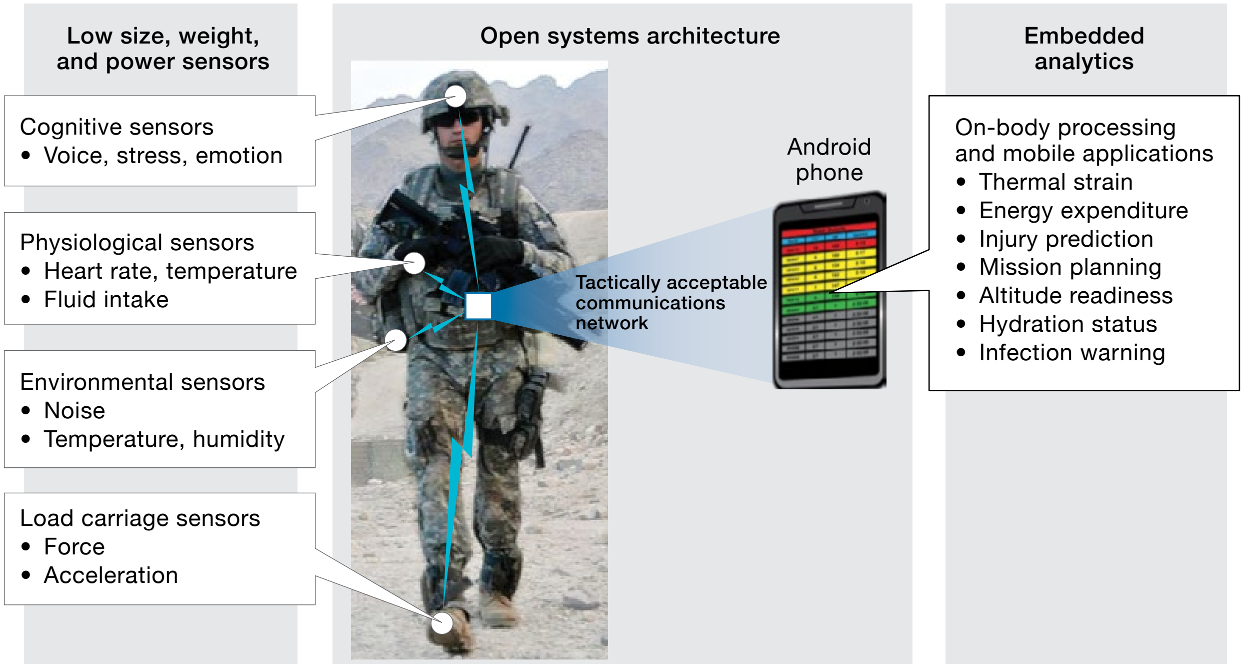


FIGURE 1. The main components of a real-time physiological status monitor (RT-PSM) are biomedical sensors, an architecture that can accommodate new technologies, and predictive analytics for providing actionable information to users. Lincoln Laboratory's experience with low-size, -weight, and -power (SWaP) sensors, open systems architectures, and embedded computing is contributing to the military's development of RT-PSMs that provide relevant evaluations of a warfighter's health and performance status while being acceptable for use in tactical and training environments.

devices are often proprietary closed systems, meaning that raw sensor data cannot be accessed for use in military-relevant algorithms, and predictive models specific to military needs cannot be integrated into their applications (apps). Other features of consumer devices—for example, relatively short battery life and reliance on wireless communications—make them insufficient or unacceptable for military use in tactical environments.

Since 2012, Lincoln Laboratory has worked with USARIEM, the Marine Expeditionary Rifle Squad (MERS), and several other government organizations to develop a series of RT-PSM prototypes to meet key requirements. As highlighted in Figure 1, these requirements include low-SWaP sensors, an open systems architecture that allows the integration of new sensors, analytics to generate real-time actionable information from sensor measurements, and tactically acceptable communications. RT-PSM prototypes have included the Open Body Area Network Physiological Status Monitor (OBAN PSM) to address thermal work strain, the Mobility and Biomechanics Insert for Load Evaluation (MoBILE) to address musculoskeletal overuse injury, and a tactical noise dosimeter to address hearing damage from operational exposures to extreme noise levels.

The OBAN PSM is the most mature of the RT-PSM efforts. The Lincoln Laboratory prototype technology was transitioned via a competitive bid process to industry to mature into a product. The winning contractor, Odic Inc., successfully completed the delivery of 300 units for use by the Army and Marines in 2018 field tests. Additional improvements are underway to support system employment at scale in military training environments, with the goal of establishing a leave-behind safety monitoring capability at Fort Benning, Georgia. The timeline for the development, testing, and transition of the OBAN PSM prototype is provided in Figure 2.

Physiological Model

The Physiological Strain Index (PSI), also referred to as Heat Strain Index (HSI) [3, 4], is a tool to identify overheating in individuals. Overheating occurs when a body cannot maintain core temperature (TC) at a safe level. Hot and humid conditions, especially when coupled with personal protective equipment, make it hard for the body to cool itself efficiently. Warfighters, first responders, and chemical, biological, radiological, and nuclear (CBRN) defense personnel are particularly prone to heat injury [3, 5–8].

Thermal-work strain is a measure of overheating (thermal) during periods of activity (work). High levels of thermal-work strain can cause heat injury at two levels. The first level is heat exhaustion, whose symptoms may include dizziness, thirst, weakness, and headache [9, 10]. If high levels of thermal-work strain persist, they may lead to heat stroke, a life-threatening condition that can cause delirium, convulsions, or coma [9, 10]. Even short of reaching heat exhaustion, thermal-work strain (i.e., heat strain) will degrade mental and physical performance capabilities [11], reducing a warfighter's combat readiness and increasing the likelihood of other injuries.

The PSI was developed by the USARIEM in response to the calculation complexity and inflexibility of the models and indices that preceded it [12]. As stated by Moran, the PSI "should be capable of indicating heat strain…and is expected to be sensitive enough to differentiate between similar exposures that differ in one variable," such as exposures which vary only in metabolic rate, level of protective clothing, or climate [12]. Since the PSI's development, Moran and others have validated it across hydration levels [13], genders [14], clothing levels [15], environmental conditions [14, 15], metabolic workloads [14–17], aerobic capacities [18], and ages [18]. Of the 14 thermal strain indices identified by de Freitas and Grigorieva [19], PSI remains the only one that operates across the desired range of conditions whose inputs are measurable from the body in real time.

The PSI combines information on thermal burden and work strain to provide a single, simple 0–10+ scale to assess physiological status [20]. The thermal and workload portions of the PSI are computed from core body temperature and heart rate, respectively. When core temperature rises from the normal 37 degrees Celsius up

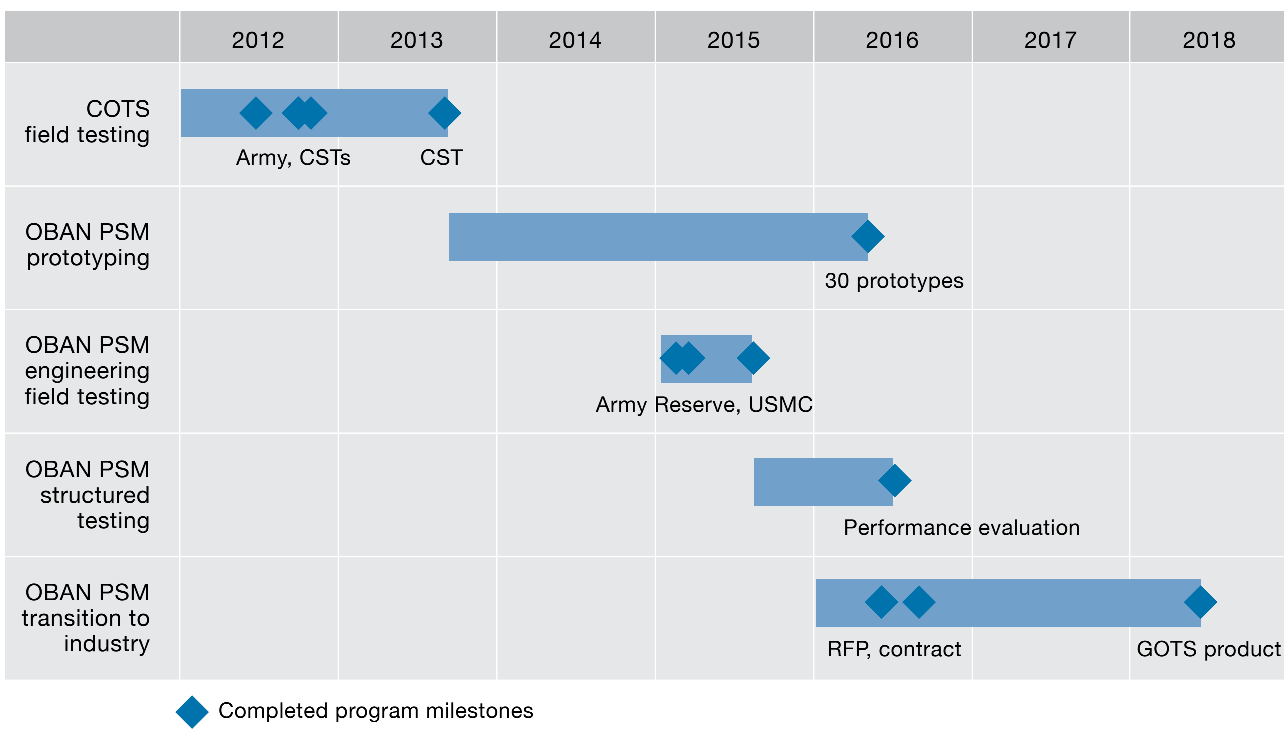


FIGURE 2. The development, testing, and transition timeline for the Open Body Area Network Physiological Status Monitor (OBAN PSM) illustrates the stages of the project spanning more than six years. Prior to the start of Lincoln Laboratory development, commercial devices were evaluated with military end users for suitability. Their identified shortcomings necessitated the government investment into the OBAN PSM development effort. COTS: commercial off-the-shelf. CST: National Guard Civil Support Team. RFP: request for proposals. GOTS: government off-the-shelf.

to 40 degrees Celsius or higher during prolonged exertion, heat stroke can occur. Heat exhaustion and heat stroke are known to occur in both training and combat, but are commonly underreported. One well-publicized example occurred at Fort Bragg, North Carolina, in September 2011 when 43 out of 60 soldiers experienced heat injuries during a 12-mile road march. Eighteen of the soldiers were taken to the hospital, and one was admitted to the intensive care unit [21].

The gold standard for measuring core temperature in the field is an ingestible temperature capsule, which is effective as a research tool but is deemed unacceptable for training and operations. To address this deficiency, USARIEM developed and validated an algorithm for estimating core temperature. The initial model is based on smoothed heart-rate estimates. The physiological basis for this algorithm is twofold. First, heart rate increases with work, which heats the body core. Muscles are only about 20 percent efficient, with 80 percent of the energy generated during work going to heat production [22]. Second, heart rate increases to support the body's heat dissipation. To dissipate heat, blood vessels near the skin vasodilate to increase blood perfusion. Thus, heart rate increases both to support the cardiac output needed to perform work and to increase skin blood flow to allow dissipation of the resulting heat.

Estimated core temperature can thus serve as an input into the PSI model, allowing thermal-work strain to be predicted from time-series heart-rate data alone. However, anticipated model improvements incorporate skin temperature measurements to help determine the level of heat strain compensation provided by evaporative cooling [23]. Activity level and neuromotor coordination measured from accelerometry may also be important inputs toward creating a more actionable alerting capability. A key goal of the OBAN PSM is to bring together these three real-time measurements—heart rate, skin temperature, and accelerometry—into an integrated platform that is acceptable for military use.

System Overview

The OBAN PSM was initially designed to monitor a team of up to 13 members. The number of team members was chosen to accommodate both Army and Marine squads, currently sized at 9 and 13, respectively. The team leader or medic monitors physiological status on an Android

FIGURE 3. The OBAN PSM system allows team leaders or medics to monitor the current physiological status of their squads via a short-range tactical wireless link.

smartphone, referred to in the Army as an end-user device (EUD), via a short-range (3–5 meters) tactically acceptable OBAN radio. This short-range body area network allows for updates during the regular, up-close status checks that a leader normally conducts with his or her team members. Alternatively, the OBAN can provide a wireless, on-body link to a longer-range radio worn elsewhere on body. The operating concept is depicted in Figure 3.

Leveraging commercial technology, Lincoln Laboratory researchers developed a prototype on-body device. Starting with a Polar chest strap and sensor (Polar Electro, Kempele, Finland), the researchers designed a "hub" to contain the required additional sensing, computing, and wireless communications electronics. Figure 4 depicts the components of the prototype OBAN PSM. The Polar sensor detects heartbeats from cardiac electrical activity and communicates beat times over a short-range (1 meter) inductive wireless link to a Polar receiver in the hub. The hub then computes heart rate and PSI. It also senses skin temperature and accelerometry, logs data, and wirelessly communicates heart rate and PSI off-body. The Polar sensor is attached to the chest strap that is worn on the front of the body centered over the heart, while the hub is worn on the side of the chest to be compatible with body armor.

The EUD also heavily leveraged commercial technology in the form of a Samsung Note 3 Android phone. The EUD includes an OBAN dongle and whip antenna, an extended-life battery, and a case. Cellular communications are disabled. The OBAN PSM EUD is a surrogate for the Army's Nett Warrior EUD, which also leverages commercial Android cell phone technology. Figure 5 depicts the electronics, packaging, and display software for the EUD.

Key needs for the wireless body area network technology are (1) minimum power to prolong battery life while transmitting infrequent, small-packet-size status updates and (2) compatibility with military wireless communications. Since Bluetooth and other

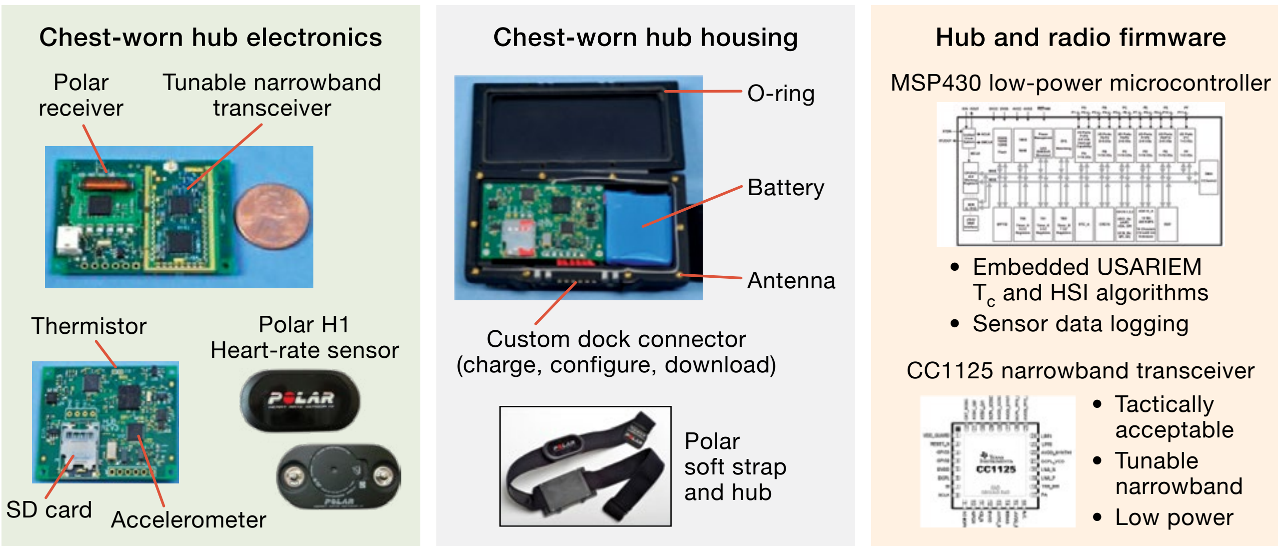


FIGURE 4. The chest-worn components of the prototype Open Body Area Network Physiological Status Monitor include the custom-built hub electronics and housing, and the embedded software that enables data analysis and communication.

FIGURE 5. The prototype end-user device for the Open Body Area Network Physiological Status Monitor uses commercial off-the-shelf (COTS) components that were adapted for use with custom software and radio hardware.

common-place commercial solutions would not be acceptable, other solutions were surveyed. The best identified option at the time (2013) was a tunable narrowband (TNB) low-power commercial transceiver operating with a messaging protocol designed by Lincoln Laboratory staff. The TNB radio is implemented on a daughterboard that is mounted on the hub and EUD dongle circuit boards. The EUD transmits a query for updates, triggering hubs within range of the EUD to transmit heart rate and PSI values. The radio communicates over a standard narrowband military frequency channel, which is assigned during the configuration process. The TNB radio has been approved by the U.S. Army through the DD1494 process for frequency allocation at military installations and operating environments.

To complete the system, a configuration laptop and docking station are required for charging and downloading data.

Engineering Field Tests

After an initial build of nine prototype devices, three engineering field tests were conducted by Lincoln Laboratory and USARIEM with the goals of identifying any technical performance issues in relevant environments and obtaining warfighter feedback on the concept of employment and human factors. The testing team was successful in obtaining feedback, in marking general successes and failures, and in identifying several system issues. A system failure analysis was performed to determine hardware and software weaknesses and to establish corrective actions that could be applied to a 30-hub build-up. This failure analysis provided the motivation for additional rigorous structured testing.

Two engineering field tests were conducted with the Army Reserve 743rd Transportation Company at Hanscom Air Force Base (HAFB), Massachusetts, and at the Camp Ethan Allen Training Site (CEATS), Vermont; one was conducted with the U.S. Marine Corps School of Infantry–East (SOI-E), Camp Geiger, North Carolina. The volunteers, 15 men and 6 women, enrolled and participated in the tests after reading and signing an informed consent form. The tests were conducted according to procedures approved by the USARIEM Human Use Review Committee, the MIT Committee on the Use of Humans as Experimental Subjects, and the U.S. Army Medical Research and Materiel Command Human Research Protection Office. The test durations progressively increased: 3 hours for HAFB, 24 hours for CEATS, and 57 hours at SOI-E. Note that participants slept while wearing the devices during the latter two tests. Photographs from the three tests are shown in Figure 6. Three aspects of these tests are reported herein: communications performance, sensor measurement quality, and reliability.

FIGURE 6. Photographs show scenes from the engineering field tests. Clockwise from upper left are scenes from Hanscom Air Force Base, the Camp Ethan Allen Training Site, and the U.S. Marine Corps School of Infantry–East.

Communication Performance

During the engineering tests, the EUDs were set to operate in manual mode, i.e., the EUD operator pushes a button on the display to send a query. Because the tests were integrated into routine warfighter training activities, uncontrolled separations between the EUD and hub were experienced. Thus, statistics on queries and replies gave a qualitative indication of communication performance.

Quantitative range testing conducted separately under controlled conditions measured 95 percent message transmission at 2.7-meter range, with and without body armor, and independent of the subject's orientation to the EUD. Although this transmission percentage would be unacceptably low for a general-purpose radio, it is judged to be acceptable for a low-power body area network that transmits status information. If desired, the percentage could be increased by simply repeating a query when a reply is not received.

SOI-E Sensor Measurement Examples

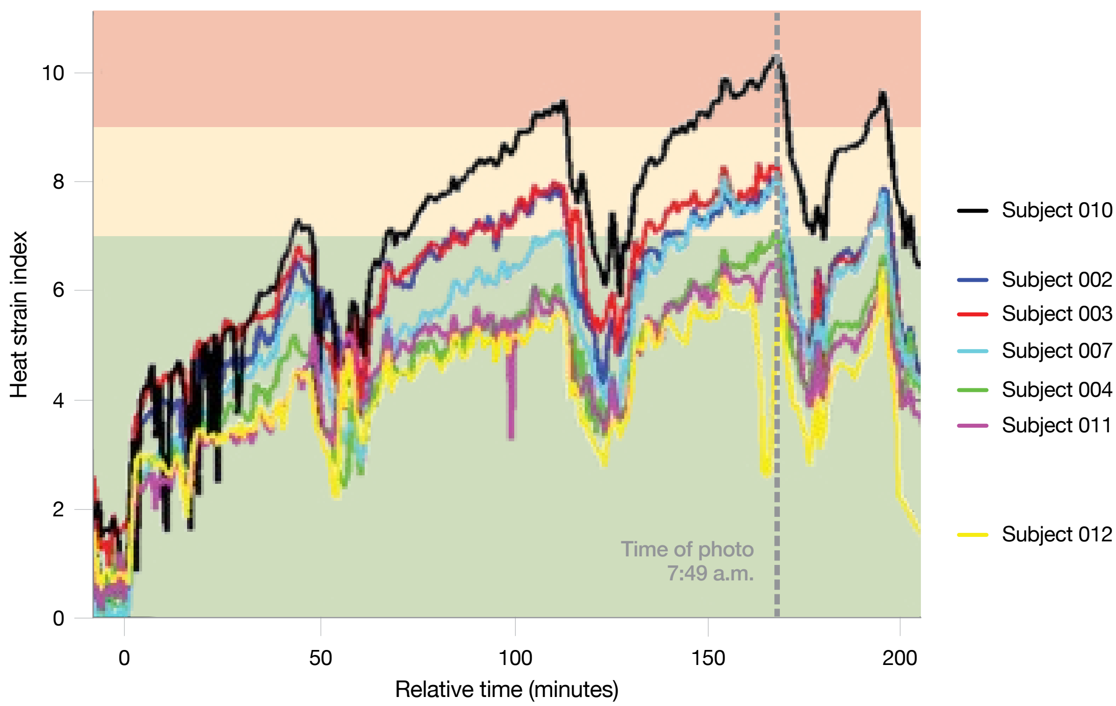
An important activity for evaluating the OBAN PSM as a heat strain monitor was the SOI-E 15-kilometer ruck march, which served as a final pass/fail event for training completion. As shown in Figure 7a, PSI values ranging between 0 and 10 were observed, increasing as expected over the duration of the march. The wide range of values across Marines at any particular point in time highlights the value of individualized, real-time monitoring. When the EUD display alerted support personnel that one Marine was approaching and then reached a PSI of 10 (shown in Figure 7b), extra attention was paid to ensure the safety of that Marine until the march was completed.

High-quality data were logged for heart rate, accelerometry, and skin temperature for a total of 57 hours for seven hubs. Figure 8 shows example sensor data from one volunteer collected when the volunteer was asleep. Figure 9 shows data collected when the volunteer was on the ruck march. Two issues were identified during the data collection. First, in approximately 0.3 percent of the data collected, the heart rate was measured as half of the true heart rate. An algorithmic correction for this was implemented during follow-on development. Second, 10 hours of accelerometry data were not logged for one hub (2.5 percent of the total). This was due to a software bug that was also corrected during follow-on development.

Structured Testing

After iterative testing with users was completed and improvements were implemented on the basis of lessons learned and component failure analysis, a set of 30 hubs was built. These devices were subjected to a rigorous laboratory and on-body testing protocol, referred to as structured testing. Tests evaluated sensor accuracy, battery life, radio functionality, and ability to operate in harsh environments. In addition, the 30 hubs were worn by volunteers in a variety of free-living activities. The results of this testing are summarized here:

- Heart-rate accuracy. The 95 percent confidence interval of errors, based on human subject data, was measured as [–3.2, 1.3] beats per minute over a range of activities. This accuracy is consistent with that of the Polar heart-rate sensor that is used by the OBAN PSM prototype.
- Accelerometer accuracy. Accelerations for the three axes were found to fall within 10 percent of those from a truth sensor, measured on a vibration table with peak acceleration of 6g. Accuracy was higher for lower levels of acceleration. Noise levels were higher than those from a truth sensor. This high noise level was determined to be caused by insufficient voltage regulation and was addressed in the technology transition.
- Thermistor accuracy. After applying a sensor-specific calibration offset, all 30 hubs were measured to be accurate to within 0.2 degrees Celsius over the range of 30 to 47 degrees Celsius. The thermistors' dynamic response was measured and was determined to be sufficiently fast to track skin temperature.
- Core temperature estimation and PSI algorithm implementation. These implementations were anchored against reference implementations and found to perform identically.
- Wireless performance. Wireless communication was tested in the lab (off-body) at 1-meter range with more than 100,000 EUD requests and more than 1,000,000 hub replies during upwards of 1,100 hours. Median message loss was 0.28 percent, and 78 percent of the tests yielded loss rates of less than 0.5 percent. Message loss measured on-body at three yards (2.7 meters) was 5 percent, with or without body armor, and with no dependence seen on the side of the body facing the EUD. An interference test was conducted with three teams, each wearing 10 hubs, with each team assigned



(a)

(b)

FIGURE 7. The PSI histories for seven Marines on a 15-kilometer ruck march during the Marine Corps School of Infantry–East test are shown in (a). The dashed gray line corresponds in time to the snapshot of the real-time display shown in (b). In the chart and display, green indicates that the level of heat strain is mild; yellow indicates elevated but nonthreatening levels of heat strain; and red indicates a dangerous level. During this test, the Marine identified as Subject ID010, indicated in (a) by the solid black line, reached a PSI of 10, indicated in (b) by the red row. This reading alerted safety support personnel that an intervention was needed.

a different frequency channel. There was no degradation of communications for the three teams when they were standing in close proximity in a room.

- Battery life. Six hubs were tested in the lab, resulting in measured battery lives of 4.8 to 5.5 days.
- Robustness to heat, vibration, and sweat. Temperature was varied from 13 to 55 degrees Celsius in a chamber. None of the 30 devices failed, although the message loss exceeded 1 percent for four hubs at the higher temeratures. This temperature dependency is understood and was addressed in the technology transition. For vibration, four hubs were tested on a vibration table that ran a standard profile simulating a Humvee driving over rough terrain. No failures or anomalies were encountered. To simulate a sweaty environment, three hubs were sprayed with a saline solution and then wrapped in a saline-soaked paper towel for one hour. No failures or anomalies were encountered.

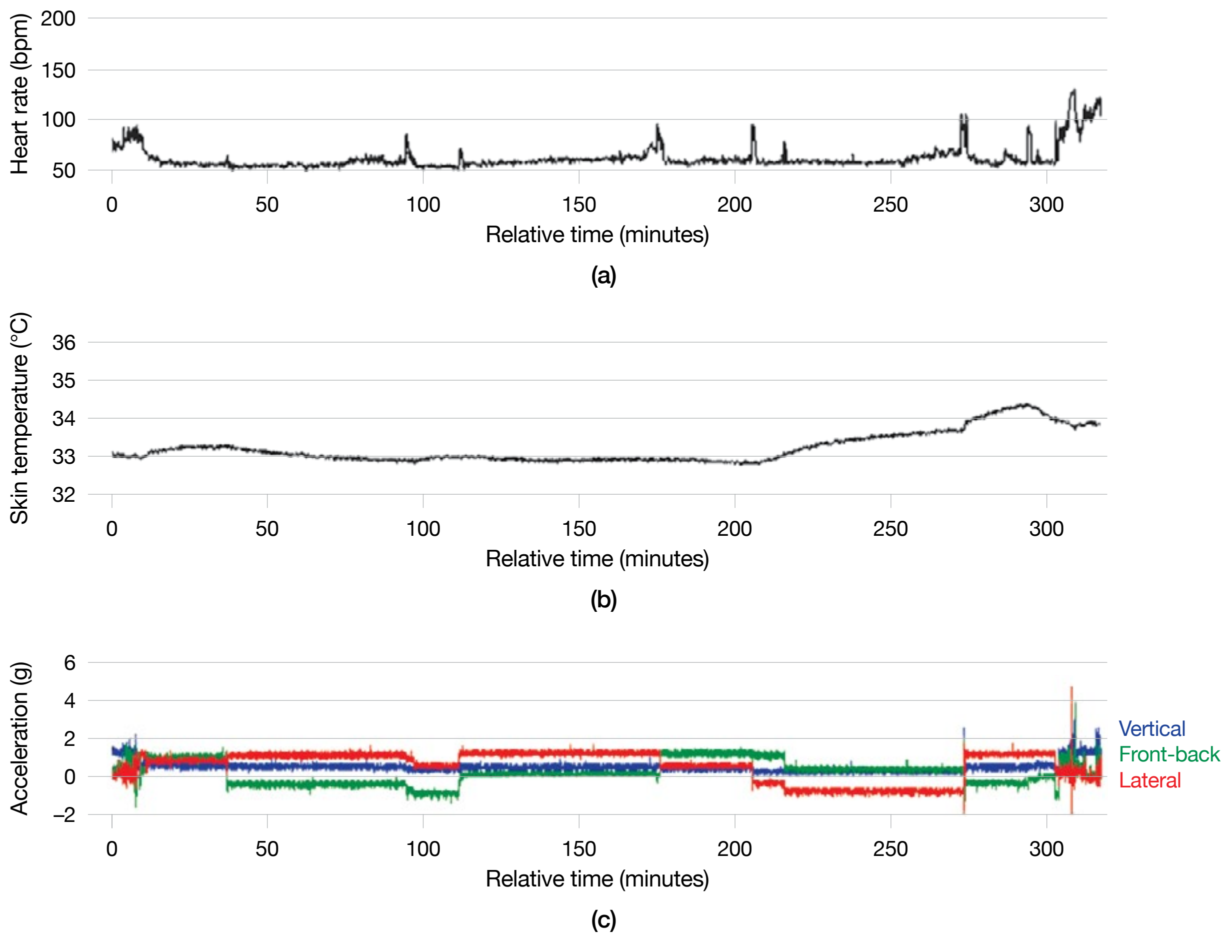


FIGURE 8. Sensor data collected during sleep, as shown here for one SOI-E Marine, can provide rich insight into sleep quality and other health factors that can impact performance during subsequent activities. Note that the accelerometry data show changes in resting position that correlate with spikes in heart-rate data.

- On-body reliability. The 30 hubs were worn repeatedly by Lincoln Laboratory staff during varied physical activities for a total of more than 180 hours. No failures were encountered.

Structured testing made use of a variety of the Laboratory's test equipment and facilities, including the RF Compact Range for radio testing, environmental chambers, and mechanical test equipment. As an example, vibration exposure was performed to evaluate whether rigorous travel conditions and activity could be expected to cause device failure in the OBAN hubs. For this test, four hubs were mounted to a single-axis T2000 vibration table (Unholtz-Dickie, Wallingford, Connecticut) with fixtures designed in-house for this purpose; only four hubs were used because of space limitations on the vibration table. A Polar heart-rate simulator was positioned alongside the vibration plate and a Polar watch (FT1 or RS100) was used to check the heart-rate truth at the test's start and finish. The EUD was set up approximately two meters from the vibration table shown in Figure 10 and set to query for updates every 30 seconds. To capture a baseline for this new testing environment, the EUD started to query for updates from the hubs 1.5 hours before the hubs were exposed to vibrations. An operationally representative Humvee profile was selected for this test. It ranges in frequency from 5 to 500 Hz and in magnitude from −8g to +8g. The profile was run for 30 minutes in each axis. No failures or anomalies were noted.

Technology Transition

After a competitive bidding process, Odic Inc. (Devens, Massachusetts) was selected to mature the OBAN

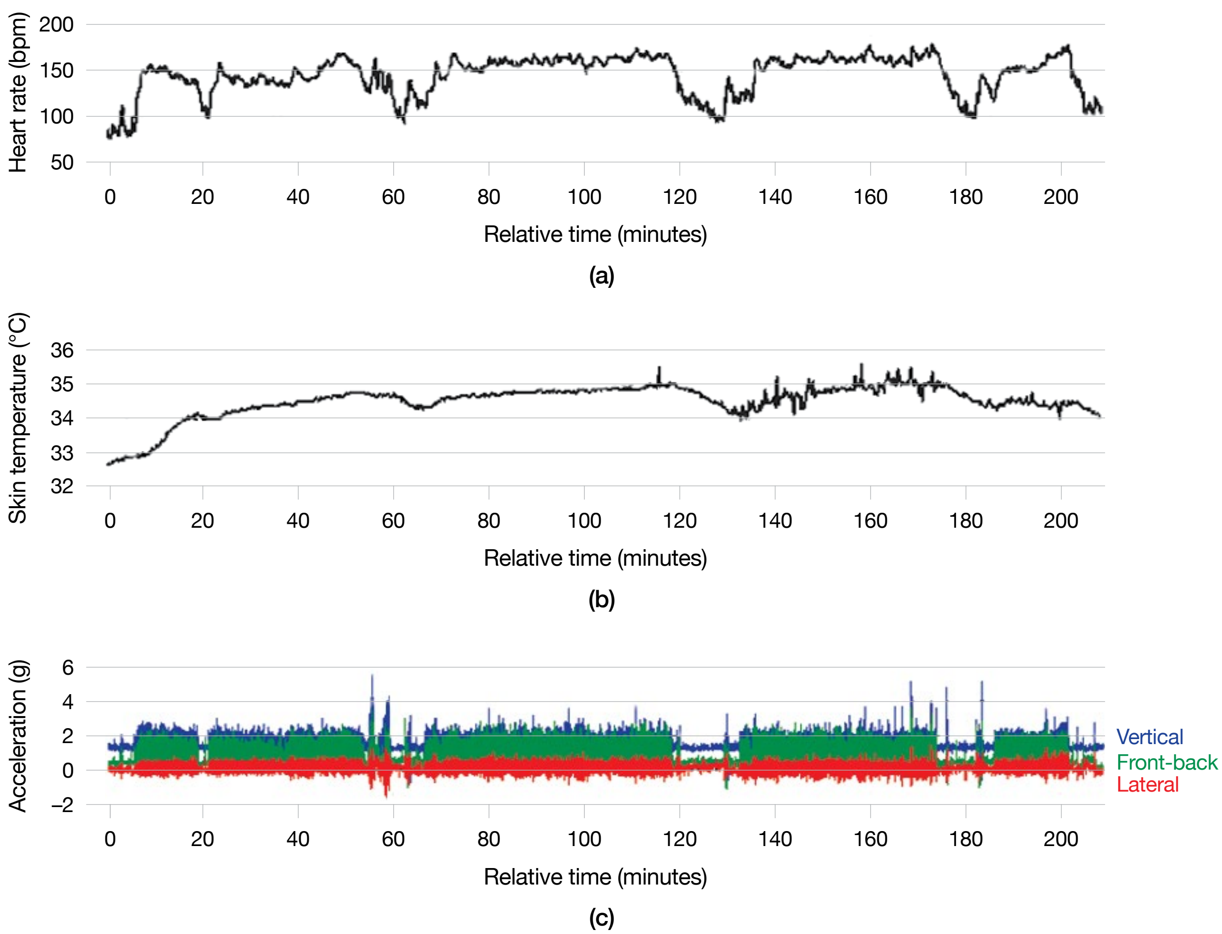


FIGURE 9. Sensor data collected from one SOI-E Marine during the 3.5-hour ruck march show the high level of sustained activity measured by the accelerometer and the resulting elevated heart rate. Recovery during the four rest breaks, noted by the periods of low acceleration measurements, can also be seen.

PSM prototype into a product. The result is shown in Figure 11. The system includes significant improvements and innovations. The single-module on-body device is significantly smaller, and it replaces the Polar sensor by snapping directly into the commercial off-the-shelf chest strap. Battery life has been extended to one week, and can be extended longer if data logging is disabled. In addition to the TNB transceiver, Bluetooth Low Energy, a variant of Bluetooth wireless technology, has been added as an option. Bluetooth Low Energy is convenient for non-tactical use, such as in domestic military training environments. The functionality of the phone dongle and the antenna have been integrated into the Moto mod add-on, which snaps onto the Moto Z Android phone, to produce a single integrated unit. The docking station is a single, compact unit that charges and downloads data from the on-body devices. As a result of this project's success, Odic was named the U.S. Small Business Administration's Subcontractor of the Year for the New England Region. Significant portions of Lincoln Laboratory's prototype have been extended and included in the product, including much of the firmware, the phone app, and the configuration PC software.

The system, consisting of 300 on-body devices, 20 EUDs, and 20 docking stations, was delivered by Odic to the Laboratory in May 2018. The devices were then loaned to the Army and Marines for field testing. Approximately 2,000 service members wore the OBAN PSM devices in 2018 and 2019 during training programs at multiple hot locations, primarily at Fort Benning, Georgia, under a human subject research protocol conducted by USARIEM. The collected data are currently undergoing analysis to further refine the PSI algorithm. Additional field testing was conducted by USARIEM to assess the usability of the system by military personnel encapsulated in the protective gear required for chemical and biological threat response. An additional round of system improvements is currently underway by Odic and Lincoln Laboratory, to be implemented prior to large-scale purchase by the military.

Future Directions

The OBAN PSM system is a significant advance in wearable monitoring for the military. The system is suitable for operational use because of its ability to provide actionable information via a wireless body area network in a small device with a one-week battery life. Although the cost in volume remains to be determined, the system's use of low-cost commercial components and design for manufacture are expected to result in an affordable cost. This affordability will allow the government to scale up the use of real-time thermal-work strain monitoring to first reduce the number of heat injuries in training environments. As the number of users increases, their collected data will allow the physiological models and actionable alerting to be improved, further extending the capabilities and employment of physiological monitoring. The system's open, government-owned architecture will allow additional wearable technologies to be integrated as they mature.

The use of a chest strap to measure heart rate is perhaps technically mundane but is an important consideration for comfort. Acceptability of chest straps has been found to vary from individual to individual, and acceptability for 24 hours may not extend to a week of wear. The objective solution is to integrate long-lived real-time monitoring within clothing and equipment. For example, commercial compression shirts are available to measure heart rate; however, individual variation in electrode fit has been an issue. More advanced methods for shirt integration, such as functional fibers that can themselves serve as sensors, are being investigated by the Army. Epidermal electronics or removable tattoos may prove suitable, although the Army has found in the past that adhesive patches are not acceptable to soldiers in hot, dirty, sweaty environments. Regardless of the particular type of integration with the body in the future, the government-owned open architecture body area network will evolve and continue to be relevant.

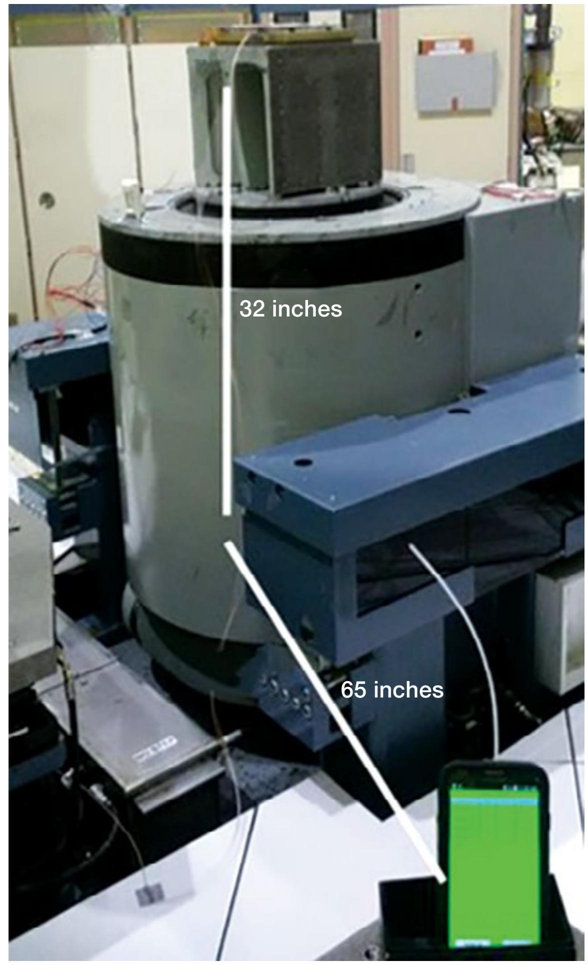


FIGURE 10. For the *z*-axis vibration durability test, the cell phone (EUD) was set up 65 inches from the vibration table on which the hubs were positioned. Additional dimensions are provided for scale. A Humvee vibration profile was selected for this test as representative of stressing field conditions.

Beyond thermal-work strain, the government has identified the need to concurrently measure multiple dimensions of human readiness, including cognitive, musculoskeletal, and immune system status, as well as environmental exposure, as was shown in Figure 1 [1]. The capability to monitor these aspects of readiness with wearable sensors is under development, but these sensors are expected to require additional sensing nodes at the head and feet. These additional sensing nodes will also need to be integrated within the open architecture.

As RT-PSM becomes integrated into equipment, decreasing SWaP will continue to be important. PsiKick (Charlottesville, Virginia) tailored its development of an ultralow-power system on chip (SoC) for the Internet

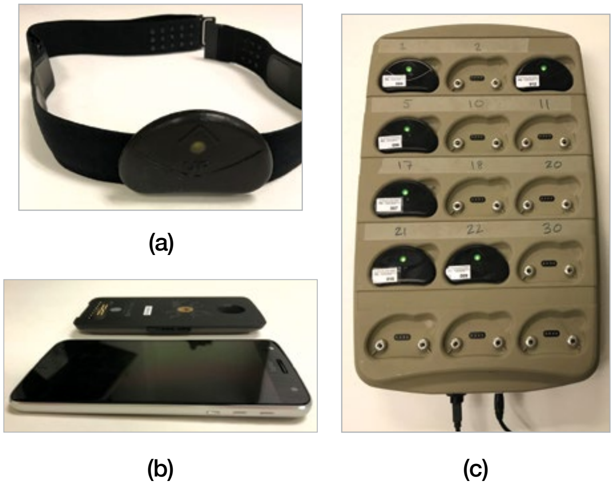


FIGURE 11. The Open Body Area Network Physiological Status Monitor product is composed of an on-body device (a), the Moto Z Android phone with Moto mod add-on (b), and a docking station (c). PHOTOGRAPHS COURTESY OF ODIC INC.

of Things to address government needs for wearable sensing. This work was funded through a Lincoln Laboratory contract and the government's Small Business Innovation Research program, with additional research funded through the National Science Foundation's ASSIST (Advanced Self-Powered Systems for Integrated Sensors and Technologies) Center. A highly innovative aspect of this work was an ultralow SWaP ultrawideband transmitter, combined with a narrowband wakeup radio. Other companies are also progressing with reduced SWaP SOCs. The SOC technology is based on the same type of subthreshold logic that Lincoln Laboratory has been pioneering for years for other government applications. The goal is an SoC that consumes less than 50 microwatts to allow the physiological status monitor to operate continuously for months, or indefinitely with energy harvesting. At that point, wearable sensing will truly become "wear and forget."

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Appendix

Evaluation of Heart-Rate Accuracy of COTS Monitors

Commercial heart-rate (HR) monitors on chest straps use electrical-signal sensing technology that has matured over several decades. More recently, optical technology has been developed to measure HR. Consumer optical HR monitors can be worn on the wrist, forearm, forehead, or ear. Wrist-worn monitors in particular have become commonplace and are usually considered to be more comfortable than chest straps for long-term wear. However, the accuracy of optical HR monitors for military applications has been questioned. Lincoln Laboratory was asked by the U.S. Army Medical Materiel Development Activity's Medical Support Systems Project Management Office to assess optical monitors for accuracy of both HR measurements and the biomedical information computed from these measurements.

We chose to test seven commercial heart-rate monitors representative of technology available between spring 2015 and fall 2016. The set represents a variety of wear locations: three were designed to be worn on the wrist or forearm, and two each were to be worn on the chest and forehead. These monitors fulfilled several military-related criteria:

- They must be wearable for days in dirty, sweaty conditions, thus eliminating ones secured with adhesive patches.
- They must not impede most military activities, thus ruling out sensors that clip onto a finger.
- They must support continuous monitoring during activity, not just resting heart rate.

The devices fell into two sensing modalities: electrocardiogram (ECG) or photoplethysmography (PPG). In wearable devices, ECG uses external, dry electrodes to measure electrical signals emitted by the heart muscles. In PPG, a light-emitting diode (LED) shining into the skin measures changes in reflectance caused by the variation in capillary blood flow during the heartbeat cycle. We chose NorthEast Monitoring's DR200 three-lead Holter monitor as the criterion device.

Eighteen Lincoln Laboratory employees enrolled in this study after signing informed consent forms. The testing was conducted according to procedures approved by the MIT Committee on the Use of Humans as Experimental Subjects and the U.S. Army Medical Research and Materiel Command Human Research Protection Office. The testing protocol was based on one developed by the U.S. Army Research Institute for Environmental Medicine for a previous evaluation of HR monitors. Volunteers engaged in approximately 50 minutes of low-, medium-, and high-intensity activities and unstructured rest breaks. Figure A1 shows the schedule of activities. Also shown is the heart-rate data for a single subject wearing a gold-standard device along with one wrist-worn and one headband HR monitor. The

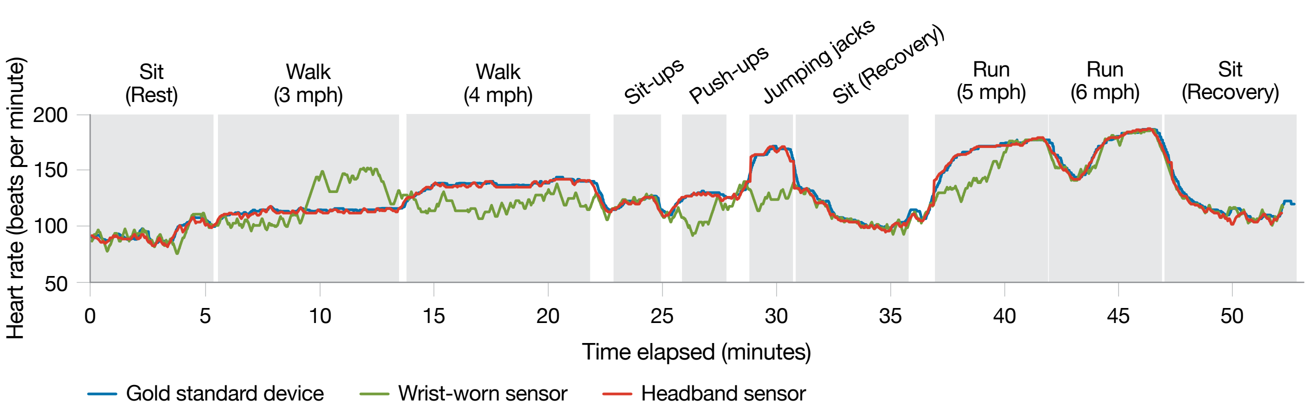


FIGURE A1. Heart-rate (HR) data are shown from a single subject concurrently wearing the criterion device and two test devices. Regions of activity are shown in gray boxes. Agreement is obtained across activity levels between the gold-standard device and the headband HR monitor, while the wrist-worn HR monitor does not track as closely.

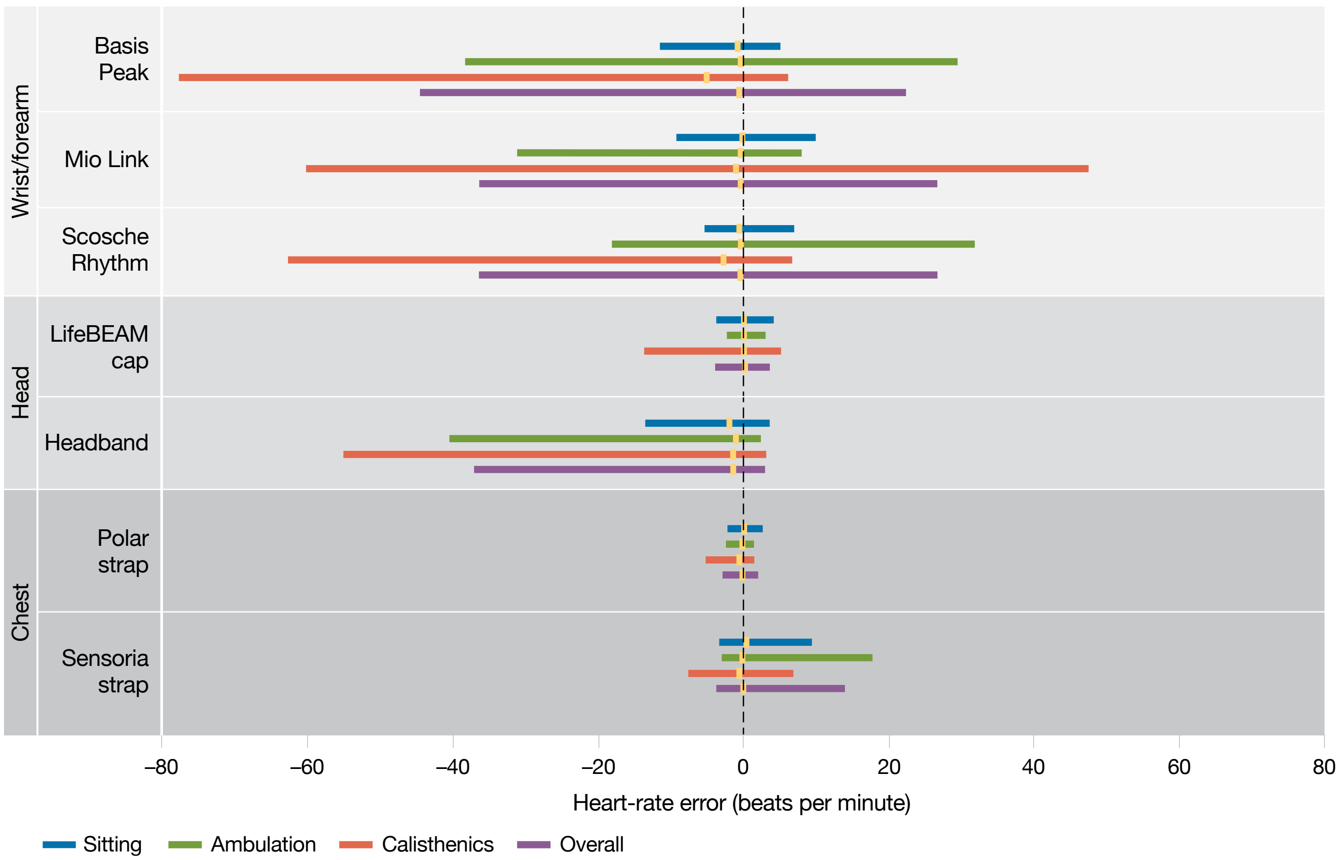


FIGURE A2. Commercial device heart-rate accuracy is shown as a function of activity and as an "Overall" metric. "Sitting" includes three dedicated periods of sitting. "Ambulation" includes two speeds of walking and two speeds of running. Sit-ups, push-ups, and jumping jacks are included in "Calisthenics." For each category, the 95 percent confidence interval is represented by the colored bar and the median by the orange mark. The Polar chest strap achieved the highest level of accuracy compared to the criterion device. Optical devices worn on the wrist and forearm were significantly less accurate, most notably during calisthenics.

figure shows the agreement across activity levels between the gold-standard device and the headband HR monitor, while the wrist-worn HR monitor does not track as closely.

Figure A2 summarizes the results of the testing by showing median HR errors and 95 percent nonparametric confidence intervals (CI). The results are broken down by type of activity, with positive differences representing an overestimate of HR by the test device, and negative differences representing an underestimate. The industry-leading Polar chest strap achieved the highest level of accuracy compared to the criterion device. The Sensoria Strap was found to have similar accuracy to the Polar Strap when it fit the subject, ensuring good electrode contact was maintained, but significantly worse accuracy when it did not fit.

The optical devices worn on the wrist and forearm were significantly less accurate than the Polar Strap. These devices were most accurate when subjects were sitting and least accurate during calisthenics, which involved changes to wrist and hand configuration. The HR accuracy for these devices varied significantly across subjects. Finally, the LifeBEAM Smart Hat accuracy was comparable to that of the Polar Strap, but the Smart Hat would need to be integrated or made compatible with a helmet for military applications.

To determine the significance of heart-rate error we looked at its effect on scores produced by the physiological strain index (PSI), the actionable metric described in the main article. We developed an error model that assumed heart-rate errors have a Gaussian distribution and may be correlated over time. The Gaussian assumption is frequently not valid for the measured heart-rate errors, but it is an approximation that is intentionally not specific to any particular test device or activity and serves as a

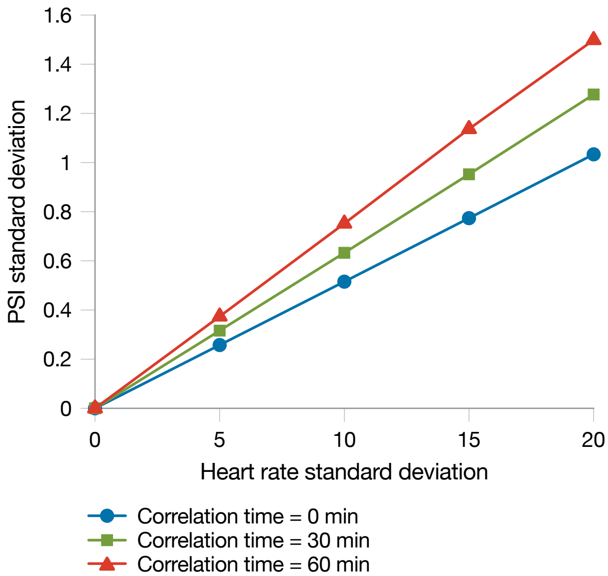


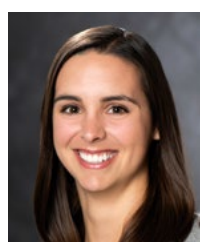
FIGURE A3. **The PSI error standard deviation is plotted as a function of the heart-rate (HR) error standard deviation (beats per minute, bpm) for three HR error correlation times. It can be seen from the plot that a typical wrist-worn HR sensor's 95 percent confidence interval of greater than ±20 bpm (±2 standard deviations) results in the PSI 95 percent confidence exceeding ±1. This performance is inadequate for operational monitoring.**

common point of comparison. Monte Carlo simulations were then performed with varying correlation times and HR errors, given a fixed true HR (Figure A3). If heart-rate errors are correlated over time, then a bias term magnifies the resulting error in core temperature estimates embedded in the PSI algorithm. Our error modeling led to the conclusion that the wrist- and forearm-worn device HR accuracy would be insufficient for measuring PSI to less than ±1 on a 10-point scale, and thus inadequate for operational monitoring.

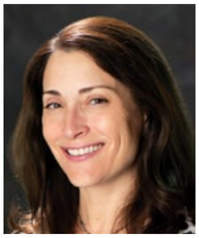
Testing results from the volunteers indicated that the consumer-grade optical HR monitors were not yet sufficiently accurate for military applications. These results need to be confirmed by testing on warfighters who are conducting operational tasks. It is clear that wrist-worn optical HR monitors are highly susceptible to motion artifacts from physical activity. In addition, the optical HR monitors' typical battery life of about one day for continuous monitoring is insufficient for military operations that could last for three days or more. Because of these two key deficiencies, we are now investigating how to improve robustness to motion artifacts while reducing the power of optical HR monitors.

About the Authors

Brian A. Telfer is a senior staff member in the Human Health and Performance Systems Group at Lincoln Laboratory. He joined the Laboratory in 1995 after working at the Naval Surface Warfare Center, where he was funded with an Office of Naval Research Young Scientist Award. His contributions to the Laboratory's R&D have been in signal processing, machine learning, artificial intelligence, and systems analysis, initially for ballistic missile defense and for the past seven years for bioengineering, particularly for physiological status monitoring. The focus of this work has been on prototyping and technology transition, with successful transitions leading to government contracts to industry for several hundred million dollars and smaller industrial contracts that have resulted in several hundred (and growing) physiological monitoring units. He has organized body sensor network workshops and has served as technical program cochair for the International Body Sensor Networks Conference in 2013 and 2015. He is a senior member of the IEEE and a member of the IEEE Technical Committee on Wearable Devices. He has also served on several Lincoln Laboratory internal funding selection boards and as the technical lead for the Laboratory's Introduction to Radar Systems course and other radar courses. He has led several studies for senior leaders in the U.S. government and has coauthored more than 70 publications. He holds a bachelor's degree in electrical engineering from Virginia Polytechnic Institute and State University and master's and doctoral degrees in electrical engineering from Carnegie Mellon University.



Kate Byrd is an associate technical staff member in the Advanced Sensors and Techniques Group at Lincoln Laboratory. Her work focuses on small RF systems and has included using optimization methods to design miniature wideband antennas for communication systems and designing small radars to detect the movement of disaster survivors under rubble. She originally joined the Laboratory in 2015 and worked in the Bioengineering Systems and Technologies Group. She was involved in biosensor design, testing, and data analysis. This work resulted in a patent for hardware designed to collect noise exposure and an R&D 100 Award for a system that monitors and prevents musculoskeletal injuries in soldiers. In 2018, she was accepted to the Lincoln Scholars tuition grant program for graduate studies. She holds a bachelor's degree in bioengineering from Clemson University and a master's degree in electrical engineering from Harvard University.



Paula P. Collins is the assistant leader for Lincoln Laboratory's Human Health and Performance Systems Group. She oversees efforts to advance integrated wearable sensing for human physiological, cognitive, and psychological performance monitoring, primarily in support of military operations. Prior to this position, she was a member of the technical staff, leading numerous projects to develop and evaluate a broad range of advanced technologies for biomedical applications; intelligence, surveillance, and reconnaissance (ISR) architectures; and air vehicle survivability. Over her career at the Laboratory, she has gained extensive experience with multimodal systems-of-systems sensor architectures, complex large-scale human-in-the-loop data collection, and data analysis for objective evaluation of proposed advanced capabilities. She holds a doctorate in experimental particle physics from the University of Pittsburgh.